Virtual power plants and integrated energy system: current status and future prospects

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Abstract

The power system is undergoing a digitalization, decarbonization and decentralization. Economic incentives along with resiliency and reliability concerns are partly driving the transition. In the process of decentralization local energy markets are forming at various places. A virtual power plant (VPP) is a by-product of this digitalization capitalizing on the opportunity to further promote renewable resources, demand side flexibility, and sector coupling. A VPP enables resilient operation of power system while assembling small to large scale generation units and demand side flexibility. Specifically, during the pandemic uncertainty virtual work meets virtual power plants. A VPP has two both cyber and physical components. On one side, the physical component presents the operational challenges in terms of security, stability, reliability and efficiency. On the other side, the cyber component introduces the challenges on communication, computation, security, and privacy. A VPP synthesizes synergies between the cyber and physical components thereby harnessing the potential in terms of enhancing energy efficiency and reducing the cost. The objective of this paper is to introduce the virtual power plant and integrated energy system with associated concepts, terminology and relation thereof. The secondary objective is to categorize the key concepts while highlighting subsequent issues in planning, operations and control of a VPP with an integrated energy system. Moreover, this paper knits together the concepts and challenges in realizing virtual power plants with integrated energy systems.

Keywords: Cyber physical energy systems, Energy informatics, Integrated energy systems, Virtual power plants

1. Introduction

Recent developments in renewable energy generation and electrical vehicles (EVs), the widespread use of combined heat and power (CHP) technology, as well as the emerging power-to-gas (P2G) devices in power systems, have provoked significant changes in energy production and consumption patterns, and at the same time presented some new opportunities towards an environmentally sustainable energy system. Therefore, the traditional multi-energy network has been endowed with new implications: the electrical power system, natural gas system, electrified intelligent transportation system, and district heating system have formed a closed-loop within a broader integrated energy system (IES) [1]. An IES is a heterogeneous system with a hierarchical and multi-modal structure, as well as a multi-level network topology [2]. The IES can be defined as a system that operates electric power and heating components in an optimal manner, to serve electric, heating, and transportation demands to the end-users. The subsets of an IES such as electric power and heat systems are coupled through CHP [3] units and energy hubs [4]. An energy hub is a multi-energy system platform with various combinations of multiple-kind energy inputs and outputs [5]. An energy hub benefits from the synergy of energy carriers. Based on the price levels of various kinds of energy, the operation strategy of an energy hub can be optimized to maximize a specified objective function [6]. Energy storage has the potential to act as a linkage among different sectors of an IES [7] for implementing optimal operation of an IES. The energy storage can broadly be classified into electrical and thermal. Linking the energy storage systems could mitigate the variations from renewable resources alongside of optimal energy conversion to meet the load demand.

In a power system, the power supply must meet the load demand in real time, otherwise frequency and voltage can deviate from the normal operating regime. This deviation could lead to damage of devices, brown outs, outages, and even blackouts. The alternating current (AC) power grid itself has no medium of storage, therefore the power in and out must be controlled to maintain the power balance. The traditional dispatchable resources can be moderated with a reasonable time delay. The portfolio of generation includes relatively small numbers of dispatchable power plants with large capacity. As renewable generation units take a sizable proportion of the portfolio of generation, and its non-dispatchable generation output poses substantial challenges to maintain the balance, then on the one hand, curtailing the renewable energy generation is not a viable option, since the clean energy is wasted and on the other, some kind of renewable generation such as solar and wind power depend will on its nature, and the production cannot be ramped up on demand. Dispatchable generation resources are necessary to maintain the security of the power supply through load following, frequency and voltage regulation, and reserve power. [8].

The renewable energy resources are usually in the form of setting of many small distributed generators which behave independently. A power network with a high share of renewable energy would require power storage units to charge during power surplus and discharge during power deficits- to maintain the power balance. Batteries, a mode of energy storage, are commonly used since they can charge and discharge rapidly to offset any power imbalances. The power grids may install very large battery banks, typically in the size of a dispatchable power unit, or utilize small residential battery units already installed in individual households. The residential batteries serve as back-up generators and contribute to the better utilization of the energy. The behind the meter battery units can be aggregated together at residential and commercial buildings to form a VPP [9, 10, 11, 12]. A VPP can also constitute large battery banks coupled with large wind farms or solar plants. Accordingly, a VPP could serve not only as a backup, but also as support to the grid in the maximum utilization of renewable energy generation [13]. This leads to significant cost reduction in grid control and motivates new and small renewable energy installations. The electric and heat load demands vary with weather, time of the year, and special occasions. In a typical day the peak load appears for a short span of time. To meet the peak load high capacity of generators are built, however they are unused most of the time outside of the peak hours. Alternatively, the balance power is purchased at a significant premium from neighbors with excess generation [14]. Power can be cheaper if the demand is offset and the load curve is flattened. However, charging the battery banks just after the peak hours might extend the peak hours [15]. Therefore, the charging is spread out over a period of time during off-peak hours. Moreover, a VPP can facilitate optimal energy management for distributed energy resources with stochastic renewable energy generation [16]. The coordinated planning and operation, as well as optimal strategies of an IES, have raised widespread concerns regarding a reasonable utilization of multi vector energy resources. The IES can also enhance the accommodation capability for renewable energy generation. However, this has not yet been systematically investigated in the existing literature. Furthermore, the potential of different kinds of energy resources as a service for the future electricity market, is yet to be investigated.

1.1. Scope and key contributions of the paper

There is a significant progress in small-scale distributed generation, behind-the-meter generation, energy storage options, EVs and flexibility at the distribution grid level. When aggregated, these small scale units can unlock the total system flexibility, while still being environmentally friendly. In order to facilitate such a transition, these assets need access to the energy market. A VPP is essentially a virtual layer on the top of the physical power units. A VPP provides a platform to access and actively participate in the market for the small scale units. Consequently the energy system is becoming decentralized and distributed while the digitization acts as an enabler. This transition also benefits the generators, retailers, distribution and transmission network providers through demand shifting, reduction in investments and reduction in network reinforcement costs while lowering reserve power requirements while improving the reliability and security of supply. The energy market framework has experienced a paradigm shift towards peer to peer trading in the last few years as reported by numerous studies. New business models, actors and participants are emerging to engage in a consumer oriented energy system. However, this shift poses many challenges in the form of decision making problems. Many pilot projects are ongoing in USA, Europe and Australia to realize the VPP's potential. However, there is a gap in listing the range of issues in terms of decision making challenges and opportunities for a VPP in an IES. One of the key challenges in deploying VPP is resiliency; specifically how to maintain or improve the grid resiliency with the virtualisation of power generation system. A VPP improves resiliency through replacing one large power generation unit with multiple small scale generators. This process improves the fault tolerance of the system and avoids the cascading of faults. However this process also brings challenges associated with power quality (PQ).

This paper sets out to summarize the emerging trends alongside providing an overview of the challenges that arise when coupling the concept of the VPP together with the concept of integrated energy systems. The objective of this paper is to provide a holistic view on the current state and future directions of VPPs. For this purpose a big picture of the role of VPPs with an integrated energy system will be presented. The VPP is also discussed as a cyber physical system with physical and cyber components' potential connections with IES, and with an energy hub as the linkage between them. The power system resiliency in the context of a VPP with an IES is discussed in detail when addressing the challenges and provisions. Moreover, the paper discusses storage options for VPPs, as well as opportunities for its participation in the energy markets, and directions for intelligent solutions of future VPPs. In summary, the proposed work provides a comprehensive and systematic overview of the challenges and potentials associated with a VPP together with IES. This is achieved by setting a context for decision making considering the emerging trends in the energy market while considering the technical challenges in the physical layer.

The current section establishes the context and key terminology. Section 2 introduces and defines the concept of a VPP compared to the concepts of microgrids and energy hubs while associated technical challenges are discussed in Section 3.1. A VPP with an IES as a cyber physical system is discussed in Section 4. Subsequently the value proposition of a VPP with an IES is discussed in section 5. In Section 6 the sector coupling for linking electrical and heating sectors is discussed. The storage options, both thermal and electrical, are discussed in Section 7. The VPP participation in the energy markets is addressed in Section 8. The future of a VPP based on current trends is covered in Section 9.1. Finally some conclusions are drawn in Section 10.

2. VPPs, microgrids and Energy Systems

Traditionally, the impediment to entry for participation in the electricity market, off-sets individual small scale entities such as a PV plant participating independently. The emergence of distributed and low-investment generation units, the incentives for increasing the share of renewable generation, and the demand side participation, are among the key issues going forward to a carbon neutral future.

This paper proposes to classify VPPs into the single owner physical VPP (P-VPP) and multi owner cyber VPP (C-VPP). A P-VPP has a portfolio of assets which are owned by the VPP. A C-VPP has a portfolio of assets which are owned by different parties. Both VPPs trade as a single unit in the energy market, while C-VPP allows peer to peer trading within the VPP through a local market formation. In addition, C-VPP is more flexible in terms of asset types and size. This means heating assets can be a part of the C-VPP and the size of the asset can be dynamically changed if a new party joins the coalition. This latter definition therefore unfolds the concept of VPP with IES that has not yet been discussed and investigated in the literature. Note that both P-VPP and C-VPP are a portfolio of technologies operated through a cyber platform. However, the former physically owns the assets while the latter forms multi-party agreements to operate as one entity.

A VPP is a portfolio of decentralized and distributed units of the power network. The units can be power generation, storage, and demand side flexibility. The objective of a VPP is to collectively trade the transactive energy (power, flexibility, and reserve power) in the electricity market. The cluster of individual assets are pooled together as a portfolio that is called a VPP. An asset can be an individual storage unit or the demand side flexibility of a consumer. As with a conventional plant, a VPP exerts a degree of control through switches to maintain the system's stability. A VPP resides between the transmission and distribution system operators. While an individual power plant is limited to the granularity, a VPP can further the scope by integrating smart meters data into the balancing of demand-and-supply. Typically a VPP receives these control signals from the transmission system operator.

