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Contribution of virtual power plants to the resilience of the electrical grid

Résumé (Français)

Dans cet article, nous nous intéressons à un système technique alternatif en plein essor : à savoir les centrales électriques virtuelles (CEV). Il s'agit de systèmes sociotechniques en réseau qui agrègent une multiplicité de sites de production, de stockage et/ou de consommation énergétique au moyen d'un dispositif numérique de pilotage centralisé dans l'objectif de participer au marché de l'énergie et à l'équilibrage du réseau.

Nous analysons en quoi et comment les CEV contribuent à la résilience du réseau électrique, ainsi que les limites de ces contributions. Nous analysons également les reconfigurations et implications financières, socio-spatiales, métaboliques et politico-institutionnelles que provoque la participation des CEV à la résilience du réseau électrique. Nous concluons en mettant en évidence les vulnérabilités inhérentes à cette nouvelle configuration systémique, qui repose lourdement sur l'efficacité des signaux-prix, la rationalité économique des opérateurs et la vigilance des régulateurs de l'énergie.

Abstract

In this research paper, we focus on a new type of system. Virtual power plants (VPPs) are networked socio-technical systems that aggregate multiple energy generation, storage, and/or consumption assets, using a centralized digital control process to participate in the wholesale electricity market and in the grid balancing mechanism. We analyze how VPPs contribute to the resilience of the power grid, as well as the limits of these contributions. We also analyze the financial, socio-spatial, metabolic, and politico-institutional changes and the impacts to the centralized power grid caused by the involvement of VPPs. We conclude by shedding light on the vulnerabilities inherent in this new system configuration, which relies heavily on the effectiveness of price signals, the economic rationality of operators, and the vigilance of energy regulation authorities.

Keywords: virtual power plants; flexibility; power grid resilience; digital tools; aggregation; financial, socio-spatial and politico-institutional implications

Introduction

¹ Contribution according to the CRediT taxonomy: Conceptualization (lead), Funding Acquisition (lead), Investigation (equal), Methodology (equal), Project administration (supporting), Supervision (lead), Visualization (supporting), Writing – Original draft (equal), Writing – review and editing (lead)

² Contribution according to the CRediT taxonomy: Conceptualization (supporting), Funding Acquisition (supporting), Investigation (equal), Methodology (equal), Project administration (lead), Supervision (supporting), Visualization (lead), Writing – Original draft (equal), Writing – review and editing (supporting)

In the industrialized countries, historically since the centralization of the grids (Poupeau, 2018), grid operators and electricity producers-suppliers were few in number and often held a monopoly. These legacy operators alone were responsible for the running of electricity infrastructures and generation plants. It was up to them to maintain, repair, and improve equipment, facilities, and power cables, but also to handle routine stresses in order to guarantee the balance between electricity supply and demand at all times and to manage consumption spikes. They also had to handle exceptional risks³, i.e. events that were rare but particularly damaging in their impact (Guihou, Lagadec and Lagadec, 2006; Lagadec, 2007).

In many countries, the situation has changed profoundly since the 1990s and 2000s, as countries moved towards deregulation and decentralization, but also with growing worldwide awareness of the impact of climate change, which now exposes centralized power grids (CPG) to higher levels of risk (Mikellidou *et alii*, 2018; Panteli and Mancarella, 2015). Today, the legacy operators share responsibility for the operation of the CPG with a host of other entities of various kinds, with a whole range of different objectives and motivations. Alternative systems to the CPG are also developing.

In response to the challenges of climate change, decarbonization policies have boosted the use of electricity for multiple purposes and led to an expansion in decentralized facilities for generating renewable energy, in particular intermittent sources that can be connected to the medium-voltage and low-voltage grid. These distributed generation methods are a significant source of congestion on distribution and transmission systems, because these were not initially designed to allow injection and draw-off in both directions.

Some entities are therefore tasked with the responsibility for balancing the grid under contracts signed with the electricity transmission and distribution operators.⁴ These entities may be electricity suppliers, big consumers, or third-party actors from the finance sector; and in markets where deregulation is underway a growing number of them are involved in balancing the grid.

Similarly, in order to handle the problems generated by intermittent power generation, some market players contribute to demand-side flexibility either by offering dynamic pricing to give consumers financial incentives,⁵ or by undertaking load reduction or load shifting measures. Under European regulations, demand response programs can form part of the wholesale markets and ancillary services markets⁶ in the same way as electricity generation.⁷ In order to valorize energy in the form of ancillary services, market players respond to calls for tenders issued by the transmission system operators aiming to exploit flexibility of demand as an alternative to reinforcing system infrastructures.⁸ As part of the so-called adjustment mechanism,⁹ therefore, parties can sign a contract with the transmission system operator to help maintain the balance between supply and demand.¹⁰

In the last 20 years, security of supply imperatives have also encouraged the (re)emergence of alternative or additional technical systems to the CPG (microgrids, smart grids, etc.).¹¹ These systems are considered to hold out prospects for sustainable cities, although they have not yet really proved themselves (Finon, 2017). What they promise is to make the energy-climate transition a reality by facilitating a relocation in urban metabolisms, self-sufficient consumption, circularity, frugality, energy autonomy (Lopez, Pellegrino, Coutard, 2019).

These alternative systems are often described as providing grid backup services, seen as a principle of resilience, and services that offer greater local control of electricity flows as well as greater security of supply¹² by maintaining supply in the event of a CPG failure (Helmrick *et alii*, 2021, Derdevet, 2020). In their organization and operation, these technical systems constitute a break with the “networked city” paradigm and raise the

³ I.e. extreme and unforeseen events, for which there is no fixed response protocol.

⁴ On October 1, 2022, in France, for example, there were 70 balance responsible parties. <https://www.enedis.fr/liste-des-responsables-dequilibre>, [accessed on 10.25.22]

⁵ In France, for example, CRE ruling No2021-135 governs the dynamic pricing bids that suppliers of more than 200,000 sites will be obliged to place on July 1, 2023, in addition to their other supply bids. <https://www.cre.fr/Actualites/la-cre-modifie-la-definition-des-offres-a-tarification-dynamique-pour-mobiliser-rapidement-de-nouveaux-leviers-de-flexibilite> [accessed on 10.25.22]

⁶ Balancing needs on Europe’s electricity market are divided into three segments which require specific response times from market players: Frequency Containment Reserve (maximum response time of 30 seconds): available electricity reserves to correct an imbalance in the frequency of the electrical system at national and international level; Automatic Frequency Restoration Reserve (maximum 15 minutes, national level); Tertiary Reserve (maximum 2 hours, regional level), also called the adjustment mechanism. In other places, such as Australia and the ISO zones in the United States, these ancillary service markets are configured on different principles.

⁷ What is called the “demand-response market”. Directive 2012/27/EU of the European Parliament and of the Council on energy efficiency, Article 15, paragraph 8.

⁸ This was the case, for example, in France, with the “flexibility tender” issued in 2021 by RTE <https://www.services-rte.com/fr/actualites/flexibilites-appels-d-offres-experimentaux-pour-la-gestion-des-congestions.html> [accessed on 10.25.22].

⁹ RTE, “Becoming a balancing service provider”, <https://www.services-rte.com/fr/decouvrez-nos-offres-de-services/participer-au-mecanisme-d-ajustement.html> [accessed on 10.25.22].

¹⁰ In France, for example, there are currently 73 balancing service providers, 31 of which are also balance responsible parties. RTE, <https://www.services-rte.com/fr/decouvrez-nos-offres-de-services/participer-au-mecanisme-d-ajustement.html> [consulté le 25.10.22]

¹¹ Historically and originally, microgrids inspired by the small electricity networks of the 1880s-1920s, but fundamentally different in their operation because in technical terms they are interoperable with the CPG (Asmus, 2010).

¹² For example, through islanding processes: this refers to the capacity of a technical system, for example a microgrid, to disconnect temporarily from the CPG and to run autonomously drawing on local energy production combined with storage.

possibility of a “post-networked” urbanism, or an “augmented” grid (Coutard and Rutherford, 2016) in several respects. This principle of disruption could lead to new forms of economic and spatial inequality in access to energy and therefore in the resilience of areas served by these systems (Hodson and Marvin, 2009).

All this tells us that the legacy operators no longer have sole responsibility for maintaining power generation capacity in good order, in particular with respect to “exceptional” risks, because there has been a proliferation of production sources and possibilities controlled by new players. This loss of monopoly also applies to the handling of the CPG’s routine stresses, since a host of other actors contribute to the flexibility and balancing services. The same is true of national security of supply, because new technical systems run by other players have been added to CPG’s operations. All in all, the legacy players are no longer exclusively responsible for managing the resilience of critical CPG infrastructure.

This paradigm shift has not happened all on its own: it is sustained and structured by a set of policies, and supported by a profound reshaping of urban ecologies and infrastructures and by socio-spatial changes (Coutard & Rutherford, 2015). In this article, we examine these reconfigurations through the prism of a fast-growing technical system – virtual power plants (VPP)¹³ – which first emerged in the late 1990s but became a real presence in the 2010s. A VPP is a networked sociotechnical system that brings multiple energy generation, storage, and/or consumption assets under a centralized digital control process for the purpose of participating in the electricity market and helping to optimize energy generation and the grid balancing mechanism (Auer *et alii*, 2006).

A VPP operator may be a capacity aggregator, a load reduction aggregator, a producer-supplier, or else an energy service company that sells balancing services to the CPG and can valorize energy on the electricity markets.

In this article, we will first explore what role these kinds of actors and systems play in the resilience of the CPG. We suggest that the impact of VPPs and more broadly the impact of the development of aggregation complements the role of the legacy players in maintaining the resilience of the CPG. In other words, VPPs could be said to represent a way of outsourcing resilience management. The first question we will ask is: in what respect and how do VPPs contribute to the resilience of the CPG? And when VPP operators become central contributors to resilience, what changes and impacts will these systems bring about?

Analytical framework, methodology and fields of enquiry, paper structure

In this research paper, the definition of resilience we adopt is “the capacity of individuals, communities, institutions, businesses and systems within a city to survive, adapt and grow no matter what kinds of chronic stresses and acute shocks they experience.”¹⁴ We identified (Barroca *et alii*, 2013) as being particularly relevant to our study. Firstly, this article focuses specifically on the resilience of a technical system, which is also the center of our research. Secondly, it suggests four categories of resilience (cognitive, functional, correlative, and organizational) that we can draw upon in order to: (i) observe the contribution of VPPs at moments of crisis, as well as in anticipating and preventing such crises;¹⁵ (ii) encompass both routine stresses and major shocks; (iii) take account of the actors and spatial dimensions associated with the morphology of the power grids, so that our analysis is not limited to the technical dimension alone.

While the model set out in (Barroca and al, 2013) enabled us to formalize a description of the processes studied, in order to construct a relevant analytical framework we drew on a body of work that focuses on the characterization, emergence, and implications of the rise of alternative technical systems to the CPG (Coutard and Rutherford, 2015; Labussière and Nadaï, 2018; Lopez, 2019; van Summeren *et alii*, 2020; Jones *et alii*, 2022; Jaglin, 2019). We then compared this scientific output with other studies that explore the rise of alternative technical systems in terms of the more general resilience of the electricity system (Graham, 2010; Reghezza *et alii*, 2012, Tiernay 2015; Sage, Fussey and Dainty, 2015; Voropai and Rebtanz, 2019; Barroca, 2019; Helmrick *et alii*, 2021). In particular, we drew on (Coutard and Rutherford, 2015), who analyze the rise of alternative technical systems as instruments for the promotion of sustainable urban transitions. These authors, adopting a critical perspective on Sustainable Studies and Splintering Urbanism approaches, set out the bases for an analytical framework in which the variety of ambivalent forms and implications of the “post-networked city” can be analyzed critically, with a focus on the financial, socio-spatial, metabolic, and politico-institutional implications of alternative and decentralized forms of service provision (Coutard and Rutherford, 2015).

¹³ The analyses presented in this article are part of a larger ongoing piece of research (project “INTENS: Energy interface functions in cities of the Global North and South: objects, systems, actors, professions” (2020-2023), I-SITE FUTURE, coord. Sylvie Jaglin and Margot Pellegrino).

¹⁴ Definition given for the “100 resilient cities” project, <https://resilientcitiesnetwork.org/what-is-urban-resilience/> [17/09/22]

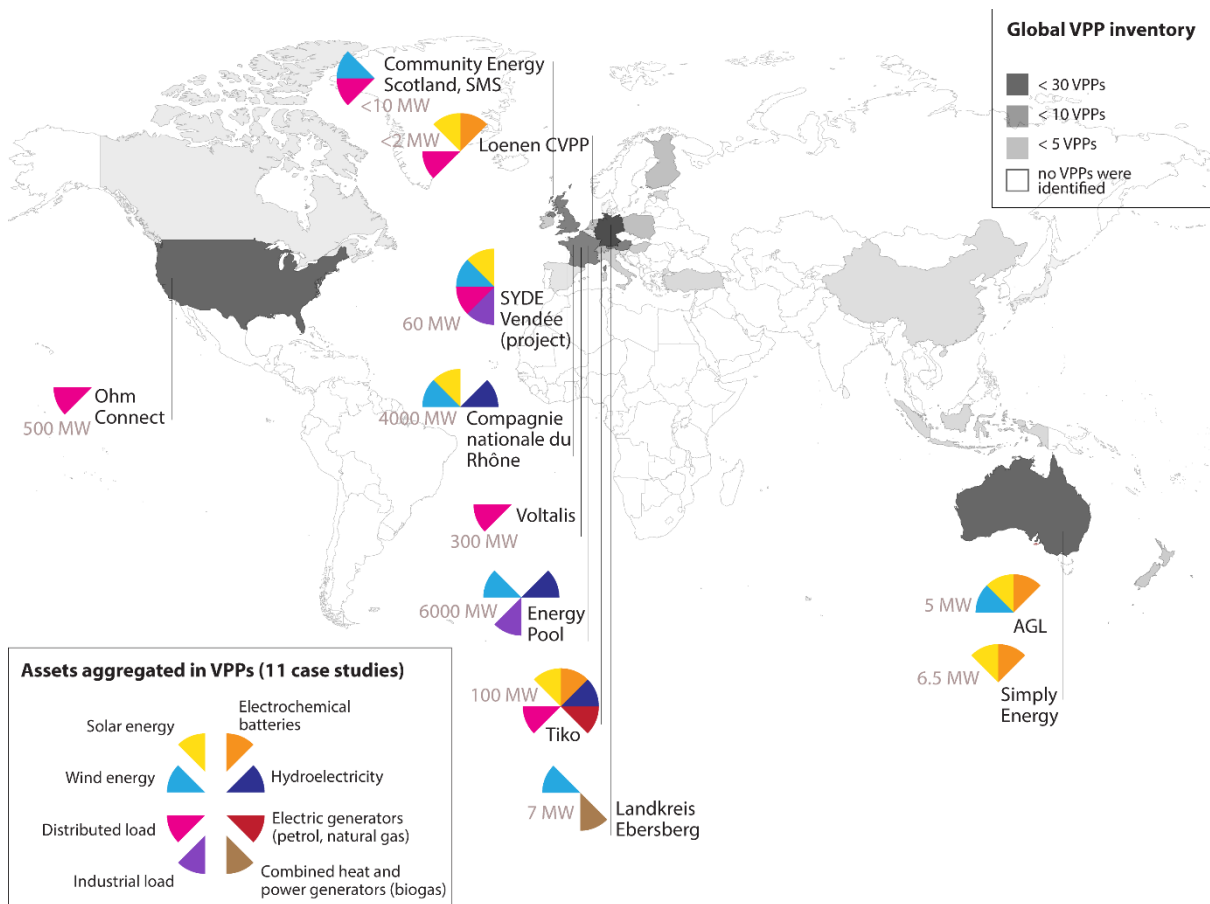
¹⁵ Because VPP operators act primarily, though not exclusively, to anticipate and prevent crisis by reducing routine risks and the possibility of an exceptional risk.

Finally, we would emphasize that what sets VPPs apart from other alternative technical systems is their dependence on the performance of the CPG, on the condition of its infrastructures and linkages. Not just the operation but the very existence of VPPs depends on innovations and investments in the digitization of the power grid, since VPPs are a system for the remote management of distributed energy assets. In addition, VPP operations depend on market mechanisms, because VPP operators make money out of electricity in the form of ancillary services or wholesale electricity markets. We therefore drew on other studies (Reverdy, 2016; Finon, 2017; Danieli, 2018; Gradclément and Nadaï, 2018; Percebois, 2021; Niebel, 2021) that explore these questions.

In terms of methodology, we began by conducting a review of the scientific and gray literature to arrive at a non-exhaustive inventory, divided into several categories, of more than 160 VPPs operating in Europe, North America, and the Asia-Pacific region (Figure 1).

By analyzing this inventory, we were able to paint a fairly comprehensive landscape of the different characteristics of operational and pilot VPPs, and to identify examples of VPPs that are particularly interesting and illustrative of the different ways such systems can contribute to the resilience of the CPG. We therefore focused on VPPs in the United States, in Australia, and in north-western and central Europe. We carried out a series of case studies and also conducted 18 semistructured interviews with representatives of VPP operators, their customers and partners, and representatives of power transmission and distribution grid operators¹⁶ (Figure 1; Table 1, in Appendix).

The article is divided into three parts. In the first section, we define and characterize VPPs on the basis of the results of our inventory, the analysis of the scientific and gray literature, and the interviews. Applying the model developed by (Barroca *et alii*, 2013), we describe the different ways in which VPPs contribute to the resilience of the CPG. In the second section, drawing on interviews and the scientific literature, we analyze the reconfigurations and the financial, socio-spatial, metabolic, and politico-institutional implications (Coutard and Rutherford, 2015) arising from the contribution of VPPs to the resilience of the CPG. Finally, we conclude by highlighting possibilities for future research.



¹⁶ Despite numerous attempts and several potential contacts, we were unable to interview anyone working for the French electricity transmission system.

Figure 1. World map with the location of the 160 VPPs identified and a breakdown of the types of energy assets aggregated within the VPPs selected for a more in-depth analysis (11 case studies). This inventory shows the concentration of the VPPs in Europe, North America, and in the Asia-Pacific region. Author: Marika Rupeka.

The contribution of VPPs to the resilience of the centralized power grid

Definition and characterization of VPPs

The term “virtual power plant” refers to the relationship of VPPs to the centralized power grid, because the effect of aggregating the output of numerous energy sources and/or numerous consumption devices is the formation of a single entity which resembles a physical power plant in its behavior (Yavuz *et alii*, 2019) (Fig. 2). In their publications, VPP operators stress the concept of pooling as the primary characteristic of VPPs. Unlike microgrids, which have an islanding function that enables them to disconnect from the CPG, VPP systems are superimposed on the CPG and run in synergy with it rather than independently.