A VPP is tightly integrated with the distribution system operator who owns and controls the medium to low voltage power network. The Supervisory Control and Data Acquisition (SCADA) is often used by the system operators for this purpose. Like the conventional power plant a VPP adjusts the portfolio through smart algorithms, to respond quickly and effectively to price signals from the power and ancilliary services markets. In contrast to the conventional power plant, a VPP is decentralized and distributed [17]. Due to the modular nature of a VPP, the chances of failure are far lower compared to a conventional large power plants. In addition, the condition of assets can be better integrated to the total risk quotient in the risk portfolio of a VPP.

A VPP is essentially grid connected and centrally controlled. The VPP can be large in size with more flexibility potential. A VPP is dependent on smart meters and associated technology to form a virtual market environment, that is flexible and open to participation. More and more power plants are employing smart algorithms for smart grid demand projection, flexibility calculations and power generation from weather patterns. A VPP is essentially a software platform that can enable a higher degree of accuracy and effectiveness on this aspect.

A microgrid represents a localized and miniature power systems and has a localized control system for efficient energy management. A microgrid can be in the form of an isolated grid, such as an island, or in a grid connected format. Microgrids engage the inverters and smart switches for effective control. Typically microgrids exist in the form of islands or military bases, where the isolation is due to the expensive cost of connection, or intent to remain self-contained units. A VPP may contain a cluster of microgrids or individual units among its assets.

An energy hub is a sector coupling instrument linking multiple energy carriers. The energy carriers range from energy generation (such as PV, or wind), energy conversion (power to X or gas to X) to energy storage (i.e. hydrogen, battery banks and EVs). An energy hub provides local control, flexibility and accessibility to the overall system. As it happens with microgrids, the energy hub may be deployed in different spatial scales ranging from a building to a city. An energy hub essentially provides the integration of uncertain renewable energy resources. An energy hub facilitates greater flexibility in the overall system while enabling transactive energy. The energy hubs are modular in structure, allowing the integration of new energy carriers or storage units while offering system flexibility.

On one hand, an energy hub can soak the excess electricity from the grid by converting electricity to heat, cold and other synthetic fluids. Thereby an energy hub aids in balancing the overcapacity or over production, and optimal power reserve allocation. An energy hub is in-fact a tool for congestion management. On the other hand, an energy hub can act as a reserve power unit when the prices are high, or when there is a scarcity in production. They do this by producing electricity from the multitude of renewable sources, heat to power technologies, and synthetic bio-fuels. Consequently, an energy hub can increase the total efficiency of a system such as a a biomass plant, by absorbing electricity and releasing either electricity or heat to aid in peak shaving.

In [18] the scheduling of a VPP containing multiple smart energy hubs is demonstrated. The VPP expands the geographical scope, while the energy hub acts as a local and physical control unit. The VPP and the energy hub may adopt a leader-follower scheme where the VPP acts as the virtual platform for energy transactions, and the energy hub acts as the physical connection enabling, and thereby following, the VPP. The flexibility offered by the energy hub would be the upper capacity/limit for the VPP platform for transactions.

A VPP renders an optimal and balanced way to integrate the distributed and decentralized energy resources towards the purpose of sustainable energy. The hierarchy of actors in a power network is presented in Figure 1. As outlined in the previous paragraphs, a VPP can act as a local energy market where both small scale units, such as demand side flexibility, and large scale units, such as large scale PV power plant, can participate. Under the energy market there are TSOs and DSOs. Each DSO has an integrated energy system underneath representing a heating and electric loop. Both loops are tied at the source and origin. The origin could be a CHP plant and the source is a consumer who might consume heat energy from heating loop and electricity from electric loop. An energy hub presents junctions between the loops that can store and transform from one form to another.

VPPs normally operate at the DSO level with assets dispersed across the network. The VPP portfolio can hold assets from a heating and electric network. The VPP operates in the energy market within the TSO on the same level as a DSO, while integrating units from multiple DSOs and microgrids. Islanded microgrids can also participate in a VPP. However since there are no physical links to the grid they are placed as an extension to the DSOs. Figure 2 presents the end-user energy consumption loops. At one end of the loop there is demand and other end is generation forming loops for different types of energy consumption: heating/cooling, transportation and electric. The loops are proportional to the share of energy consumption. For instance the energy consumption for heating or cooling is higher in comparison to transport and electric. An IES sets out to tie the loops of generation together thereby increasing the total system throughput.

3. Technical challenges in a VPP

The VPP is primarily a software platform with switches. Subsequently there are a range of challenges that arise in terms of distributed energy and software. A VPP platform needs to collect, process and render decisions for portfolio management in real time. The sources range from smart meters to bids from small scale generation units. However, there are often inconsistencies in the data management from various stakeholders and clients. Where the data structure of a VPP do not fit with a client's data structure, there is a significant cost of development. In the energy sector new business models are formed frequently and adapted to the regulations and changing landscape. Accordingly, consistent software protocols need to be in place. A

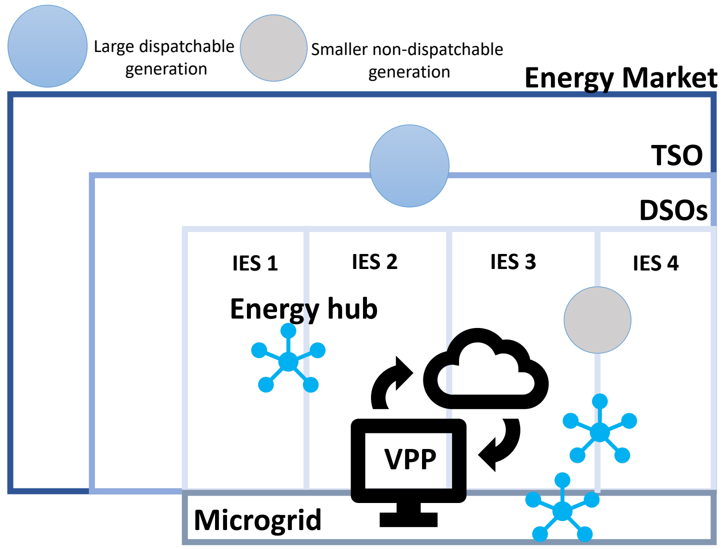

Figure 1: Hierarchy of integration of a VPP in power system

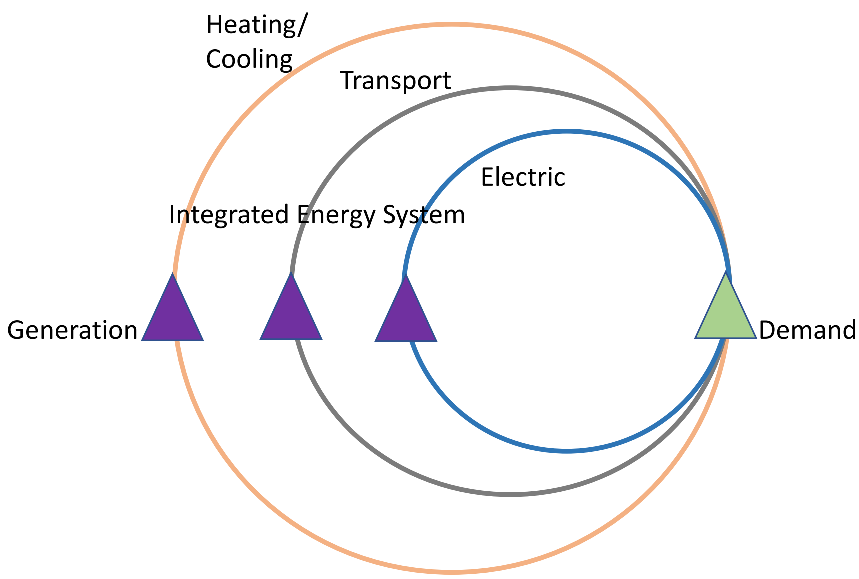

Figure 2: End-user energy consumption loop

microservice oriented architecture for a VPP is presented in [19]. A software architecture to manage the smart metering systems with existing software for outage and workforce management is presented in [20]. Finally, a cloud computing solution for the VPP platform with reduced infrastructure cost for a VPP is presented in [21].

The output of renewable energy generation is influenced by environmental characteristics like solar radiation and wind speed. This reliance can lead to power quality disturbances [22]. A high penetration of renewable energy generation can cause voltage fluctuations, current harmonics, voltage harmonics, voltage swell or sag, unbalance, malfunction of protective devices, overloading, and failure of electrical equipment [23, 24]. A typical distribution of power quality (PQ) disturbances by duration, shows that disturbances lasting less than one second far outnumber the others in occurrence [25].

The voltage fluctuations are one of the major power quality concerns that distributed renewable energy generation imposes on the system [26]. The intermittent nature of renewable energy generation causes fast voltage fluctuations (fast changes in voltage amplitude) [27]. The voltage deviations are further amplified by the large R/X ratio of medium voltage and especially low voltage networks [27]. The voltage rises caused by the distributed generation can interfere with the operation of tap changers, since the voltage reference is no longer indicative of the voltage profile of the feeder [28]. The voltage fluctuations caused by the fast changes in the weather conditions can have detrimental effects on the voltage regulation equipment present in the feeder, such as On Load Tap Changing Transformers, Switched Capacitor Banks , and Step Voltage Regulators [29]. Premature wear and tear can occur due to the increased numbers of operations of these devices [29].

The distributed renewable energy generation can cause high voltages when interconnected in small residential areas sharing a distribution transformer [28]. If the transformer primary voltage is already at the upper limit, the DR can reduce the voltage drop through the transformer and secondary conductors, which will cause high voltages to be experienced by other customers on the transformer [30].