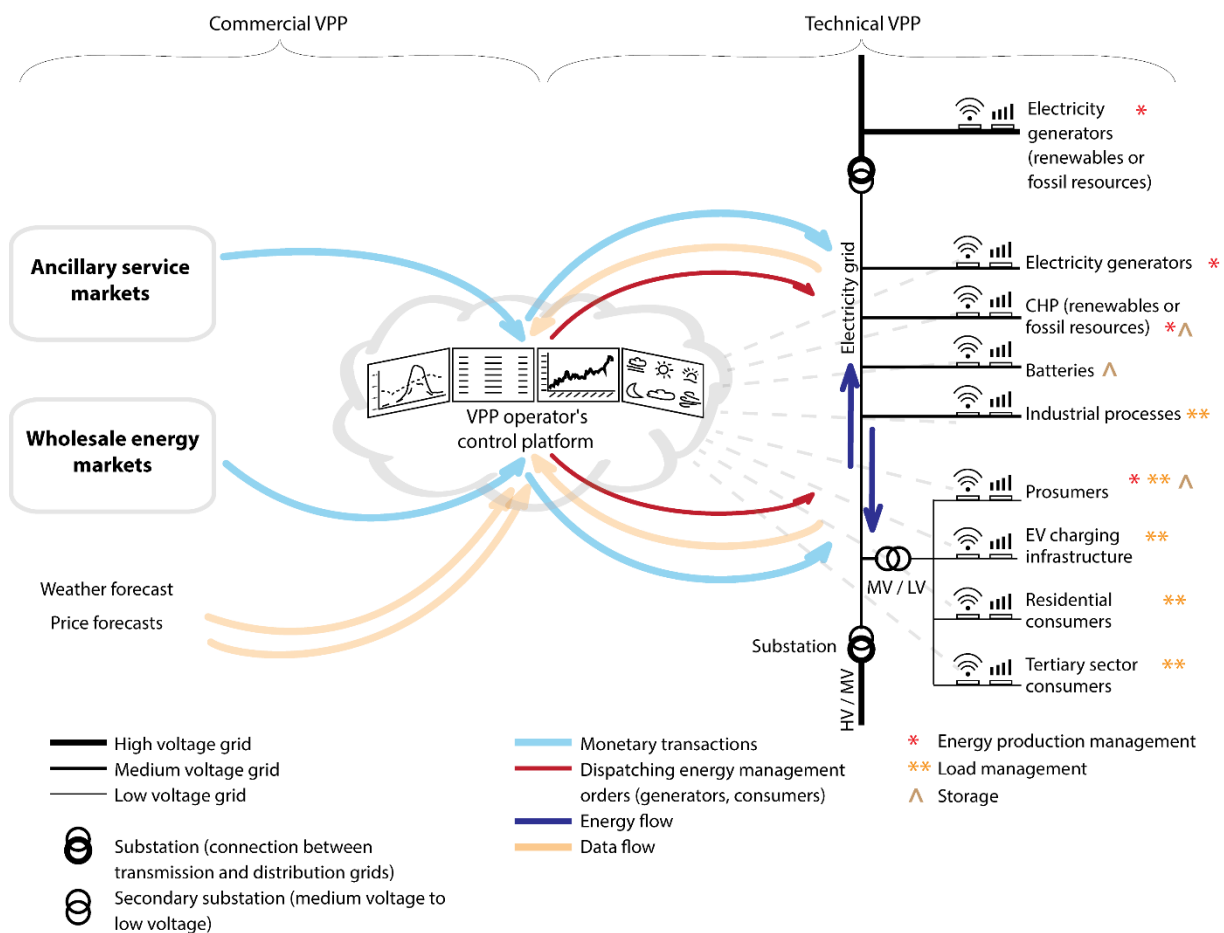


Figure 2. Flow diagram of a VPP, which appears as an interface between the energy markets and its energy-producing customers and partners, consumers, and prosumers. Energy assets are equipped with an Internet connection and/or a Sim card so that they can be managed remotely; these communication devices are sometimes doubled up for security reasons. Authors: Marika Rupeka and Margot Pellegrino.

There are different aspects to the benefits of VPPs for market players. Because a VPP operator plays the aggregator role, it can give small energy producers access to wholesale markets from which they are often excluded because of the capacity thresholds imposed by the regulations. The principle of aggregation enables the

VPP operator to reduce the imbalance settlement prices¹⁷ that solar and wind energy producers are obliged to pay in order to offset the difference (negative or positive) between energy sold on the wholesale market and energy actually produced on the reference day. The VPP operator asks them to defer or even cancel their energy consumption in return for a payment that the VPP operator is able to offer because of its participation in the markets.

VPPs run semi-automatically via a system that consists of a software platform and technical devices (smart boxes, sensors, smart meters) installed at the VPP customers' sites and connected to the platform via mobile and Wi-Fi networks (Figures 3 and 4).

Schéma indicatif d'une installation (monophasée)

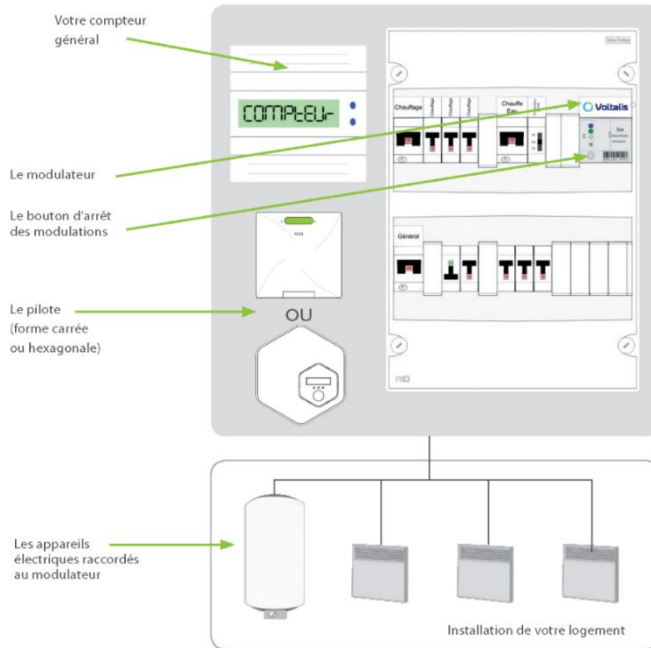


Figure 3. Sample schematic of a Voltalis set-up on a customer site. From top to bottom: general electricity meter, modulator, modulation stop switch, pilot, electric devices connected to the modulator. Iconography by Voltalis. Source: Voltalis, *Electrical heating consumption and management monitoring system. User manual*, March 2021, p.7. <https://www.voltalis.com/wp-content/uploads/2021/04/Notice-dutilisation-GAMME-CPL-Mars-2021.pdf>



Figure 4. Voltalis VPP control room and dashboard, France. Photographed by the authors.

While centralized aggregation and management of distributed entities is the defining characteristic of all VPPs, they differ from each other in many other respects.

A VPP works by aggregating scattered sources of generation, storage, or consumption within “pools”. Two thirds of the VPP we inventoried cover both production and consumption.

¹⁷ RTE, “Imbalance Settlement price calculation”, RTE, <https://www.services-rte.com/en/learn-more-about-our-services/becoming-a-balance-responsible-party/Imbalance-settlement-price.html> [22.04.2022]).

Our inventory highlights the wide variety of actors that can be VPP operators: energy aggregators, suppliers, and producers, manufacturers of electrochemical storage systems, and companies in the ICT sector. The great majority of VPP operators are private companies, with a few exceptions: local electricity companies under municipal ownership (like the Finnish firm Savon Voima Oyj), state owned companies (like Norway's Statkraft), companies under majority public ownership (such as Compagnie Nationale du Rhône in France).

With respect to energy sources and transmission, VPPs can aggregate a wide variety of contributors to the electrical system: windfarms, solar farms, hydroelectric plants, cogeneration plants (fueled by natural gas, oil, coal, biogas), but also electrochemical storage, which is set to play an ever-growing role as battery prices fall in the coming years (Fortune Business Insight, 2021).

When it comes to the volume of aggregated flexibility, VPPs vary very widely. Some VPP operators claim to operate with thousands of MW of flexible energy: these include Statkraft DE (>11,000 MW), Next Kraftwerke (>8,000 MW), Energy Pool (>6,000 MW). However, most of the fully operational VPPs run with a few hundred megawatts. The size of the VPPs is linked with the type of customers aggregated, which can range from private residential housing, through public and private facilities (hospitals, stores), right up to big energy generation and industrial sites.

Most of the VPPs we inventoried aggregate energy assets spread across significant spatial areas, either entire countries or, in federal states where the boundaries are imposed by national regulation, across territorial units. Some atypical VPPs are embedded in specific geographical areas, either for historical reasons (e.g. Compagnie Nationale du Rhône) or because of particular needs (e.g. Blue Pillar, which operates VPPs involved in maintaining security of supply for hospitals). More rarely, we identified community VPPs run by small operators on behalf of citizens with the aim of "taking back control" of the local community's energy supply (VPP at Ebersberg in Germany and at Loenen in the Netherlands; "Rescoop" demonstrator VPP currently on the drawing board in several European countries).

The diversity of models reflects the variety of VPP typologies, the common denominator being to capture value by selling energy products, whether on the wholesale energy markets, on the ancillary services markets, or on both (Braun, 2009, Ropuszynska-Surma, Weglarz, 2019).

Our survey also identified some VPP operators that export their services to countries other than their own. The industrial load reduction aggregator Energy Pool, for example, makes its aggregation platform available to a transmission system operator in Japan with the aim of finding customers that are big energy consumers and equipping them with smart boxes so that load reduction can be handled remotely. Finally, there is a specific business model that has been introduced by providers of services to VPP operators, like the German company Energy & Meteo Systems. As they explain: "(...) we are doing this business on behalf of the aggregators. We're not a market participant ourselves. (...) Now we are active for customers in five European countries with ancillary services and to aggregate renewables, we're active at least I think in 12 or 13 European countries, and also outside of Europe, like in India or some other like in Turkey."

The role of VPPs in the cognitive, functional, correlative, and organizational resilience of the grid

In their model, Barroca et alii (2013) describe the resilience of a technical system in terms of four categories: cognitive, functional, correlative, and organizational. We adopt the same categories to analyze the role of VPPs in the electric power system.

Cognitive resilience is the process of acquiring knowledge and know-how about risk so that stakeholders in a sociotechnical system can better understand its requirements and foresee the effects of any crises on this system or other similar systems (e.g. the electric power system or water infrastructures). Indeed, stakeholders' lack of knowledge, information, and awareness is a major obstacle to the implementation of resilience strategies (Beraud, 2013), increasing uncertainties and reducing the effectiveness of responses to risks. VPPs contribute to the cognitive resilience of the CPG through their capacity to generate knowledge about the components of the decentralized power system.

Indeed, VPP operators possess a mass of information about the energy consumed or generated by their customers, which may number in their thousands in aggregated pools in the case of distributed load reduction.¹⁸ Through the analysis of these data over both the short and long term, VPP operators can arrive at a better understanding of customer behavior, as explained by our interlocutor at Ohm Connect: "We feel very, very confident in our predictions of how users are going to behave during different events because we have so much data to tell us how different types of users perform in different circumstances." In addition to generating knowledge, VPPs help to make connections between existing data. The VPPs' digital platforms, generally called "SCADA systems",¹⁹ are used to collect the necessary data, to make decisions, and to send commands to

¹⁸ The quantity of energy consumed by the data flows generated by the VPPs is also an important subject, but we cannot estimate its scale accurately within the context of this study.

¹⁹ Supervisory Control And Data Acquisition systems.

customer sites, as well as to bring together large volumes of data that are normally lacking or processed separately.

Aggregated management of the VPP's assets also helps to reduce uncertainty and forecasting errors. Our interviewee at Compagnie Nationale du Rhône illustrates this capacity for the aggregation of power generation sites, which applies a scaling up and optimization principle that is also present in consumption pools. "[For] all these assets, the more you aggregate, the more production-related uncertainties will be balanced out between one set of assets and another. The uncertainty level is much higher on everything renewable and so Rhône's flexibility can be used to offset it [...]. It is the scale effect that makes this a valuable business."

However, the way the VPPs manage the data they produce and exploit raises questions about the complete lack of visibility of the VPP's internal operations for the legacy energy operators.

The algorithms developed by each VPP operator remain private, which means that the way they manage their assets is a black box for the other players in the energy system.

Moreover, our interviewees emphasized the importance of market "design" and of the rules that market actors must follow to stay in business and contribute positively to the resilience of the CPG. Yet this "design" cannot always prevent gaming practices that arise when market players find ways of profiting from asymmetries in strategic information. "(...) if you have a very liquid market, you hope that the market parties will compete with each other, then you will get a low price to solve your congestion problem, but there's also a risk for gaming (...) where market parties make abuse of the market circumstances" (interview with Tennet).

Functional resilience, in a situation of crisis, is defined as the capacity to keep the most important infrastructures operating by drawing on energy storage systems or other critical resources from other sources to maintain operations. This type of resilience requires a system with excess capacity or even a degree of redundancy in its components (Barroca *et alii*, 2013). The VPPs apply this principle of redundancy insofar as their goal is to offer additional components, for example electrochemical batteries and cogeneration systems, which can back up the centralized grid to avoid the risk of failure.

European Directive 2019/944 stipulates that electricity transmission and distribution operators must not develop and manage large-scale energy storage systems. However, system operators can sign contracts with other market players which invest in, run, and manage storage systems.²⁰ In Belgium, for example, a VPP was created for a group of industrial customers and for facilities in a local leisure park. To this end, the Centrica Business Solutions group formed a partnership with the transmission system operator ELIA and with Tesla for the supply of 140 batteries²¹ in order to meet local energy autonomy needs and avoid consumption spikes. However, a significant challenge to the use of battery storage is the requirement that the hosting capacities on the grid should be sufficient for these systems to be connected. In order to tackle this issue in the Netherlands, a recent change in the rules has allowed system operators to establish time-limited contracts with owners of industrial batteries.²²

The system operator Liander, which has already set up two pilot operations under this new contract method, recognizes that industrial batteries can aggravate congestion on the CPG, but takes the view that this way of handling energy and transmission system assets will ultimately be beneficial. "As a grid company, we will say: okay, if there is a 20-megawatt storage device, then we have to build the grid, so that we can provide 20 megawatts positive and 20 megawatts negative (...) So, the storage device can make the congestion problems even worse. And it is a solution for congestion [at the same time]."

To cite other examples, there are backup generators at Frankfurt airport that are integrated into the VPP run by the firm E.ON.²³ In the USA, optimum use of backup generators has been a significant help in mitigating the damage caused by grid blackouts. The company Blue Pillar Inc. started out as a provider of energy management services to hospitals, in particular the optimization of their diesel fueled generators.

In services of this kind, storage systems can play a leading role. In Australia, Tesla and the electricity supplier Energy Locals are in the process of developing the world's biggest VPP, comprising some 50,000 domestic solar battery systems with total storage capacity of 20 MW/54MWh. It has already proved its effectiveness in the event of grid failure (Figure 5). However, a significant constraint is the Australian market's dependence on European and South Korean companies, since at present Australia has no industrial battery production sector

²⁰ The European Federation of Energy Traders, "EFET position paper on the ownership and operation of storage assets A guidance proposal for the implementation of the recast Electricity Directive (2019/944)", EFET, 13 September 2019, p.2, https://eepublicdownloads.entsoe.eu/clean-documents/Network%20codes%20documents/Implementation/stakeholder_committees/MESC/2019-09-17/EFET_SO%20Ownership%20of%20Storage_13092019.pdf?Web=1 [24.10.2022].

²¹ « Retour d'expérience Terhills », site de l'entreprise Centrica Business Solutions, <https://www.centricabusinesssolutions.be/fr/case-study/la-centrale-electrique-virtuelle-la-plus-moderne> [23.11.2020].

²² Ames Biogradlija, "Regional operators begin battery storage trials for more efficient grid use", Industry & Energy, 11/07/2022, <https://www.industryandenergy.eu/storage/regional-grid-operators-begin-large-scale-battery-storage-trials-for-more-efficient-grid-use/> [24.10.2022].

²³ "E.ON expands its virtual power plant", *Energy Business*, 01.11.2017, <https://www.nsenerybusiness.com/features/featureeon-expands-its-virtual-power-plant-5961077/> [19.08.2021].

(interview with Simply Energy). In addition, a more general problem with the large-scale use of battery storage is the availability of raw materials, such as nickel, copper, and lithium, sectors that are highly sensitive to geopolitical conditions. The bigger the role of these battery storage devices becomes in our power systems, the greater will be the dependence on the security of supply chains for critical materials.

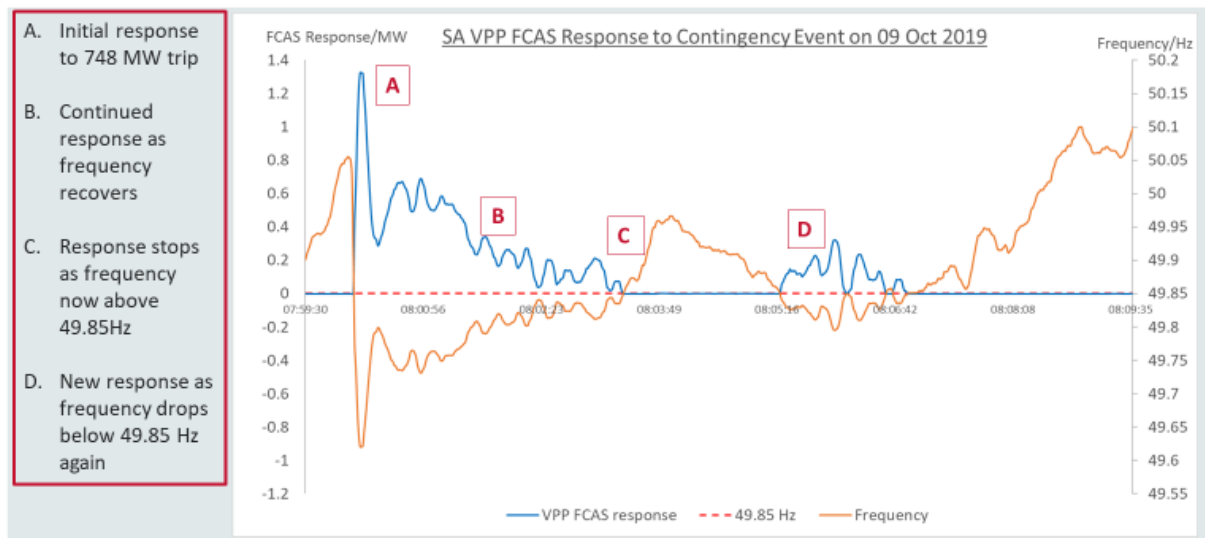


Figure 5. In October 2019, the National Electricity Market’s (NEM) biggest generation unit (at Kogan Creek in Queensland) malfunctioned and the frequency of the grid immediately dropped to 49.61 Hz, which is below the normal operating range. South Australia VPP (SA VPP) detected this frequency anomaly and immediately responded by injecting energy into the system and helping to stabilize the frequency. Source: AEMO, 2020.

Correlative resilience is defined as the adaptation of needs to service capacity through the possibility of running in fail-soft mode (Barroca *et alii*, 2013). The technical, digital, and operational systems that maintain synergy between the energy producers, storage devices, and consumers, enable VPPs to optimize energy flow management by reference to market price signals and weather forecasts. As a result, both energy needs and supply can be adjusted to the capacity of the grid, thereby preventing routine risks (congestion, stress, imbalance between supply and demand).

In Switzerland, biogas production is used as an instrument of flexibility in the VPP run by the aggregator Fleco Power, which combines the output of methanisation plants by using cogenerators with the output of photovoltaic and hydroelectric plants. When there is overcapacity on the grid, the biogas plants continue to produce gas which will be temporarily stored. Later, this biogas can be used to generate electricity in order to compensate for fluctuations in photovoltaic production (Vogel, 2017). However, there are limits to the flexibility provided by biogas, because the storage facilities can only accommodate a specific volume. It is difficult to increase these volumes given that the stakeholders will not spend their own money on them if they see no direct benefit.

VPPs also contribute to the CPG’s correlative resilience through their capacity to adjust the operating mode of either all or some of the assets they manage in order to avoid a system malfunction. VPP operators may therefore need to “call” on their customers to adjust their consumption or production very frequently. In 2018, Ohm Connect handled 726 dispatch cases in 182 days at times of high stress on the grid (interview with Ohm Connect).

Any large-scale aggregation of energy assets relies on the performance of the telemetry and remote control devices (Percebois, 2021, Niebel, 2021). The people we spoke to at the energy generation-supply company AGL note that all smart systems are vulnerable to cyber-attack, and VPPs are no exception.

In addition, as evidenced by the example of City-Zen Smart in the Netherlands, digital communication failures (whether 4G or Wi-Fi) can result in “relatively low reliability of the VPP (..), far lower than the reliability of vital infrastructures like the energy grid.”²⁴ Finally, given current prices, the actions of VPP operators can sometimes exacerbate stresses on the grid. In the case of City-Zen, VPPs have been observed to have a negative effect on the grid when energy is sold and delivered at times of peak load. Conversely, current prices can negatively affect VPP operators. As Mr. De Vries, CEO of Ohm Connect in California explained, “(..) after being asked by a state official to provide load, the company lost \$100,000 to \$200,000 after paying its customers. Ohm Connect was happy to help the state through a major crisis, but can’t regularly lose money as a

²⁴ Emma Gerritse (LIAN), *City-zen, a balanced approach to the city of the future*, 2019, http://www.cityzen-smartcity.eu/wp-content/uploads/2019/12/city-zen_d5-7_d5-10_d5-11_d5-12_d7-4_cityzen_smart_grid.pdf [27/10/22].

result of the market not working properly” (Cohn, 2020). The current market structure is not always able to reward load reduction aggregators sufficiently for the service they provide, which could prompt them to stop supplying this type of service at specific times.

Organizational resilience is the capacity of a group of actors to cover technically and spatially larger perimeters and recruit the skills and resources of other actors to exploit solidarity between scales and absorb the negative effects of an incident (Barroca *et alii*, 2013).

Hence, especially in the case of extreme events (Barton, 2021), the VPP can use its assets to relieve stress on the CPG and avoid or reduce the risk of failure. In the US, for example, VPPs contribute to the resilience of the grids during heatwaves or cold snaps, or in the event of storms. During a heatwave in California, Ohm Connect committed its customers to reducing total energy consumption by almost a GWh, the equivalent of removing more than 600,000 homes from the grid for an hour. Ohm Connect activated and deactivated its customers’ equipment 739,000 times to save energy and reduce stresses on the grid, paying users a million dollars and helping to avoid additional blackouts (Pickerell, 2020): “To put it simply, [the grid operator] was going to run short of energy (...). So they went to OhmConnect, they went to virtually every provider that there is out there. (...) OhmConnect issues our alert and says: Can you please reduce your energy usage? And it drops by 20%. We held it there for two hours until the grid could come back and be able to produce the amount of energy that they needed to meet demand” (Fig. 6).

A few similar cases have been recorded in France. Our contact at Energy Pool, for example, mentioned an operation carried out in Brittany during a storm that had deprived part of the grid of its power generation resources, a shortfall that the aggregator offset via load reduction measures.