3.1. Mitigation of Power Quality Disturbances

Conventionally, the voltage at service locations is maintained by utilising fixed designs of the system (e.g., conductor selection, substation and distribution transformer tap settings and fixed capacitor banks) and by voltage control equipment such as automatic load tap changers, step-type voltage regulators (SVR), and switched capacitors [28]. The design of the feeder is based on the assumption that the loading profile follows a predictable pattern: with real power loading on the feeder causing voltage to decrease monotonically from the substation [28]. SVR controls continuously monitor voltages and load currents to adjust tap positions accordingly [28]. Capacitors (switched and fixed) compensate reactive current, reducing the current from the source to the capacitor location, resulting in reduced line voltage drop [28].

The currently used voltage regulation methods with conventional voltage/volt-ampere reactive (VAR) control devices cannot respond well and promptly to the voltage limits violations that may occur due to renewable energy injection and Plug-In Electric Vehicle charging [27]. One way to mitigate the adverse effects caused by the interaction of renewable energy generation and voltage regulating devices is control coordination [31, 32, 33, 34, 35, 36]. A review of communication-based non-centralized control schemes that can be applied specifically to voltage regulation of distribution networks can be found in [27].

Another mitigation method is the use of a Dynamic Voltage Restorer (DVR), which can be used for handling voltage sags and swells, and for damping voltage fluctuations [24]. Power quality disturbance mitigation by the use of DVR is proposed and discussed in [37]. According to [24], DVR is one of the best devices for mitigating power quality issues in the conventional power system and micro grids.

In recent years Static Synchronous Compensators and Static VAR Compensator have been used extensively for solving many PQ issues that were caused by renewable energy generation integration [24]. The use of flexible AC Transmission Systems devices for PQ improvement in integrated wind energy system is discussed in [38]. A static var compensator and static synchronous compensator are used for overcoming sags [39, 40], and compensating reactive power [41, 42]. A static synchronous compensator is used for damping voltage fluctuations in [43, 44].

A promising solution [45] for mitigating power quality disturbances such as sag, swell and flicker [46, 47, 48] can be a Unified Power Quality Controller [49, 50, 51, 52, 53, 54]. A unified power quality conditioner is a complete configuration of hybrid filters, which is identified as a multifunctional power conditioner utilized to compensate for different voltage disturbances [24].

4. VPP with IES: an Energy Informatics approach

The concept of VPPs is highly interdisciplinary, touching upon subjects ranging from engineering, to computer science and economics, together with power and energy systems. From this point of view, VPPs fall fully into the novel domain of Energy Informatics, which aims at "exploring the intersection of informatics, power engineering and energy economics" [55]. Renewable VPPs in particular, can make a decisive contribution to the main scope of Energy Informatics by reaching the two main goals- energy efficiency, and renewable energy supply [56], thus facilitating the global transition towards sustainable and resilient energy systems [57]. This section aims to present an Energy Informatics approach to address VPP with IES.

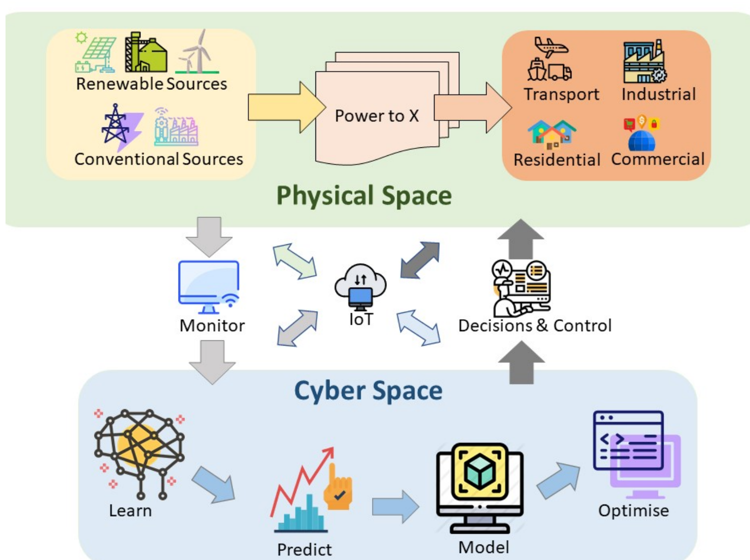

Figure 3: Overview of a VPP in the context of Energy Informatics

Fig. 3 illustrates the links between VPPs and computer science in the broad context of Energy Informatics. As shown in Fig. 3, the concept of the VPP can be described by two main parts. First we identify a physical space, that is represented by the physical resources available for energy production, classified as renewable sources (i.e wind plants, biomass plants, solar plants) and conventional sources, together with the transmission and distribution grid infrastructures. Within the physical space, sector coupling (power-to-X technologies) has an important role, to interconnect and integrate the energy consuming sectors - transport, industrial, residential, and commercial - with the power producing sector.

The physical space outlined above, can be investigated, understood, and controlled through modern mathematical and computer science techniques, which together form part of a so-called cyber space. A cyber space can successfully function through four main tasks that are strongly interconnected:

- Learn: understand the data
- Predict: forecast and generate new data
- Model: build technological mathematical optimisation models
- Optimize: utilize the data and the models to make optimal decisions that can positively influence the physical space

The first task is "learning", which means to gain a deep understanding of the data gathered from the physical space, identifying patterns and understanding the peculiar properties and trends. Once the data has been understood and handled through the learning process, they can be utilized for the second task which is "predict". This refers to the ability to forecast the future based on the information previously obtained in the available dataset. Typical forecast that are necessary within a VPP are related to demand, weather, price, production etc. Within the learning and forecast tasks, a key role is played by computer science subjects such as machine learning, big energy data, data analytics, artificial intelligence, database systems. Once the learning and prediction tasks are over, the key is how to utilize this new generated knowledge to build mathematical optimization models that represent the energy systems and the main technical properties of the resources involved. Finally, the knowledge, the data, and the models can then be utilized within optimization tasks, in order to make optimal decisions that can positively impact the physical space where the VPP resources are located. Such optimal decisions refer to both investment decisions and operational decisions. Investment decisions deal with optimal design which can for instance impact the optimal portfolio of a flexibility mix within the energy market. Operational decisions deal with optimal real time control of the existing VPPs where the main objectives can be (but may not be limited to) profit maximization, together with emissions reduction. The optimization tasks involve both applied mathematics (with particular regard to Operations Research, in form of mathematical optimisation in general and Smart Energy and Power Systems modelling in particular [58]) and programming skills that allow the development of decision support systems (DSS) tools for the specific VPP application and objectives. Within the DSS tools, key subjects play important roles, such as parallel computing (especially when scalability issues arise), data processing, data integration, data synthesis and visualization. Fig. 4 shows an overview of a DSS for a VPP application and the subjects involved.

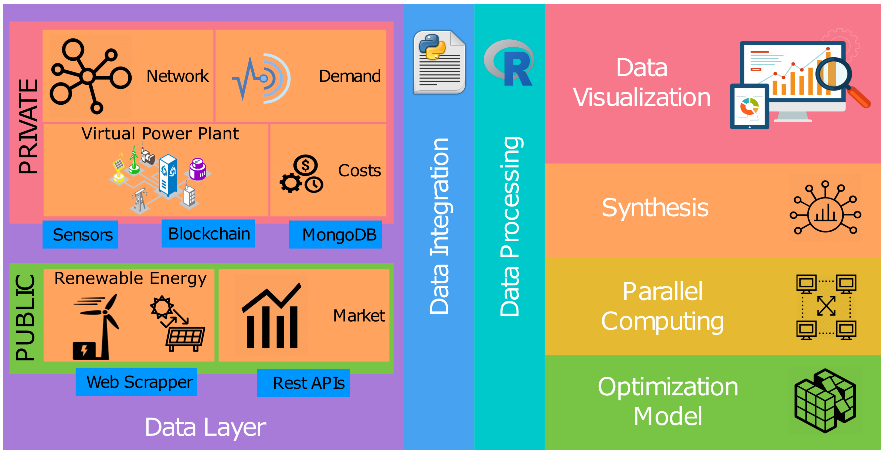

Figure 4: A proposed decision support system architecture for VPP

The physical space and the cyber space introduced above, are linked through two main tasks. “Monitoring” allows the transferring of data from the physical space into the cyber space (a typical example in this case is represented by the use of sensors, devices, and smart meters). In contrast, “Decision and Control” takes the decisions developed in the cyber space, and implements them back into the physical space for an optimized management of the VPP. Through monitoring and control, by linking a physical space to a cyber space, the overall described system, defines the so-called Cyber Physical Energy System (CPES) [59]. By adding the perspective of CPES to the concept of VPP, the concept of VPP-CPES is identified. On top of the CPES defined above, it is possible to add the Internet of Things (IoT). Through IoT, the VPP-CPES can be connected to the internet, and decisions can be automatized and enhanced. A typical example of a VPP would be the possibility to connect to the market, and optimize the operational use of the flexibility mix, through bidding strategies, arbitrage and demand response. IoT is therefore at the heart of the VPP-CPES, with connections to all the main tasks. Through IoT the data gathered through monitoring can be uploaded onto the cloud. Moreover, the outcome of the data manipulation (through learning, predictions, and optimization) can be accessed remotely. In addition, control and decision making tasks can be enhanced through cloud computing, thus avoiding the barrier of software installation and maintenance inside the companies' computers. A cloud-based service can perform software updates seamlessly and can deliver a generic product that can be used by everyone independently of the knowledge in data-science.

5. Value of VPP with an IES

VPPs are typically comprised of flexible loads, energy storage units, and dispatchable and non-dispatchable resources. These geographically dispersed resources are aggregated as a VPP participating in the energy market [60]. The power network infrastructure can be categorized into levels such as pico, micro, and macro grid, which are interconnected.