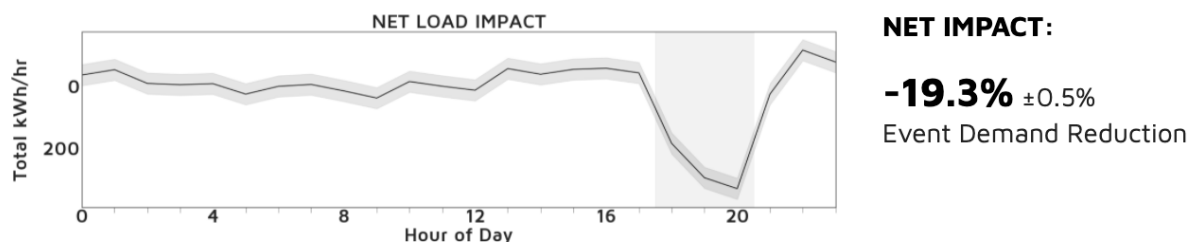


Figure 6. Net hourly impact of load reduction by Ohm Connect on energy demand (August 14, 2020). Source: (Recurve, 2020)

According to the aggregator Voltalis, another type of service that VPPs can perform for the grid is to avoid or reduce the use of load shedding for entire *départements*, or even regions. Load shedding refers to the deliberate implementation of rolling electricity blackouts by grid operators on a section of the grid in the event of stresses and severe congestion in order to avoid a full grid blackout.

Solidarity between scales can also work for islands. The VPP developed on the Orkney Islands in the north of Scotland shows the advantage of maintaining a link with the Scottish grid to optimize investment and take maximum advantage of renewable energy sources. In this case, the VPP is able to optimize energy generation and reduce congestion on the power grid that supplies the 8 largest of the total 70 islands in the group. Our interlocutor at Community Energy Scotland, a renewable energy action group, believes that disconnecting the island group is not an option, either now or in the near future. On the contrary, the aim is to take advantage of the connection with the Scottish grid, which currently relies on several undersea cables that the grid operator intends to reinforce and double in the near future.

These examples show the importance of the synergies between VPPs and centralized grids. However, the representatives of the company AGL we spoke to relayed a concern expressed by the stakeholders on Australia’s grids, which is the difficulty of foreseeing how each VPP operator will behave in cases where large numbers of them are present on a single energy market. Their reliance on price signals could be a source of imbalance, because the pursuit of economic profit is not necessarily consonant with the physical needs of the grid. According to our interviewees, it is up to the energy market regulators to set the framework governing the operation of the VPPs, in order to ensure that they benefit the grid and consumers, and do not cause collateral damage.

In this part of the article, we have described how VPPs contribute to the resilience of the grid, and analyzed the limits to the effectiveness of their contribution.

To sum up, for VPPs to make a positive contribution to grid resilience, the “design” of the markets is particularly important. The operating conditions in the ancillary service and electricity wholesale markets are developing

unevenly in countries where the electricity sector is deregulated. The quantity and complexity of these markets is both an advantage and a problem for the stakeholders, who have to learn how to reconcile the imperatives of financial profit with a more general contribution to the smooth running of the grid. But it is also a problem for the grid operators who have to make sure that sharing responsibilities with other players does not generate negative externalities.

The VPPs' contribution to the resilience of the grid seems to depend on the smooth operation of the communication networks, but there is also the question of grid density and interconnection in terms of cables and optical fibers. Some areas are already better equipped in this respect, or capable of becoming so rapidly. We are hence seeing the emergence of an issue of territorial inequalities for energy consumers and producers.

In a scenario where the VPPs' contribution to the resilience of the grid depends on battery storage, the availability of critical materials and the robustness of recycling processes constitute real medium-term and long-term challenges. And in the short term, installing batteries in areas of high grid congestion is often limited by the size of the grid, which may be insufficient to connect large additional capacity.

Our study also shows that VPPs have a role to play when they aggregate both customers scattered across large areas and customers concentrated in small areas. Indeed, organizational resilience is needed, especially in setups where solidarity between areas and stakeholders can be a game-changer, but it is not necessarily an economically profitable service. To what extent can VPPs act as a mechanism for managing the power system without evidence of immediate financial returns?

Financial, socio-spatial, metabolic, and politico-institutional implications of the contribution of VPPs to the resilience of the grid

Reconfigurations and financial implications

According to some aggregators, it is likely that the contribution of VPPs to the resilience of the grid is one of the indirect consequences of underinvestment in the reinforcement and modernization of public grids. Our interviewee at Voltalis, for example, claimed that “the fact that we are in a critical situation today is due to 25 years of chronic underinvestment in the development of electricity generation. (...) What we can do is make sure that there is no need for load shedding with rolling blackouts.”

Mirroring this, some VPP operators emphasize the capacity of VPPs to act as a genuine alternative to structural operations on centralized grids, and hence to avoid the need for costly investment in grid reinforcement. According to the English start-up Moixa, combining electricity storage systems with solar panels can reduce the need for extra spending on the grid, because software algorithms can identify the best time to charge and discharge batteries, thereby reducing pressure on the grid (Sanderson, 2021).

Some market players take these ideas to the extreme. For example, the CEO of Sunnova²⁵ recently claimed that public energy policies in the United States should rely more on consumer flexibility than on grid modernization: “Let the market work, let consumers have a choice of what they want (...). The market will find a more efficient change to the energy system than a top down, almost communistic-style approach” (Sanderson, 2021). So new long-term possibilities seem to be emerging, between the development of flexibility options and the construction of new power cables in congested areas (Finon, 2017).

Together, all these factors suggest that in most of the current business models based on energy and associated services, revenue generation is moving “downstream” towards the commercial end of the business. As a result, financial resources for the “upstream” parts of the system (big power stations, grids) are under constantly growing pressure (Coutard and Rutherford, 2015). The emergence of flexibility options, encouraged by public policies, can be seen as an alternative that avoids or defers the cost of improvements to grid infrastructures. Moreover, in many European countries, such as France and the Netherlands,²⁶ grid operators are not allowed to set up commercial services like VPPs.

This means that some of the costs of making the grid more resilient to routine stresses are passed onto private actors other than the legacy operators. The result is that the grid's capacity for resilience is entrusted to a market-based form of governance (Reverdy 2016). This observation accords with the views of a number of authors: by gradually implementing the EU's regulatory frameworks and adopting a neoliberal approach, energy and climate policies have increasingly come to rely on the supposed capacities of the market to overcome the current obstacles and dependence on highly carbonized energy sources (Grandclémant and Nadaï, 2018).

In countries where there is less pressure on the grid, some authors warn against overestimating the scale of what can be done by means of flexibility (Finon, 2017). Among the representatives of the electricity transmission and distribution system operators we interviewed, there are varying degrees of confidence about the possibility of

²⁵ One of the main suppliers of residential solar energy and energy storage services in the United States.

²⁶ Wet Onafhankelijk Netbeheer., in: “Regulering”, Netbeheer Nederland, [https://www.netbeheer Nederland.nl/dossiers/regulering-20\[21.10.2022\]](https://www.netbeheer Nederland.nl/dossiers/regulering-20[21.10.2022]).

avoiding investment in infrastructure through the flexibility offered by VPPs. These differences of perspective can be attributed to multiple factors, which are specific to the territories concerned, to institutional cultures, and to conditions of the activity system. The operator of Consolidated Edison's distribution systems in the United States describes the VPP as "one of those non-wire solutions that essentially makes it possible to reduce demand so that we don't need to upgrade the infrastructure and can defer that infrastructure upgrade". By contrast, the representative of CAISO, which operates transmission systems in California, expresses a more moderate level of confidence, because he sees difficulties with the technical, legal, and economic complexity of VPPs.

Overall, grid operators continue to plan long-term infrastructure investment and to develop resilience programs and measures, like the new emergency load reduction market that the operator of California's transmission grids set up as an experiment in 2021. The Dutch distribution grid operator Liander told us that they plan to invest massively in infrastructures, which are experiencing serious stresses (Figure 7), in order to increase capacity. However, since these are big, costly operations that take time, the role of VPPs is seen as a short-term solution.

In other words, VPPs would appear to function as a supplementary mechanism, superimposed on other physical and economic solutions that grid operators are gradually implementing.

If these sociotechnical systems grow, the centre of value could shift. Decentralized power generation resources would count less, and value would firstly shift back to the grids as a fundamental means of stabilizing, connecting, and satisfying local needs, and secondly to the VPP itself as a sociotechnical system which, while lacking the capacity to transmit or generate electricity, is able to aggregate and optimize the management of multiple points of production or consumption, in other words capable of managing electricity flows.

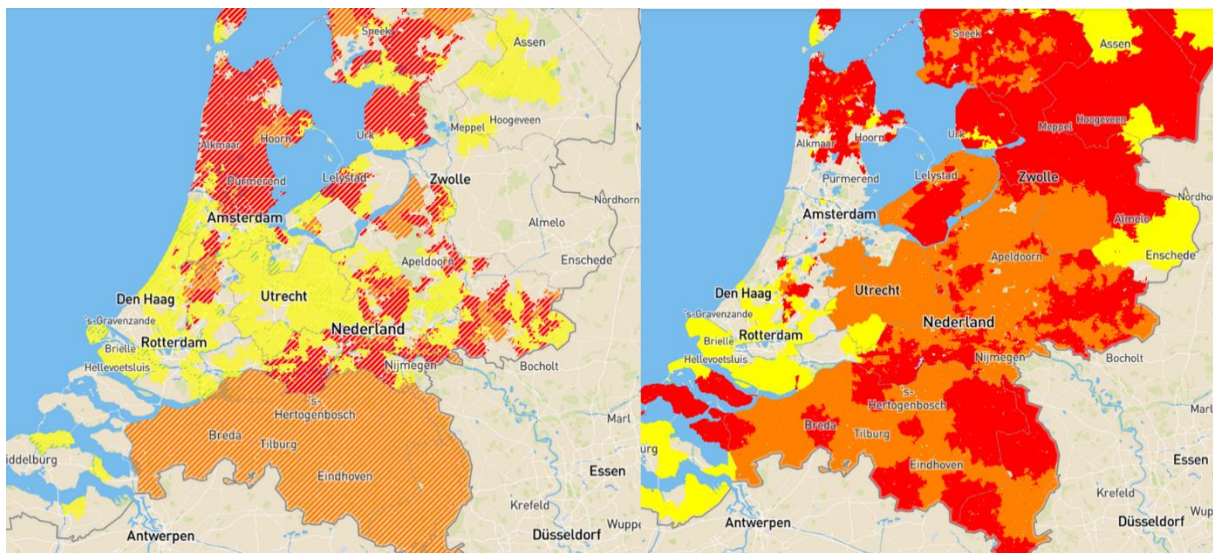


Figure 7. Capacity map of the Dutch national power grid: Withdrawal (on the left) and injection (on the right). Legend: yellow, threat of transmission shortage; orange, warning of structural congestion; red, structural congestion, new transmission requests are not met. Source: « Capaciteitskaart elektriciteitsnet », Netbeheer Nederland, <https://capaciteitskaart.netbeheernederland.nl/> [27/10/22]

Reconfigurations and metabolic and socio-spatial implications

The aggregated management of multiple electricity consumption points raises questions about the role of users. Recent directives and public policies over the last 10 years, both in Europe and elsewhere, place end-users at the center of electricity markets and encourage frugality and individual responsibility.²⁷ In these directives and policies, end-users are perceived as particularly rational and connected players, capable of actively and independently monitoring and reducing their consumption thanks to devices such as Linky smart meters in France. Responsibility for the resilience needs of the grid is partly handed over to consumers (Bhuiyan *et alii*, 2021). The burden of commitment and responsibility is placed on the individual: consumers thus become "heroes" of resilience (Reghezza-Zitt, 2012; Tierney, 2015).

²⁷ This has further intensified since the energy crisis that has followed the war in Ukraine.

However, a number of studies have shown that it is very difficult to get end-users to adopt active attitudes, since they are either unwilling or unable to track their own consumption in real time, or to modify it in response to price signals (Farruqi and Segerci, 2009, Danieli, 2018). It seems more plausible to imagine this role being played by VPP operators, which are tasked by some consumers with the management of their hourly consumption (Finon, 2017). In most VPPs, consumption management is centralized and automated and individuals therefore play a passive role, which is simply to agree the overall framework of interventions with the VPP operators.²⁸

These observations suggest that VPPs, because of their aggregation-based method of operation, represent a new form of centralization. In tomorrow's electricity system, aggregation may become crucial to the smooth operation of the grid and aggregation actors would play an essential role, leading to a new distribution of competences with the legacy energy operators or else to a reconfiguration of the latter's role.

This new form of centralization has socio-spatial implications and the potential to create a number of pressures. First, the way VPP governance is managed by the new players seems to be partially disconnected from geographical location. Indeed, unlike other alternative technical systems such as microgrids, VPPs can be structured at a variety of scales: local, regional, national, theoretically even international.²⁹ The aggregated management of renewables alters and potentially reverses their intrinsic meaning: rather than local sources of energy for short supply chains or self-consumption (horizontal integration), they become a means to stabilize the existing grid (vertical integration), under a process described by (Macrorie and Marvin, 2019). This is true even where the goal of the VPP is to provide a local scale service and it is run by the community. On this question, the account given by SDP Loenen, a community organization involved in the development of a local VPP, is very significant: "Originally, we said: we're only going to work on residential. (...) But we have a lot of farmers in the village (...) we actually also said: well, we also have some industry nearby. (...) Ok, but if I scale up, don't I lose identity? (...) I think that's the phase that we're in now: to find out if you can find the sweet spot for economy of scale." Van Summeren et alii (2020) showed with their study of the development of three community level VPPs that, over time, the initial goals of creating a local service for local consumption evolved into the pursuit of revenue in return for grid balancing services. This obliged the three communities to conform to the existing market rules and to operate at a larger scale, in collaboration with the system's incumbent players.

Secondly, as our interlocutor at ENEDIS pointed out: "There is something rather contradictory between the desire of the aggregators to aggregate and cover multiple hazards, and the fact that the local constraints of the grid are by definition local. This has resulted in the situation that for problems of excess consumption we have called for bids for flexibility services and that they have largely been fruitless. VPPs that manage diffuse national scale assets can only contribute in proportion to the density of their customers at local level, and may not be able to deal with localized stresses on a section of the grid. This situation could change if the aggregators are able "to concentrate enough load reduction contracts within an area close to a congestion point (...), or else if the grid operators were allowed to build storage units in those same areas, which for the moment runs counter to EU principles" (Finon, 2017, p. 28).

It should be emphasized that there is a significant difference between transmission system operators and distribution system operators in their relationship with VPPs and the services they provide for the grid. In areas where they have set up ancillary services of some kind, transmission system operators have already become coordinators of shared responsibility in maintaining the balance between electricity supply and demand. However, this is much less the case for distribution system operators, although the creation of local flexibility markets is a significant possibility that is being tested in exploratory projects.³⁰ Today, the debate on the contribution of VPPs to grid resilience is more about the density of the transmission system, a principle that might seem paradoxical in that many VPP customers are connected to the distribution system (especially residential customers).

In addition, while VPPs provide services to avoid or reduce the risk of grid failure, they are less useful when such a failure occurs. Indeed, unlike microgrids, only VPPs equipped with batteries and power generation systems can provide electricity for individual customers, rather than at neighborhood scale. Another form of energy geography emerges in relation to microgrids when there is a grid failure, but it raises the same questions with respect to spatial justice around energy supply services (Barroca, 2019).

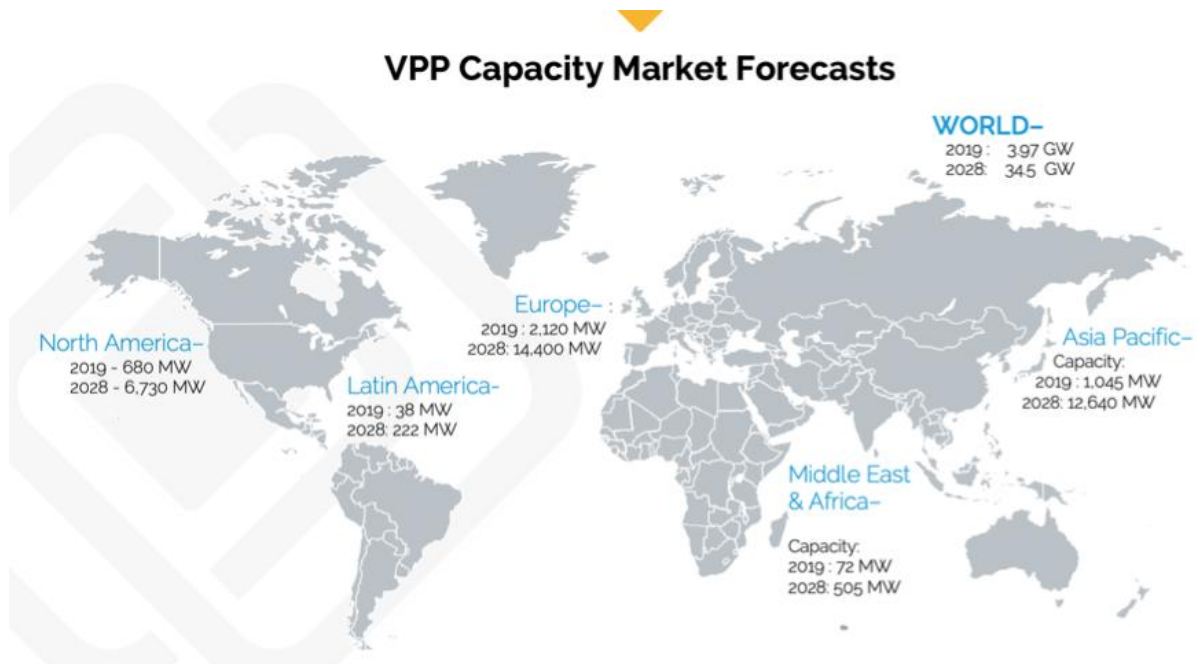
Reconfigurations and politico-institutional implications

²⁸ For example, deciding what piece of equipment can be cut off, indicating that no operation can be carried out at a given moment, etc.

²⁹ Nonetheless, limits remain: "There are criteria of distance, proximity, angiography, because (...) you have to manage activation times. (...) If my load reduction message has to go all round the world before it reaches my software, (...) it will never work" (interview with Energy Pool).

³⁰ Such as the "Rescoop VPP" in Belgium, the "GOPACS" platform in the Netherlands.

Historically, VPPs have their roots in the concept of the “virtual operator” defined in the 1990s to describe a new form of supply of energy services at a time of energy market deregulation in the United States. The “virtual operator” was an aggregator of energy assets belonging to partner-customers who wished to participate in different energy markets, which themselves were undergoing rapid change (Hyman & Smith, 1997; Awerbuch & Preston, 1997). So the goal was to contribute to a change in the energy markets by defining a new kind of actor, which would be able to find economic value elsewhere than the traditional players and would support the centralized grid through future changes by supplying it with services. In the last decade or so, VPPs have developed all around the world, driven in particular by energy transition policies (Yavuz *et alii*, 2019, Yu *et alii*, 2019), as well as the possibilities afforded by digital technology (Percebois 2021). The expectation is that this



development will continue (Figure 8).

Figure 8. (Navigant, 2019) foresees a significant increase in the number of VPPs used around the world, from capacity of almost 4 GW in 2019 to almost 35 GW in 2028.

In France, and globally in Europe, the emergence of VPPs can be linked with the need for flexibility and demand management. In his study on the emergence of distributed load reduction services in France, notably conducted by the VPP operator Voltalis over the period 2006-2013, (Reverdy, 2016) explores the question of the connection between political planning and techno-economic expertise in the adaptation of market rules to emblematic and innovative services associated with energy transition, and reveals the tensions between the different players. The author argues that while, on the one hand, the electricity sector remains very tightly and rigidly regulated, it is also characterized by a powerful political dimension, since the political authorities have no intention of relinquishing control to independent authorities. Moreover, “Voltalis’s strategy helps to politicize the debate. Its action probably led to distributed load reduction becoming one of the essential technologies of the energy mix” (Reverdy, 2016, p.24). In other words, the use of load reduction is the outcome of public action by the regulatory bodies, but also by the main commercial players that provide this service (Grandclément and Nadaï, 2018).

In other countries, the emergence of VPPs has more to do with climate risks and the exponential growth in decentralized energy sources, in particular photovoltaic electricity production units.

In California, VPPs offer a specific advantage, because they have the potential to provide backup services in the event of grid failures caused by forest fires and extreme heat events (Jones *et alii* 2022, p.144). The people we spoke to at CAISO and at the aggregator Ohm Connect stress the scale of the problems caused by a timing imbalance between energy supply and demand over a single day as a significant factor in the emergence of VPPs in California. The expression “duck curve” is commonly used in the energy sector to refer to the graph of this imbalance phenomenon, because the mass influx of renewable energy leads to an energy supply surplus in the middle of the day. As for the regulatory framework, the VPP business remains relatively ill-defined in California, and elsewhere in the United States, and the operators of these systems enjoy a range of economic opportunities that are gradually emerging, for example the “Demand Response Auction Mechanism”, a

consumption management market that was introduced into California in 2016 by the transmission system operator and the California Public Utilities Commission (CPUC) (Jones *et alii*, 2022).