The power system can be classified in ascending order in terms of size and scale to - pico, micro and macro grid. Fig. 5 represents the scale and operations of a VPP through pico, micro and macro grid. A VPP can integrate resources from a picogrid to a macrogrid level. Thanks to the recent advances in edge, cloud and fog computing [21] these resources can be coordinated to operate seamlessly. On a residential scale, picogrid level operations can be identified, such as data mining, load profiling along with participation in a VPP through load flexibility. The microgrid level is essentially the aggregation of picogrids at the level of residential and commercial buildings. Microgrids present modularity, aggregated flexibility, resiliency and accessibility to clean resources. Subsequently, the macrogrid level combines the former, pico and micro, and presents non-critical reserve power, grid synchronization and aggregated power. This classification aids in planning solutions that fit the requirements of scale and size. For instance the objectives on a building at the pico grid level are different from those of the macro grid. Moreover, for a VPP the scale and size of operation would determine optimal portfolio and operational regime in a decentralized and distributed setting. VPPs can be classified into three categories based on the size, scale and operational priorities.

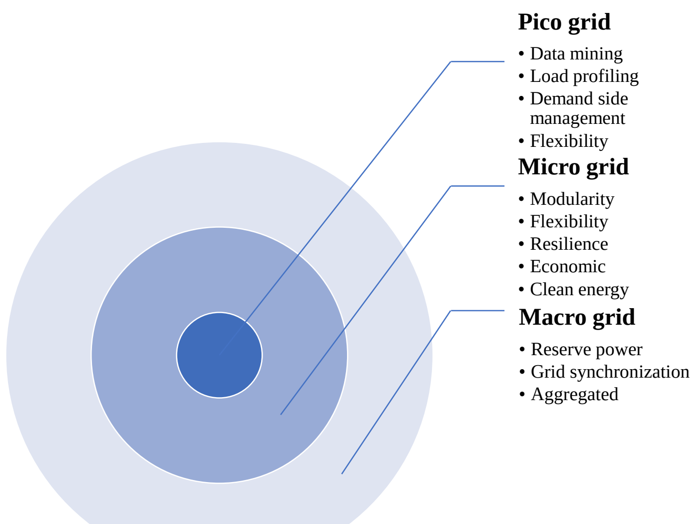

Figure 5: Grid structure

A VPP enables flexible integration of geographically dispersed and different resources to achieve low emission and low-cost power. A VPP operates in a electricity market driven by price signals resulting from policy measures. For instance CO2 prices would be consequential to the share of renewable energy based generation units in the VPP portfolio. Fig. 6 presents the operational mechanism of a VPP. A VPP through coordinated planning determines optimal operational regimes in the day ahead, intra day and balance market. The figure also includes the variables of generation, storage and load/flexibility that a VPP would optimize. Of course, the VPP may also participate in the reserve market, reactive power support market and others.

The following are among the key performance indicators and value propositions for a VPP with IES.

- VPP overcomes uncertainties inherent in non-dispatchable resources such as wind and solar energy resources through collaboration and coordination of operation [61].

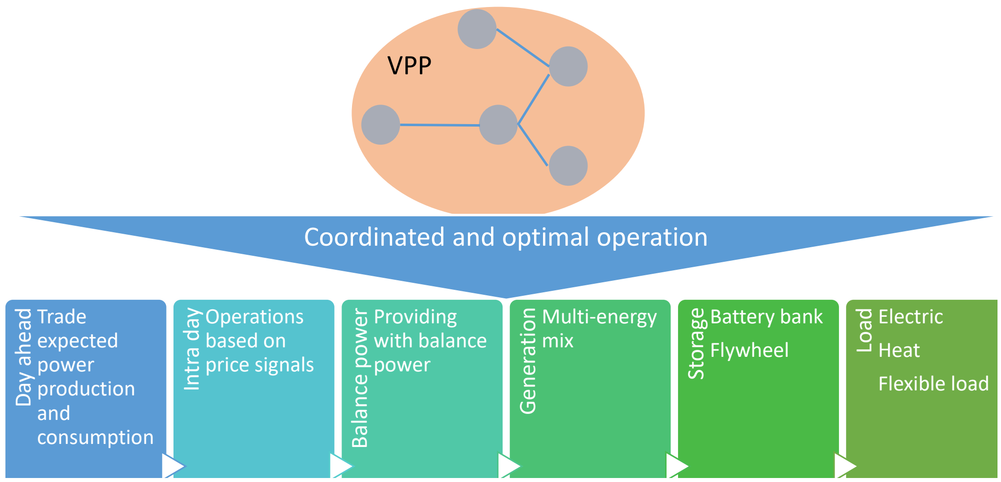

Figure 6: VPP market and scope for optimal portfolio

- VPP overcomes risks by avoiding up-front investments and operational failures.
- VPP improves flexibility from both demand [62] and supply sides.
- VPP overcomes geographical barriers as in virtual participation.
- VPP portfolio leads to cost reduction while maintaining supply-demand balance and impacting production volumes.
- VPP portfolio comprises a wide range of technologies in the portfolio, ranging from a pico-grid (prosumer) to microgrid level.
- VPP integrates participation of the demand side as the ancillary service and flexibility provider in power grid operation.
- VPP enables optimal utilization of energy produced from renewable.
- VPP enables accessibility ranging from a very small-scale producer (prosumer) to a mid-range wind park to participate.
- VPP facilitates emission reduction through participation and awareness.
- VPP provides scope for new and innovative, customer centring, and participatory value streams generation. In addition, it incentives participation of consumers and small producers. An example is represented by coordinated planning of optimal flexibility [63, 14].

The VPP technology is relatively new and thereby has its own challenges namely technology, policy, and market oriented. Technology challenges include asset management, risk aggregation, software architecture and privacy related issues from the energy usage. In addition, there are policy, regulation, law and framework challenges for defining the scope. Market challenges include a sustainable financial business model development, and electricity market reforms concerning VPPs. These challenges are still open questions in relation to the fast evolving power and energy space, in particular within emerging VPPs. Owing to geographical and consumers energy behaviour, the regulations would also differ. There, different requirements and potentials exists in different geographical areas. For instance high potential of PVs in southern EU and high concentration of wind in northern EU, or high heating demand in the north and high cooling demand in the south. However, a VPP can enable better market coupling if these issues are solved where consumers also play a role through coordinated decision making for a decentralized and distributed power gird. A VPP also strengthens the grid resiliency of the decentralized and distributed power network through:

- distributed asset monitoring considering the condition of assets at demand, generation, transmission, energy storage and measurement
- complementarity control to flatten the overall demand curve and stable power generation capacity
- contingency aware power flow and grid in-feed
- accessibility for small, large and EV generation units
- integration of heating and power requirements of a network

6. Sector coupling options for VPPs

Sector coupling refers the concept of a purposeful connection and interaction of energy sectors to increase the flexibility of supply, demand, and storing [64]. Coupling the heating and the power sector can play a key role in a decarbonized power system [65]. The sector coupling concept is particularly relevant within the C-VPP definition introduced in Section 2. Indeed, a C-VPP is described by a portfolio of assets that are owned by different parties. In this setting, a C-VPP allows peer to peer trading within the VPP, through a local market formation. This means heating assets can be part of the C-VPP, and therefore sector coupling options arise. Power-to-X technologies represent a way to achieve sector coupling. Within the Physical Space identified in Fig. 3, the sector coupling options are embedded within the Power-to-X module, as the interface that connects the renewable and conventional sources, with the residential, commercial, industrial and transport sectors.

The coupling between the heating and the power sector is identified by two main processes within the so-called power-to-X methods:

- Power-to-heat refers to the conversion of electrical energy into heat. This is allowed for instance through the use of heat pumps.
- Power-to-gas refers to the use of surplus wind generation to produce hydrogen through electrolysis.

In addition, the broader definition of sector coupling also includes the possibility of coupling the energy and the transportation sector [66]. In particular, the so called power-to-mobility refers to the use of batteries of electric cars as a buffer. This is also known as vehicle-to-grid technology, through which energy is pushed back to the power grid from the battery of electric cars.

For the specific purpose of a VPP we are more interested in the coupling between the heating and the power sectors, which has the highest potential within the frame of C-VPP described earlier in this paper.

When including heating concepts within the C-VPP frame, two main technologies show promising potential: low temperature district heating and Organic Rankine Cycles.

District heating systems provide the heat generated in a centralized location to a set of users for their residential and commercial heating requirements such as space heating and water heating. The heat is often obtained from a cogeneration plant burning fossil fuels or biomass. Heat distribution is generally obtained by using hot water or steam flowing through a closed network of insulated pipes and heat exchange stations at the users' locations [67]. District heating can be linked to electricity systems through co-generation of electricity and heat, and through power-to-heat production in large-scale heat pumps.

Low temperature district heating refers to district heating where the network supply temperature is reduced down to approximately 50 degrees or even less (ultra-low temperature district heating). Low temperature district heating offers new possibilities for greater energy efficiency and utilization of renewable energy sources, which lead to reduced consumption of fossil fuel-based energy [68].

The integration of low temperature district heating within C-VPP solutions, can therefore enhance the renewable potential of a VPP. From this perspective, low temperature district heating represents one key option to move from the conventional concept of VPP towards a more holistic concept of VPP with an integrated energy system, like the C-VPP outlined earlier in this paper.

An Organic Rankine Cycle has been recognized as a promising technology for conversion of heat into electricity since it can be designed for operation at low temperatures with suitably-selected working fluids [69]. An Organic Rankine Cycle uses an organic, high molecular mass fluid with a liquid-vapor phase change, occurring at a lower temperature than the water-steam phase change. The fluid allows Rankine cycle heat recovery from lower temperature sources (i.e. biomass combustion, industrial waste heat, geothermal heat, solar ponds etc). The low-temperature heat is converted into useful work, that can itself be converted into electricity. Various sources can provide the heat for the Organic Rankine Cycle, from solar radiation, to biomass combustion, geothermal heat, or waste heat from industry. Hence, a small-scale Organic Rankine Cycle can be an appropriate option for sunny remote areas [70] where combined with photovoltaic panels, it can be a suitable alternative for electricity generation. Moreover, a tailored model and fine management can provide both electricity and thermal energy for the local inhabitants [71].

The Organic Rankine Cycle also plays an important role in waste heat valorisation in the process industry since the residual heat can be converted to electricity. It has been proven that coupling waste heat recovery with a district heating network can provide flexibility to the electricity generation. This flexibility can be utilised by a VPP, to compensate for the variable output of renewable energy sources [72]. It is therefore possible to implement strategies to balance variable renewable production with industrial waste heat, instead of compensating the power fluctuations only by traditional power plants such as gas and coal.

In summary, both low temperature district heating and the Organic Rankine Cycle can actively and successfully contribute to renewable VPP solutions, by expanding the concept of VPPs towards the broader concept of VPP with integrated energy systems.

7. Storage options for VPPs

Storage technologies	Maximum Power (MW/h)	Drain time	Life span (Yrs/cycles)	Energy density (Wh/lt)	Efficiency (%)	Power Network level
Pumped hydro	3000	4 to 16h	30 to 60	0.2 – 2	70-85	Transmission
Compressed air	1000	2 to 30h	20 to 40	6 - Feb	40-70	Transmission
Li-ion	100	1 min to 8h	2 to 3	200-400	85-95	Transmission and Distribution
Lead-acid	100	1 min to 8h	3 to 5	50-80	80-90	Transmission and Distribution
Flow-based	100	hours	12000 to 14000 cycles	20-70	60-85	Transmission and Distribution
Hydrogen	100	Mins to week	5 to 30	600 at 200 bar	25-45	Transmission
Flywheel	20	Seconds to minutes	20 to 30	20 to 80	70-95	Transmission

Table 1: Energy storage technologies [73, 74]

Electricity storage has been a pivotal point in the power system - specifically to harness the full potential of the renewable energy resources. The key energy storage technologies in practice in the smart energy system are explored in [75]. Some of the technologies are placed on transmission level and others are in the distribution system level owing to the capacity and size of initial investment. In table 1 a classification of electrical energy storage technologies is provided.

A VPP enables the participation of a single battery unit at distribution level alongside large scale battery banks. EVs present a spatially dynamic energy storage solutions that may also participate in the VPP. In [76] charging of EVs as a VPP is explored. These technologies through VPP can provide services for peak demand shifting, voltage and frequency control. A VPP, being decentralized and distributed presents a better value for the utilization of the total energy potential in the system. VPP can respond quickly to the variation in renewable energy resources such as utilizing the peak energy generation and scope for small storage units of EVs, to participate where there is less or no RES based energy available.

A sizable proportion of energy consumption is due to heating and cooling demand. Thermal energy storage therefore can play a significant role in providing system wide flexibility through low cost storage of heat. In [77] authors indicate that 45% of the total energy usage in EU is attributed to heating. In [78] the authors perform a case study to demonstrate how thermal energy storage coupled with variable renewable energy capacity can attain goals to reduce the environmental impacts while better utilizing the energy potential in RES.

Converting electricity to heat generates losses due to the Carnot cycle. However, the energy contents in the fuel can be converted to useful heat more efficiently. This high conversion efficiency can facilitate RES fluctuations and unlock flexibility. Surplus production during off-peak hours can be converted to heating fuels. Then the value of surplus energy rises to the value of fuel. The conversion efficiency in,for example, a heat pump is higher than that of the direct-resistance heaters based on electricity [79]. The heating demands can be broadly classified into space heating and water heating. A district heating system is primarily used for heating demand due to the low cost. In [80] it is demonstrated how high temperature heat pump can be effectively integrated to a district heating network as both a source and sink. Note that the heating in this context is also applicable to cooling. In the EU the sources of heat include natural gas, coal, oil and biomass. Combined Heat and Power (CHP) power plants are rising in share. A case study on the impact of electricity prices on energy flexibility for a heat pump and thermal storage in a residential building, is examined by the authors in [80]. The authors highlight how the flexibility potential is unlocked with better utilization of the boiler tank. In [81] the authors discuss the solar water heating potential across different regions in Europe. With growing urbanization and habitation, the space cooling requirements are rising in Europe. A cubit meter of water changing 55-95 °C offers around 58 kWh of thermal energy storage for a moderate residential house in a typical winter day. However house insulation also plays a significant role in this setting. An adequately insulated house provides load flexibility between 2 to 12 hours while maintaining occupant comfort. In Denmark for example the large wind power generation is coupled with district heating network. Surplus power generation during off-peak hours can be stored through a combination of electric heaters and heat storage with CHP as a balancing unit. Table 2 presents the thermal energy storage system potential.

Thermal energy storage	**Capacity (kWh/t)**	**Power (MW)**	**Efficiency (%)**	**Storage Period**	**Cost (€/kWh)**
Sensible (hot water)	10-50	0.001-10.0	50-90	day/months	0.1-10
Phase change material	50-150	0.001-1.0	75-90	hours/months	10-50
Chemical reactions	120-250	0.01-1.0	75-100	hours/days	8-100

Table 2: Thermal energy storage potential [82, 83]

8. Scale of a VPP in an electricity market

The scope for a VPP ranges from distribution to transmission levels in a power system. Within the power systems, VPPs are interconnected and share a common power market. VPP integrates more RES in the distribution and transmission networks.

Many RES are placed into distributed generation in the low to medium voltage grid. The grids networks can be classified as radial and meshed. Radial networks are often found in sub-urban areas whereas the meshed networks in found in urban areas. Often these networks have a few large scale centralized generators. Placing variable RES based distributed generation in this network, may cause issues such as an islanding effect due the variations in the power generation from wind or solar, and insulation damage due to high voltage at the end of the distribution network.

A VPP formed with a selection of RES can have complementary effects in mitigating the fluctuations from wind and solar. A dispatchable generator, such as a hydro power unit, will further increase the scope of the VPP. In addition, inclusion of energy storage units or demand side flexibility can further decrease the overall fluctuations. The VPP portfolio ranges from small scale (single battery unit, residential demand side flexibility, roof-top PV) to large scale (wind parks, PV parks and hydro power). The VPP can also be formulated in different levels from small and regional to distributed and wide. This flexibility enables the VPP to increase the scope of participation and coordination. Furthermore since VPP is not geographically constrained, islands, rural areas and cities can also participate as in residential, commercial and industrial consumers.

Currently there are multiple demonstration projects around the world at a distribution system level, to study the feasibility and profitability. However the geographic scope of VPPs is directly related to the power market and actual grid control. Cross border VPPs can play a crucial role in further integrating the power networks and energy prices through increasing market competition. There is a wide choice of markets that are accessible to a VPP such as the spot market, reserve power market and ancillary service market. Example of VPPs are Tesla Energy in Australia, Next Kraftwerke in Germany and PREMIO in France, to name just a few as found in table 3.

In place of installing new dispatchable or non-dispatchable generation units to meet the rising demand, the system can benefit from the exploitation of flexibility. However, the scope of flexibility varies from region to region. For example there is a high degree of system flexibility in Norway due to the hydro power plants. Furthermore, the pattern of demand side flexibility is different in northern and southern Europe due to the climatic conditions. A VPP provides a solution to pool together flexibility from both supply and demand side.

In Fig. 7 a framework listing market services and products alongside responsible parties is presented. Constraint management services aid system operators (DSO and TSO) optimizing the grid operation in a flow-based market coupling. Adequacy services are designed to increase the security of supply through managing the total capacity to offset the long-term peak and non-peak power demand. This service is requested by TSO and Balance responsible party (BRP) while the Capacity Service Provider (CSP) is the trading party. Wholesale services, controlled by BRP, aim to reduce the cost of electricity purchase in day-ahead, intra-day markets and cost adjustment in balancing mechanisms. Balancing services include frequency regulation mechanisms. This service is requested by TSO and traded by a Balance Service Provider (BSP). This mechanism pools together the demand side flexibility in the system. A VPP can participate in this mechanism in coordination with the DSO and TSO for peak load management and reserve power allocation. For example a single EV can participate in a VPP in different locations. Based on the scale of VPP it can be uni-lateral on distribution level, or bi-lateral contracts on TSO, or cross-border level. Moreover, a VPP can expand both the demand and supply side flexibility to broaden the scope.

The tariff is a monthly fee in addition to the absolute power consumption for the maximum hour average power output in kW during a month. VPP by utilizing the flexibility can flatten the curve and reduce the peak input from the external grid. Consequently the cost to the TSO is reduced.

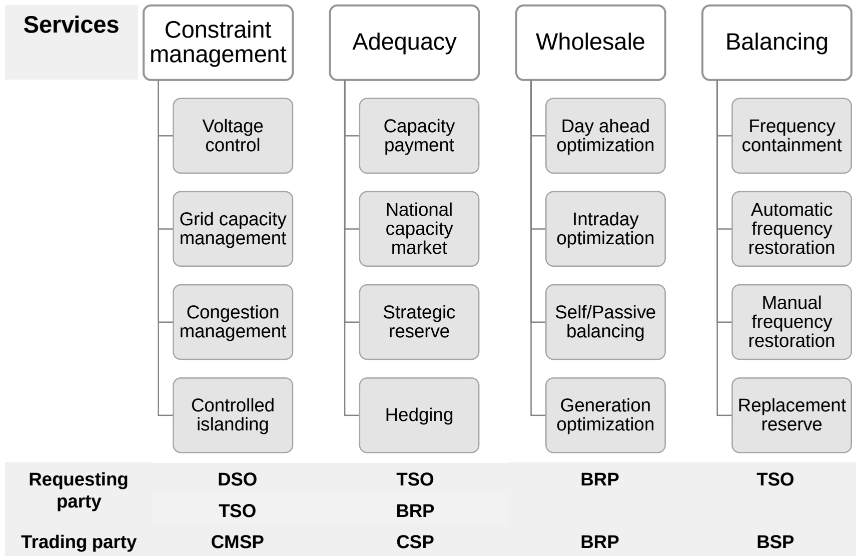

Figure 7: Scope for VPP in market and products for flexibility [84]

Table 3 presents a list of planned and operational VPPs corresponding to their capacities. It is clear that more and more power companies and start-ups are forming VPPs.