In Australia, renewable energy capacity per inhabitant is increasing 10 times faster than the global average. In some regions, like South Australia and Queensland, where there are large numbers of solar installations, the stability of the grid is particularly threatened at certain times when low electricity demand coincides with high solar generation. In consequence, regulations were introduced in 2020 to allow electricity generation from solar panels to be curtailed during peak grid periods. The Australian energy market operator (AEMO) had forecast potential capacity of 700 MW for the development of VPPs before 2022. While this level was not reached, several very large VPPs³¹ have nevertheless emerged recently, encouraged by other policies that strongly support the use of batteries and their integration into centralized power grids to mitigate the imbalance effects caused by renewable energy (Jones *et alii*, 2022). Indeed, according to the people we spoke to at the supplier Simply Energy, the emergence of VPPs in Australia is closely tied to the roll-out of batteries. The public sector in that country is playing a leading role in the development of VPPs. In fact, the Australian Renewable Energy Agency (ARENA) is funding several projects with the aim of studying the possibilities of incorporating VPPs into the operation of the grid, and is running a Distributed Energy Integration Program. This program brings together a total of 13 organizations, including market authorities, regulators, trade organizations, and consumer groups, with the aim of supporting research on the aggregation of renewables, batteries, and other systems such as electric vehicles (AEMO, 2020; interview with AGL).

In this section, we have analyzed the multiple implications of the contribution of VPPs to the resilience of the grid. With the input of VPPs, methods of maintaining the resilience of the electrical system are evolving steadily, and this resilience is both a current and long-term reality. These virtual systems seem to be as important in the management of the uncertainties and specifics of the grid as in the response to exogenous uncertainties, whether geopolitical, economic, or linked to legislative changes. This belief in the capacity of the VPP to act as a “Swiss army knife” in the electrical system, in partially or totally liberalized markets, implicitly entails outsourcing and delegating part of the investment in grid resilience to the private sector. This raises questions about the future risk of underinvestment in infrastructure resources specific to the electricity transmission and distribution systems, investment that is required at all territorial scales. Aggregated management of renewable energies leads to value being transferred from the transmission and distribution systems to the management of energy flows. It is also driving a (re)centralization process that is transforming the role of renewable energies from local resources to resources that serve the grid. Finally, it would seem that the role of the end consumer is becoming secondary, while at the same time there is a trend towards an (over)emphasis on individual responsibility.

Conclusion

The emergence and roll-out of VPPs is the outcome of liberalization and energy transition policies, as well as the possibilities afforded by digital technologies. Many electricity transmission and distribution system operators, and obviously the VPP operators themselves, believe in the capacity of VPPs to increase the resilience of the grid through a range of services. These services are built around the principle of aggregation and seem to constitute a new form of centralization applied to the management of energy flows, as well as an outsourcing of responsibilities for grid resilience to actors other than the legacy operators.

But while VPPs carry a promise of resilience for the grid, could they also represent a new source of fragility?

The way VPPs function with the centralized power grid is in fact somewhat ambivalent. On the one hand, VPPs place the grid back at the heart of the electricity system by precluding any process of disconnection, islanding, and energy secession, as networks of other types seem to do.³² In fact, VPPs act in symbiosis and solidarity with the grid, by providing it with the services we have mentioned. But on the other hand, VPPs make the grid dependent on their services, because they do not directly increase its resilience, as would investment in infrastructure reinforcement. Instead, the presence of VPPs contributes indirectly to resilience by mitigating the fragilities of the grid with services that are controlled exclusively in-house by the VPP operators, most of them private.

VPPs rely largely on existing energy assets and to a lesser degree on new investments by customers (batteries, energy generation sites), and their hopes for sufficiently large-scale behavioral adjustment to avoid any

³¹ Like the one, mentioned above, run by Tesla and the electricity supplier Energy Locals.

³² This is the case of certain microgrids. Regarding these processes and their connections with the notion of energy autonomy, see also (Lopez, Pellegrino, Coutard, 2019), notably the introduction (Lopez, Pellegrino, Coutard, 2019), and chapters 13 (S. Jaglin, 2019) and 14 (B. Barroca, 2019).

destabilization of the power grid. Themselves dependent on the communications system for their operation,³³ VPPs have their own intrinsic vulnerabilities that expose them to the risk of hacking and cyber-attacks. In addition, the financial viability of VPPs depends on constantly evolving market mechanisms. The fact that these mechanisms are unpredictable in both the short and long term can become problematic. The market as currently structured does not always seem to ensure that load reduction aggregators achieve returns commensurate with the service they provide. Another concern is the difficulty of predicting the behavior of every VPP operator when there are large numbers of them on a single energy market. Their reliance on price signals, together with market gaming practices, are possible sources of imbalance, because the pursuit of economic profit is not necessarily consonant with the physical needs of the grid. In other words, there is a case for wondering whether the VPP, as a response to the instability and fragilities of the grid, is not itself reliant on systems that are themselves globally unstable, evolving, and fragile.

Appendix

³³ VPP operators are aware of this dependency and are developing ways of establishing secure connections to the communication network. Voltalis, for example, uses smart boxes with several Sim cards, making it possible to shift between mobile networks.

N	Subject of the interview	Actor's identity	Interviewee's profile	Country	Date
VPP operators					
1	Voltalis VPP	Voltalis, distributed load aggregator	Head of markets and innovation	France	11.02.2022
2	OhmConnect VPP in California, Texas, New York	OhmConnect, distributed load aggregator	Head of VPP operations	USA	23.02.2022
3	Energy Pool VPP	Energy Pool, industrial load aggregator	Information technology business director	France	07.03.2022
4	Tiko VPP	Tiko, capacity aggregator	Head of regulation and public affairs	Switzerland	02.08.2022
5	CNR VPP	Compagnie Nationale du Rhône, electricity producer and capacity aggregator	Project manager	France	11.03.2022
6	AGL VPP	AGL, electricity producer and supplier	Interviewee 1: Group Head of distributed energy resources Interviewee 2: Policy and market regulations manager	Australia	18.05.2022
7	Simply Energy VPP	Simply Energy, electricity supplier	Interviewee 1: Manager of energy solutions Interviewee 2: Senior product manager	Australia	10.05.2022
Partners, contributors and VPP clients					
8	"Rescoop VPP" project	RESCOOP, European federation of citizen energy cooperatives	Project manager	Belgium	17.03.2022
9	"Orkney Reflex" project	Community Energy Scotland, independent charity, provides support for renewable energy projects	Project manager	United Kingdom	17.06.2022
10	VPP "Regenerative Energie" in Ebersberg	Bürgerenergie im Landkreis Ebersberg, citizen cooperative for renewable energy production (VPP client)	Shareholder and member of citizen cooperative	Germany	27.04.2022
11	"CVPP" project in Loenen	Stichting Duurzame Project Loenen, local NGO (VPP client); Translyse BV, energy service company	NGO board member, company manager	The Netherlands	12.09.2022
12	E&MS company's services to VPP operators	Energy & Meteo Systems, service provider to VPPs	Senior business developer	Germany	10.05.2022
Grid operators					
13	The role of VPPs in France	ENEDIS, distribution system operator	Head of relations with energy regulatory authorities	France	23.02.2022
14	"Brooklyn Queens DR" project	Consolidated Edison, distribution system operator	Project officer, energy efficiency department	USA	23.02.2022
15	"Smart Grid Vendée" project	Syndicat Départemental d'Énergie et d'équipement de la Vendée, owner of distribution grids	Innovation project manager	France	24.02.2022
16	The role of VPPs in The Netherlands	Liander distribution system operator	Innovation project manager	The Netherlands	14.10.2022
17	The role of VPPs California	CAISO transmission system operator	Senior advisor for smart grid technologies	USA	28.09.2022
18	The role of VPPs in The Netherlands	Tennet transmission system operator	Electricity market developer	The Netherlands	21.10.2022

Table 1: List of interviews conducted in our study of virtual power plants.

Bibliographie

- AEMO, 2020, *AEMO Virtual Power Plant Demonstration*, [en ligne] (consulté le 23/02/23) Disponible à l'adresse <https://arena.gov.au/knowledge-bank/aemo-virtual-power-plant-demonstration-knowledge-sharing-report-1/>

- Asmus P., 2010, Microgrids, virtual power plants and our distributed energy future, *The Electricity Journal*, vol. 23, n°10, p.72-82.
- Auer H., Haas R., Faber T., Weisensteiner L., Obersteiner C., Fuchs E., Heher A., Hohne U., Molnar P., Kastner S., 2006, *Faire Wettbewerbsbedingungen für Virtuelle Kraftwerke. Berichte aus Energie- und Umweltforschung*, Vienna, Undesministerium für Verkehr, Innovation und Technologie, [en ligne] (consulté le 12/04/22) Disponible à l'adresse https://nachhaltigwirtschaften.at/resources/edz_pdf/0645_virtuelle-kraftwerke.pdf
- Awerbuch S., Preston A. (eds), 1997, *The Virtual Utility. Accounting, Technology & Competitive Aspects of the Emerging Industry*, Boston : Springer.
- Barroca B., Serre D., Duchemin E., Maingui G., 2013, Behind The Barriers: A Resilience Conceptual, *Surveys and Perspectives Integrating Environment and Society*, vol.6, n°.1, [en ligne] (consulté le 23/09/22) Disponible à l'adresse : <https://journals.openedition.org/sapiens/1529>
- Barroca B., 2019, L'autonomie énergétique, aspiration ou condition de la resilience urbaine? In : Lopez F., Pellegrino M., Coutard O. (sous la direction de), *Les territoires de l'autonomie énergétique : espaces, échelles et politiques*, London : ISTE, p. 339-352
- Barton N., Virtual power plants may be the answer to power shortages during extreme weather events, [en ligne] (consulté le 29/05/22) Disponible à l'adresse <https://powergrid.news/2021-07-15-vpp-can-be-useful-in-extreme-weather.html>
- Beraud H., 2013, *Initier la résilience du service de gestion des déchets aux catastrophes naturelles : le cas des territoires urbains et de l'inondation*. Thèse de doctorat en Génie Urbain sous la direction de Gilles Hubert et Bruno Barroca, Université Paris-Est.
- Bhuiyan E., Hossain Z. Mueen S. M., Fahim S.R., Sarker S. K., Das S. K., 2021, Towards next generation virtual power plant: Technology review and frameworks, *Renewable and Sustainable Energy Reviews*, vol. 150., C, DOI: 10.1016/j.rser.2021.111358
- Braun M., 2009, *Virtual power plants in real applications: Pilot demonstrations in Spain and England as part of the european project FENIX*, [en ligne] (consulté le 22/05/22) Disponible à l'adresse https://www.researchgate.net/profile/Martin-Braun-2/publication/43248789_Virtual_power_plants_in_real_applications_Pilot_demonstrations_in_Spain_and_England_as_part_of_the_european_project_FENIX/links/53e44b570cf25d674e94bcf5/Virtual-power-plants-in-real-applications-Pilot-demonstrations-in-Spain-and-England-as-part-of-the-european-project-FENIX.pdf?origin=publication_detail
- Cohn L., *As It Plans World's Biggest Virtual Power Plant, OhmConnect Warns of Market Flaws in California*, [en ligne] (consulté le 11/12/20) Disponible à l'adresse <https://www.microgridknowledge.com/distributed-energy/article/11428432/as-it-plans-worlds-biggest-virtual-power-plant-ohmconnect-warns-of-market-flaws-in-california>
- Coutard O., Rutherford J., 2015, Vers l'essor de villes « post-réseaux » : infrastructures, innovation sociotechnique et transition urbaine en Europe, in : Forest, J., Hamdouch (Sous la direction de), A. *L'innovation face aux défis environnementaux de la ville contemporaine*, Lausanne : Presses Polytechniques Universitaires Romandes
- Coutard O., Rutherford J. (sous la direction de), 2016, *Beyond the networked city: Infrastructure reconfigurations and urban change in the North and South*. London : Routledge.
- Danieli A., 2018, The French electricity smart meter: reconfiguring consumers and providers, in : Shove E. Trentmann F. (eds), *Infrastructure in practice : the evolution of demand in networked societies*, Routledge, Londres, p. 155-167.
- Derdevet, M., 2020, La résilience des réseaux d'électricité face aux aléas climatiques et aux nouveaux paradigmes, in : Chardonnet Darmaillacq, S., Lesueur, É., Louda, D., Maisonneuve, C., (sous la direction de), *Villes et territoires résilients*, Colloque de Cerisy, Hermann.
- Farruqui A., Sergici S., 2009, Household response to dynamic pricing of electricity: A survey of the experimental evidence, [en ligne] (consulté le 11/12/20) Disponible à l'adresse https://www.smartgrid.gov/files/documents/ssrn_id1134132.pdf
- Finon D., 2017, Le mythe du paradigme électrique décentralisé. Comment dépasser l'effet de mode?, *La Revue de l'Énergie*, n° 635
- Fortune Business Insight, 2021, *Virtual power plan market, 2021-2028*, [en ligne] (consulté le 12/12/21) Disponible à l'adresse <https://www.fortunebusinessinsights.com/industry-reports/virtual-power-plant-market-101669>

- Graham S., 2010, *Disrupted cities. When Infrastructure Fails*. New York, London : Routledge
- Grandclément C., Nadaï A., 2018, Transitioning through markets, in : Labussière O., Nadaï A., (eds), *Energy Transitions A socio-technical enquiry*, Palgrave : Macmillan
- Guihou X, Lagadec P, Lagadec E., 2006, *Les crises hors-cadre et les grands réseaux vitaux*, Mission de retour d'expérience [en ligne] (consulté le 15/12/21) Disponible à l'adresse http://www.patricklagadec.net/fr/pdf/EDF_Katrina_Rex_Faits_marquants.pdf
- Helmrich A., Markolf S., Li R., Carvalhaes T., Kim Y., Bondank E., Chester M., 2021, Centralization and decentralization for resilient infrastructure and complexity, *Environmental Research: Infrastructure and Sustainability*, vol.1, n°. 2
- Hodson M., Marvin S., 2009, Urban ecological security: a new urban paradigm?, *International Journal of Urban and Regional Research*, vol. 33, n°. 1
- Hyman L. S., Smith B., 1997, The Bottom Line: The Virtual Utility Must Be a Business. *Strategic Planning for Energy and the Environment*, issue 1, vol.17.
- Jaglin S., 2019, Autonomie et réseaux électriques en Afrique: des expérimentations rurales aux hybridations urbaines, in : Lopez F., Pellegrino M., Coutard O. (sous la direction de), *Les territoires de l'autonomie énergétique : espaces, échelles et politiques*, London : ISTE, p. 313-333
- Jones K. B., Franco M., Mashke K., Pardee S. A., 2022, How Virtual Power Plants Can Advance Electrification and Mitigate Infrastructure Needs As We Race to Meet Our Climate Challenges, *San Diego Journal of Climate & Energy Law*, vol. 13.
- Labussière O., Nadaï A., 2018, *Energy transitions. A socio-technical enquiry*, Palgrave : Macmillan
- Lagadec P., 2007, Crise hors-cadre. Oser un enseignement, *Ethique, médecine, société*, p. 347-355. [en ligne] (consulté le 12/12/21) Disponible à l'adresse https://www.patricklagadec.net/wp-content/uploads/2021/11/crises_horscadre.pdf
- Lopez F., 2019, *L'ordre électrique. Infrastructures énergétiques et territoires*, Genève : Metis Presses.
- Lopez F., 2023, Les micro-réseaux électriques : un outil pour la TE francilienne ? in : Gallez C., Coutard O. (sous la direction de), *Vers une France post-carbone ? Freins et leviers d'une transition énergétique régionale*, Paris : L'Œil d'or, coll. Critiques et Cités.
- Lopez F., Pellegrino M., Coutard O., 2019, Introduction, in : Lopez F., Pellegrino M., Coutard O., (sous la direction de), *Les territoires de l'autonomie énergétique : espaces, échelles et politiques*, ISTE.
- Macrorie R., Marvin S., 2019, Bifurcated urban integration: The selective dis-and re-assembly of infrastructures, *Urban Studies*, vol. 56, n°. 11, p. 2207-2224, DOI:10.1177/0042098018812728
- Mikellidou C. V., Shakou L. M., Boustras G., Dimopoulos C., 2018, Energy critical infrastructures at risk from climate change: A state of the art review, *Safety Science*, vol. 110, p. 110-120, DOI:10.1016/J.SSCI.2017.12.022
- Navigant 2019, *2019 Market Data: Virtual Power Plants*, [en ligne] (consulté le 11/12/21) Disponible à l'adresse <https://blog.enbala.com/global-virtual-power-plant-market-trends>
- Niebel V., 2021, Coévolution des systèmes électriques et informatiques du Groupe EDF depuis vingt ans, *Enjeux numériques*, n.15
- Panteli M., Mancarella P., 2015, Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies, *Electric Power Systems Research*, vol. 127, p. 259-270, DOI:10.1016/j.epsr.2015.06.012
- Percebois J., 2021, Le numérique au service de la modernisation des réseaux d'électricité, *Enjeux numériques*, n.15
- Pickerell K., 2020, 550-MW virtual power plant could support California's 5-GWh shortfall during blackouts, [en ligne] (consulté le 07/12/21) Disponible à l'adresse <https://www.solarpowerworldonline.com/2020/12/550-mw-virtual-power-plant-could-support-californias-5-gwh-shortfall-during-blackouts/>
- Poupeau F. M., 2018, *L'électricité et les pouvoirs locaux en France (1880–1980): Une autre histoire du service public*. Bruxelles : Peter Lang International Academic Publishers.
- Recurve, 2020, *Applying Energy Differential Privacy To Enable Measurement of the Ohm Connect Virtual Power Plant*, [en ligne] (consulté le 07/12/21)

- Disponible à l'adresse <https://www.recurve.com/blog/revenue-grade-analysis-of-the-ohmconnect-virtual-power-plant-during-the-california-blackouts>
- Reghezza-Zitt M., Rufat S., Djament-Tran G., Le Blanc A., Lhomme S., 2012, What Resilience Is Not: Uses and Abuses, *Cybergeo: European Journal of Geography*, document 621 [En ligne], (consulté le 22/7/22) Disponible à l'adresse <http://journals.openedition.org/cybergeo/25554>
 - Reverdy T., 2016, Construire la valeur d'un service énergétique : la trajectoire de l'effacement diffus en France, *Colléner*, étude de cas n. 19 [en ligne] (consulté le 11/10/22) Disponible à l'adresse <https://halshs.archives-ouvertes.fr/halshs-01174292/file/Effacement%20diffus%2C%20note%20finale%202.pdf>
 - Reverdy T., 2022, La valeur du Négawatt : effacer la consommation électrique, in : Goulet, F., Vinck, D. *Faire sans, faire avec moins. Les nouveaux horizons de l'innovation*, Paris, Presses de l'Ecole des Mines.
 - Ropuszynska-Surma E., Weglarz M., 2019, The Virtual Power Plant – a Review of Business Models, *Energy and Fuels 2018, E3S web of conferences*, vol. 108.
 - Sage D., Fussey P., Dainty A., 2015, Securing and scaling resilient futures: neoliberalization, infrastructure, and topologies of power, *Environment and Planning D: Society and Space*, vol. 33, n°. 3, DOI:10.1068/d14154p
 - Sanderson H., 2021, *Extreme weather fuels rise of 'virtual power plants'*, [en ligne] (consulté le 12/01/22) Disponible à l'adresse <https://www.ft.com/content/4e350d50-d4cb-4447-bc2a-debfdec702f8>
 - Tierney K., 2015, Resilience and the Neoliberal Project: Discourses, Critiques, Practices—And Katrina, *American Behavioral Scientist*, vol. 59, n°. 10, p. 1327–1342, DOI: 10.1177/0002764215591187
 - van Summeren L. F., Wieczorek A. J., Bombaerts G. J., Verbong G. P., 2020, Community energy meets smart grids: Reviewing goals, structure, and roles in Virtual Power Plants in Ireland, Belgium and the Netherlands, *Energy Research & Social Science*, vol. 63, 10.1016/j.erss.2019.101415
 - Vogel B., 2017, *Bioénergie : un réseau n'est pas toujours suffisant*, [en ligne] (consulté le 07/12/21) Disponible à l'adresse https://www.researchgate.net/profile/Benedikt_Vogel/publication/325646007_Bioenergie_un_reseau_n'est_pas_toujours_suffisant/links/5b1a63ed45851587f29cab34/Bioenergie-un-reseau-nest-pas-toujours-suffisant.pdf
 - Voropai N., Rehtanz C., 2019, Flexibility and resiliency of electric power systems: Analysis of definitions and content, *EPJ Web of Conferences*, vol. 217
 - Yavuz L., Önen A., Muyeen S. M., Kamwa I., 2019, Transformation of microgrid to virtual power plant—a comprehensive review, *IET Generation, Transmission & Distribution*, vol. 13, n°. 11, p.1995-1996.
 - Yu S., Fang F., Yajuan L., J., 2019, Uncertainties of virtual power plant: Problems and countermeasures, *Applied Energy*, vol. 239, p. 454-470, DOI:10.1016/j.apenergy.2019.01.224