Company	Capacity (MW)	Countries
NextKraftwerke-Ecotricity [85]	6.9	UK
KiWiPower [86]	300	
Statkraft [87]	2000	
Open Energi [88]	60	
Flexitricity [89]	540	
Moixa [90]	17	
E.on-Thyssenkrupp [91]	600	
UK Power Reserve (UKPR) [92]	533	
Limejump [93]	150	
EDF [94]	866	FR
NextKraftwerke [95]	2	BE
Centrica's Restore [96]	32	BE
E.on-Thyssenkrupp [97]	600	DE
sonnenVPP [98]	2	
Steag [99]	800	
AutoGrid [100]	5000	
Energy2market [101]	3500	
Lichtblick [102]	5	
Next Kraftwerke [103]	1000	
WEMAG [104]	5	
AGL "Bring Your Own Battery" [105]	5	AU
Simple Energy SA [106]	6	
Tesla Energy Plan [107]	250	
Origin Virtual Power Plant [108]	5	
Plico Energy VPP [109]	6.5	
AusGrid "Power2U" [110]	1	
Engie-KiWi [111]	4.1	US
ENEL [112]	157	
Enbala [113]	350	
Sunrun [114]	295	
PG&E [115]	200	

Table 3: Planned and operational VPPs around the world

9. VPPs of the future

With reference to table 3 investments are flowing in for capacity expansion along with new VPPs. Apart from the PV based capacities, there is a surge in storage capacity or battery bank oriented VPP along with demand side flexibility. Reshaping the peak demand is among the primary objectives among new VPPs. This facilitates new and emerging technologies such as hydrogen for storage.

Energy policies and regulations are adapting to encourage the share of RES in the total energy mix. VPPs will further catalyze the adoption and integration of RES based distributed and decentralized sources and demand side flexibility. Reduction of unitary energy price and climate neutrality are key motivators behind the adoption of VPP technologies.

With distributed generation based VPPs, comes the challenge of resiliency and reliability. The sector coupling of power and energy sectors further increase such challenges. Risks owing to loss of load expectation and energy expected not served in a VPP are discussed in [116]. Since a VPP is primarily a software solution with hardware switches, security challenges become prominent. In this report [117] the authors describe the scope of VPPs to provide a range of grid support services. The cyber security and cyber threats associated with VPPs are discussed in [118]. Strategies to mitigate cyber threats and communications disruptions in a VPP are discussed in [119]. A draft framework for cyber security for smart grids in EU is presented in [120].

A VPP is essentially a bottom-up framework where small and medium scale generation units form a centralized entity to participate in the market. However, asset management and ownership arises as a challenge as opposed to the conventional top-down power plants. In [121] a Lean sigma approach is discussed for the power sector. Lean Sigma (LS) is a method to improve the quality to transfer the value while increasing profit and maintaining a competitive advantage. An LS approach can be applied to VPPs for deriving value for small scale generation units and consumer participation for the demand side flexibility. Through this, it is possible to unlock an incremental and continuous growth potential for stake holders, from both the demand and supply side.

A VPP of the future would employ intelligent strategies for fast response to volatile prices and adapt to weather changes. EVs can participate in a geographically distributed manner to charge or discharge in coordination with peak demand. From this point of view, a VPP can ensure high interoperability such as API, protocols and data exchanges in order to accommodate assets of different technologies and ensure optimal communication between the assets). Along with scalability, a VPP of the future would be implemented with sophisticated systems that allow for the rapid identification of operational strategies including preventive, corrective and restorative actions that ensure high reliability of the technologies involved.

9.1. Towards intelligent VPP solutions

Intelligent and self-learning algorithms can be integrated to the proactive operational planning of the VPP. The consumer devices such as charging plugs, television, etc. are becoming smart with cognitive learning of user behaviour. A VPP can learn and be responsive to this behaviour, customized to each household to adapt to fluctuations from weather, prices, generation, and the likes, in other regions.

Smart control strategies can be implemented in the VPP to facilitate the larger grid for self-healing, frequency and voltage control. A VPP can enable the formation of cognitive-twins (CT) [122]. CT have augmented semantic capabilities for identifying the dynamics to formulate inter-links between VPPs. Beyond residential and commercial demand, industrial processes such as manufacturing can also be adapted to a VPP [123]. Future VPPs can enable human machine interaction through reasoning and learning based approach in industries [124]. The power grid control strategies are in transition from conventional centralized to distributed. The last few years have seen rapid advances in communication technologies and cognitive devices. Therefore the control strategies need to further develop towards cognitive and responsive control while being distributed. A VPP as a platform can facilitate these transformations towards a transactive energy. Since VPPs are not limited to geography while wide in scale and level, virtual control strategies can be further incorporated to enhance the VPP. Even though all vectors of energy demand are weather aware, these vectors are not aware of each other. If the vectors are aware of each other the scope of flexibility can be further improved while being more coordinated. This feature can be provided by a VPP. The devices we use (i.e. fridge, computers, etc.) are also becoming more energy efficient. Energy efficient manufacturing as a part of industry 4.0 is also on the horizon. A VPP can also facilitate such projects through trading values in terms of how the price is set for a device. Beyond the price and quantity relationship, in economy the quality and resiliency of curves can be further integrated by a VPP.

10. Conclusion

This paper has explored the scope of virtual power plants in an integrated energy system. Detailed discussions on the definition of the VPP, classification of VPPs and evolution are provided. Challenges associated to the VPP both in context of power system, cyber security and asset management are discussed. The IES oriented VPP in the context of sector coupling is also explored. The current and planned VPPs around the world with an insight to the scale of VPPs are discussed. Subsequently the future scope of VPP considering intelligence, smart control and lean sigma process optimization techniques are also brought into discussion. This paper sets out in an investigative understanding of the state-of-art while shedding light on the future outlook of VPP. The review and discussions brought forward in this paper has underlined the scope, opportunity and challenges for a virtual power plant in an integrated energy system. The proposed scheme expands the opportunity to low cost power generation through integration of distributed energy systems with high share of renewable resources. Furthermore, the virtual power plant have been categorized into physical and cyber components. The challenges related to security and privacy are addressed. In the outlook, the policy measures are required along with regulatory reforms to increase the scope for a virtual power plant. Specifically sector coupling within the integrated energy systems among electric power system and heating system require further investigation. Beyond this, energy can be also traded like a currency, forming an energy bank where the value of energy is traded as a currency in the bank.

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References

[1] L. Bai, F. Li, H. Cui, T. Jiang, H. Sun, J. Zhu, Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty, Applied Energy 167 (2016) 270–279. doi:10.1016/j.apenergy.2015.10.119.

[2] Q.-H. Wu, J. Zheng, Z. Jing, X. Zhou, Large-Scale Integrated Energy Systems, Energy Systems in Electrical Engineering, Springer Singapore, Singapore, 2019. doi:10.1007/978-981-13-6943-8. URL http://link.springer.com/10.1007/978-981-13-6943-8

[3] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system, Energy 160 (2018) 720–739. arXiv:1801.05290, doi:10.1016/j.energy.2018.06.222.

[4] X. Zhang, M. Shahidehpour, A. Alabdulwahab, A. Abusorrah, Optimal Expansion Planning of Energy Hub with Multiple Energy Infrastructures, IEEE Transactions on Smart Grid 6 (5) (2015) 2302–2311. doi:10.1109/TSG.2015.2390640.

[5] M. Jadidbonab, B. Mohammadi-Ivatloo, M. Marzband, P. Siano, Short-term Self-Scheduling of Virtual Energy Hub Plant within Thermal Energy Market, IEEE Transactions on Industrial Electronics (2020) 1–1doi:10.1109/tie.2020.2978707.

[6] M. Emarati, F. Keynia, M. Rashidinejad, A two-stage stochastic programming framework for risk-based day-ahead operation of a virtual power plant, International Transactions on Electrical Energy Systems 30 (3). doi:10.1002/2050-7038.12255.
URL https://onlinelibrary.wiley.com/doi/abs/10.1002/2050-7038.12255

[7] R. Hemmati, H. Saboori, S. Saboori, Stochastic risk-averse coordinated scheduling of grid integrated energy storage units in transmission constrained wind-thermal systems within a conditional value-at-risk framework, Energy 113 (2016) 762–775. doi:10.1016/j.energy.2016.07.089.

[8] G. Papaefthymiou, K. Dragoon, Towards 100% renewable energy systems: Uncapping power system flexibility, Energy Policy 92 (2016) 69–82. doi:10.1016/j.enpol.2016.01.025.

[9] R. Boampong, D. P. Brown, On the benefits of behind-the-meter rooftop solar and energy storage: The importance of retail rate design, Energy Economics 86 (2020) 104682.

[10] K. El Bakari, W. L. Kling, Virtual power plants: An answer to increasing distributed generation, in: IEEE PES Innovative Smart Grid Technologies Conference Europe, ISGT Europe, 2010. doi:10.1109/ISGTEUROPE.2010.5638984.

[11] G. Plancke, K. De Vos, R. Belmans, A. Delnooz, Virtual power plants: Definition, applications and barriers to the implementation in the distribution system, in: International Conference on the European Energy Market, EEM, Vol. 2015-August, IEEE Computer Society, 2015. doi:10.1109/EEM.2015.7216693.

[12] G. Zhang, C. Jiang, X. Wang, Comprehensive review on structure and operation of virtual power plant in electrical system (jan 2019). doi:10.1049/iet-gtd.2018.5880.

[13] D. Pudjianto, C. Ramsay, G. Strbac, Virtual power plant and system integration of distributed energy resources, IET Renewable Power Generation 1 (1) (2007) 10–16. doi:10.1049/iet-rpg:20060023.

[14] S. Mishra, C. Bordin, A. Tomasgard, I. Palu, A multi-agent system approach for optimal microgrid expansion planning under uncertainty, International Journal of Electrical Power & Energy Systems 109 (2019) 696–709.

[15] S. Babaei, C. Zhao, L. Fan, A data-driven model of virtual power plants in day-ahead unit commitment, IEEE Transactions on Power Systems 34 (6) (2019) 5125–5135.

[16] A. Alahyari, M. Ehsan, M. Moghimi, Managing Distributed Energy Resources (DERs) Through Virtual Power Plant Technology (VPP): A Stochastic Information-Gap Decision Theory (IGDT) Approach, Iranian Journal of Science and Technology - Transactions of Electrical Engineering 44 (1) (2020) 279–291. doi:10.1007/s40998-019-00248-w.
URL https://link.springer.com/article/10.1007/s40998-019-00248-w

[17] P. Asmus, Microgrids, virtual power plants and our distributed energy future, The Electricity Journal 23 (10) (2010) 72–82.

[18] I. Gerami Moghaddam, Scheduling a smart energy hub-based virtual power plant using benders decomposition to considering power system constraints, International Transactions on Electrical Energy Systems 28 (10) (2018) e2608.

[19] M. Wickert, S. Liebehentze, A. Zündorf, Experience report: First steps towards a microservice architecture for virtual power plants in the energy sector, in: Joint Post-proceedings of the First and Second International Conference on Microservices (Microservices 2017/2019), Schloss Dagstuhl-Leibniz-Zentrum für Informatik, 2020.

[20] S. Vukmirović, A. Erdeljan, F. Kulić, S. Luković, Software architecture for smart metering systems with virtual power plant, in: MELECON 2010-2010 15th IEEE Mediterranean Electrotechnical Conference, IEEE, 2010, pp. 448–451.

[21] A. Aldegheishem, R. Bukhsh, N. Alrajeh, N. Javaid, Faavpp: Fog as a virtual power plant service for community energy management, Future Generation Computer Systems 105 (2020) 675–683.

[22] P. K. Ray, S. R. Mohanty, N. Kishor, Classification of power quality disturbances due to environmental characteristics in distributed generation system, IEEE Transactions on sustainable energy 4 (2) (2012) 302–313.

[23] P. K. Ray, S. R. Mohanty, N. Kishor, J. P. Catalão, Optimal feature and decision tree-based classification of power quality disturbances in distributed generation systems, IEEE Transactions on Sustainable Energy 5 (1) (2013) 200–208.

[24] A. A. Alkahtani, S. T. Alfalahi, A. A. Athamneh, A. Q. Al-Shetwi, M. B. Mansor, M. Hannan, V. G. Agelidis, Power quality in microgrids including supraharmonics: Issues, standards, and mitigations, Ieee Access 8 (2020) 127104–127122.

[25] R. Thallam, G. Heydt, Power acceptability and voltage sag indices in the three phase sense, in: 2000 Power Engineering Society Summer Meeting (Cat. No. 00CH37134), Vol. 2, IEEE, 2000, pp. 905–910.

[26] A. Hariri, M. O. Faruque, Impacts of distributed generation on power quality, in: 2014 North American Power Symposium (NAPS), Ieee, 2014, pp. 1–6.

[27] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, N. D. Hatziargyriou, Distributed and decentralized voltage control of smart distribution networks: Models, methods, and future research, IEEE Transactions on smart grid 8 (6) (2017) 2999–3008.

[28] R. Walling, R. Saint, R. C. Dugan, J. Burke, L. A. Kojovic, Summary of distributed resources impact on power delivery systems, IEEE Transactions on power delivery 23 (3) (2008) 1636–1644.

[29] A. Hariri, M. O. Faruque, R. Soman, R. Meeker, Impacts and interactions of voltage regulators on distribution networks with high pv penetration, in: 2015 North American Power Symposium (NAPS), IEEE, 2015, pp. 1–6.

[30] R. Saint, N. Friedman, The application guide for distributed generation interconnection-the nreca guide to ieee 1547, in: 2002 Rural Electric Power Conference. Papers Presented at the 46th Annual Conference (Cat. No. 02CH37360), IEEE, 2002, pp. D2–1.

[31] D. Ranamuka, A. P. Agalgaonkar, K. M. Muttaqi, Examining the interactions between dg units and voltage regulating devices for effective voltage control in distribution systems, IEEE Transactions on Industry Applications 53 (2) (2017) 1485–1496.

[32] D. Ranamuka, A. P. Agalgaonkar, K. M. Muttaqi, Examining the interactions between dg units and voltage regulating devices for effective voltage control in distribution systems, IEEE Transactions on Industry Applications 53 (2) (2016) 1485–1496.

[33] D. Ranamuka, A. Agalgaonkar, K. Muttaqi, Online voltage control in distribution systems with multiple voltage regulating devices, IEEE Transactions on Sustainable Energy 5 (2) (2013) 617–628.

[34] A. Kulmala, S. Repo, P. Järventausta, Coordinated voltage control in distribution networks including several distributed energy resources, IEEE Transactions on Smart Grid 5 (4) (2014) 2010–2020.

[35] X. Liu, A. Aichhorn, L. Liu, H. Li, Coordinated control of distributed energy storage system with tap changer transformers for voltage rise mitigation under high photovoltaic penetration, IEEE Transactions on Smart Grid 3 (2) (2012) 897–906.

[36] F. A. Viawan, D. Karlsson, Combined local and remote voltage and reactive power control in the presence of induction machine distributed generation, IEEE Transactions on Power Systems 22 (4) (2007) 2003–2012.

[37] A. Q. Al-Shetwi, M. Hannan, K. P. Jern, A. A. Alkahtani, A. PG Abas, Power quality assessment of grid-connected pv system in compliance with the recent integration requirements, Electronics 9 (2) (2020) 366.

[38] V. Yuvaraj, S. Deepa, A. R. Rozario, M. Kumar, Improving grid power quality with facts device on integration of wind energy system, in: 2011 Fifth Asia Modelling Symposium, IEEE, 2011, pp. 157–162.

[39] A. Q. Al-Shetwi, M. Z. Sujod, Modeling and control of grid-connected photovoltaic power plant with fault ride-through capability, Journal of Solar Energy Engineering 140 (2).

[40] M. Molinas, J. A. Suul, T. Undeland, Low voltage ride through of wind farms with cage generators: Statcom versus svc, IEEE Transactions on power electronics 23 (3) (2008) 1104–1117.

[41] K. Ilango, A. Bhargav, A. Trivikram, P. Kavya, G. Mounika, M. G. Nair, Power quality improvement using statcom with renewable energy sources, in: 2012 IEEE 5th India International Conference on Power Electronics (IICPE), IEEE, 2012, pp. 1–6.

[42] S. T. Chavhan, C. Bhattar, P. V. Koli, V. S. Rathod, Application of statcom for power quality improvement of grid integrated wind mill, in: 2015 IEEE 9th International Conference on Intelligent Systems and Control (ISCO), IEEE, 2015, pp. 1–7.

[43] T.-L. Lee, S.-H. Hu, Y.-H. Chan, D-statcom with positive-sequence admittance and negative-sequence conductance to mitigate voltage fluctuations in high-level penetration of distributed-generation systems, IEEE Transactions on Industrial Electronics 60 (4) (2011) 1417–1428.

[44] P. Chaudhari, P. Rane, A. Bawankar, P. Shete, K. Kalange, A. Moghe, J. Panda, A. Kadrolkar, K. Gaikwad, N. Bhor, et al., Design and implementation of statcom for reactive power compensation and voltage fluctuation mitigation in microgrid, in: 2015 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES), IEEE, 2015, pp. 1–5.

[45] E. Hossain, M. R. Tür, S. Padmanaban, S. Ay, I. Khan, Analysis and mitigation of power quality issues in distributed generation systems using custom power devices, Ieee Access 6 (2018) 16816–16833.

[46] Y. Zhao, Electrical power systems quality, University Of Buffalo.

[47] N. Edomah, Effects of voltage sags, swell and other disturbances on electrical equipment and their economic implications, in: IEEE Proc. of 20th International Conference on Electricity Distribution, IET, 2009, pp. 1–4.

[48] C.-I. Chen, Y.-C. Chen, C.-N. Chen, A high-resolution technique for flicker measurement in power quality monitoring, in: 2013 IEEE 8th Conference on Industrial Electronics and Applications (ICIEA), IEEE, 2013, pp. 528–533.

[49] A. Honrubia-Escribano, T. García-Sánchez, E. Gómez-Lázaro, E. Muljadi, A. Molina-Garcia, Power quality surveys of photovoltaic power plants: characterisation and analysis of grid-code requirements, IET Renewable Power Generation 9 (5) (2015) 466–473.

[50] V. Khadkikar, Enhancing electric power quality using upqc: A comprehensive overview, IEEE transactions on Power Electronics 27 (5) (2011) 2284–2297.

[51] M. Kesler, E. Ozdemir, Synchronous-reference-frame-based control method for upqc under unbalanced and distorted load conditions, IEEE transactions on industrial electronics 58 (9) (2010) 3967–3975.

[52] A. Ghosh, G. Ledwich, A unified power quality conditioner (upqc) for simultaneous voltage and current compensation, Electric power systems research 59 (1) (2001) 55–63.

[53] D. Graovac, V. Katic, A. Rufer, Power quality problems compensation with universal power quality conditioning system, IEEE Transactions on Power Delivery 22 (2) (2007) 968–976.

[54] V. Khadkikar, A. Chandra, A. Barry, T. Nguyen, Analysis of power flow in upqc during voltage sag and swell conditions for selection of device ratings, in: 2006 Canadian Conference on Electrical and Computer Engineering, IEEE, 2006, pp. 867–872.

[55] S. Lehnhoff, A. Nieße, Recent trends in energy informatics research, it-Information Technology 59 (1) (2017) 1–3.

[56] C. Goebel, H.-A. Jacobsen, V. del Razo, C. Doblander, J. Rivera, J. Ilg, C. Flath, H. Schmeck, C. Weinhardt, D. Pathmaperuma, et al., Energy informatics, Business & Information Systems Engineering 6 (1) (2014) 25–31.

[57] Springer, Aims and scope of energy informatics journal, `https://energyinformatics.springeropen.com`, online; accessed 2020.

[58] C. Bordin, A. Håkansson, S. Mishra, Smart energy and power systems modelling: an iot and cyber-physical systems perspective, in the context of energy informatics, Procedia Computer Science 176 (2020) 2254–2263.

[59] T. B. Rasmussen, G. Yang, A. H. Nielsen, Z. Dong, A review of cyber-physical energy system security assessment, in: 2017 IEEE Manchester PowerTech, IEEE, 2017, pp. 1–6.

[60] J. M. Morales, A. J. Conejo, H. Madsen, P. Pinson, M. Zugno, Integrating renewables in electricity markets: operational problems, Vol. 205, Springer Science & Business Media, 2013.

[61] L. Lin, X. Guan, Y. Peng, N. Wang, S. Maharjan, T. Ohtsuki, Deep reinforcement learning for economic dispatch of virtual power plant in internet of energy, IEEE Internet of Things Journal.

[62] H. T. Nguyen, L. B. Le, Z. Wang, A bidding strategy for virtual power plants with the intraday demand response exchange market using the stochastic programming, IEEE Transactions on Industry Applications 54 (4) (2018) 3044–3055.

[63] K. Aduda, T. Labeodan, W. Zeiler, G. Boxem, Demand side flexibility coordination in office buildings: A framework and case study application, Sustainable Cities and Society 29 (2017) 139–158.

[64] G. Fridgen, R. Keller, M.-F. Körner, M. Schöpf, A holistic view on sector coupling, Energy Policy 147 (2020) 111913.

[65] J.-P. Jimenez-Navarro, K. Kavvadias, F. Filippidou, M. Pavičević, S. Quoilin, Coupling the heating and power sectors: The role of centralised combined heat and power plants and district heat in a european decarbonised power system, Applied Energy 270 (2020) 115134.

[66] M. Robinius, A. Otto, P. Heuser, L. Welder, K. Syranidis, D. S. Ryberg, T. Grube, P. Markewitz, R. Peters, D. Stolten, Linking the power and transport sectors—part 1: The principle of sector coupling, Energies 10 (7) (2017) 956.

[67] C. Bordin, A. Gordini, D. Vigo, An optimization approach for district heating strategic network design, European Journal of Operational Research 252 (1) (2016) 296–307.

[68] M. A. Ancona, M. Bianchi, L. Branchini, A. De Pascale, F. Melino, A. Peretto, Low temperature district heating networks for complete energy needs fulfillment, International Journal of Sustainable Energy Planning and Management 24.

[69] J. Freeman, I. Guarracino, S. A. Kalogirou, C. N. Markides, A small-scale solar organic rankine cycle combined heat and power system with integrated thermal energy storage, Applied thermal engineering 127 (2017) 1543–1554.

[70] J. Lizana, C. Bordin, T. Rajabloo, Integration of solar latent heat storage towards optimal small-scale combined heat and power generation by organic rankine cycle, Journal of Energy Storage 29 (2020) 101367.

[71] J. S. Pereira, J. B. Ribeiro, R. Mendes, G. C. Vaz, J. C. André, Orc based micro-cogeneration systems for residential application–a state of the art review and current challenges, Renewable and Sustainable Energy Reviews 92 (2018) 728–743.

[72] B. Zwaenepoel, J. Vansteenbrugge, T. Vandoorn, G. Van Eetvelde, L. Vandevelde, Renewable energy balancing with thermal grid support, in: 16th International conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES 2013), Vol. 35, AIDIC Servizi, 2013, pp. 535–540.

[73] Y. Wong, L. Lai, S. Gao, K. Chau, Stationary and mobile battery energy storage systems for smart grids, in: 2011 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), IEEE, 2011, pp. 1–6.

[74] S.-i. Inage, Prospects for large-scale energy storage in decarbonised power grids, International Energy Agency 3 (4) (2009) 125.

[75] A. Ajanovic, A. Hiesl, R. Haas, On the role of storage for electricity in smart energy systems, Energy (2020) 117473.

[76] S. G. Argade, V. Aravinthan, I. E. Büyüktahtakın, S. Joseph, Performance and consumer satisfaction-based bi-level tariff scheme for ev charging as a vpp, IET Generation, Transmission & Distribution 13 (11) (2018) 2112–2122.

[77] J. Kiviluoma, S. Heinen, H. Qazi, H. Madsen, G. Strbac, C. Kang, N. Zhang, D. Patteeuw, T. Naegler, Harnessing flexibility from hot and cold: heat storage and hybrid systems can play a major role, IEEE Power and Energy Magazine 15 (1) (2017) 25–33.

[78] S. Wong, J.-P. Pinard, Opportunities for smart electric thermal storage on electric grids with renewable energy, IEEE Transactions on Smart Grid 8 (2) (2016) 1014–1022.

[79] K. J. Chua, S. K. Chou, W. Yang, Advances in heat pump systems: A review, Applied energy 87 (12) (2010) 3611–3624.

[80] C. Mateu-Royo, S. Sawalha, A. Mota-Babiloni, J. Navarro-Esbrí, High temperature heat pump integration into district heating network, Energy Conversion and Management 210 (2020) 112719.

[81] Y. Yohanis, O. Popel, S. Frid, B. Norton, Geographic variation of solar water heater performance in europe, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 220 (4) (2006) 395–407.

[82] I. Sarbu, C. Sebarchievici, A comprehensive review of thermal energy storage, Sustainability 10 (1) (2018) 191.

[83] A. Hauer, Storage technology issues and opportunities, international low-carbon energy technology platform, in: Proceedings of the Strategic and Cross-Cutting Workshop "Energy Storage—Issues and Opportunities", Paris, France, Vol. 15, 2011.

[84] A. Van der Veen, M. Van der Laan, H. De Heer, E. Klaassen, W. Van den Reek, Flexibility value chain (2018).

[85] Vpp: Why ecotricity has entered the flexibility market — theenergyst.com, `https://theenergyst.com/ecotricity-enters-flexibility-market/`, (Accessed on 10/21/2020).

[86] 'modelling electricity demand the key' as uk comes out of lockdown: Kiwi power — s&p global platts, https://www.spglobal.com, (Accessed on 10/21/2020).

[87] Statkraft unveils 1gw virtual power plant in uk, intends to double capacity by summer — current news, https://www.statkraft.com/newsroom/news-and-stories/archive/2020/vpp-balancing-services/, (Accessed on 10/21/2020).

[88] Open energi - dynamic demand 2.0 distributed energy platform, https://www.openenergi.com/, (Accessed on 10/21/2020).

[89] Quinbrook invests in flexible generation, grid support and demand response, https://www.quinbrook.com, (Accessed on 10/21/2020).

[90] Moixa to build virtual power plant as first phase of uk smart energy project – pv magazine international, https://www.moixa.com/, (Accessed on 10/21/2020).

[91] E.on and thyssenkrupp bring hydrogen to the electric market - energy live news, https://www.energylivenews.com/2020/06/30/e-on-and-thyssenkrupp-bring-hydrogen-to-the-electric-market/, (Accessed on 10/21/2020).

[92] Uk's largest independent distributed energy supplier sold for £216m, https://www.eenewspower.com/news/uks-largest-independent-distributed-energy-supplier-sold-ps216m, (Accessed on 10/21/2020).

[93] Limejump gets all clear to chase big six in uk grid balancing market - rethink, https://rethinkresearch.biz/articles/limejump-gets-all-clear-to-chase-big-six-in-uk-grid-balancing-market/, (Accessed on 10/21/2020).

[94] Edf offers 866 mw at vpp auction, no additional power tenders on horizon — icis, https://www.icis.com/explore/resources/news/2007/11/29/9300807/edf-offers-866-mw-at-vpp-auction-no-additional-power-tenders-on-horizon/, (Accessed on 10/21/2020).

[95] Next kraftwerke connects 2 mw battery to its vpp in belgium – pv magazine international, https://www.pv-magazine.com/2018/07/13/next-kraftwerke-connects-2-mw-battery-to-its-vpp-in-belgium/, (Accessed on 10/21/2020).

[96] Centrica's restore business launches 32 mw 'virtual power plant' in belgium — centrica plc, https://www.centrica.com/news/centricas-restore-business-launches-32-mw-virtual-power-plant-belgium, (Accessed on 10/21/2020).

[97] E.on and thyssenkrupp bring hydrogen to the electric market - energy live news, https://www.energylivenews.com/2020/06/30/e-on-and-thyssenkrupp-bring-hydrogen-to-the-electric-market/, (Accessed on 10/21/2020).

[98] Software for virtual power plants powered by residential solar-plus-storage, https://www.pv-magazine.com/, (Accessed on 10/21/2020).

[99] A4 large scale storage options under special consideration of 6x15 mw battery example, http://www.eqmagpro.com/wp-content/uploads/2017/06/VGB-Congress_Benesch.pdf, (Accessed on 10/21/2020).

[100] Navigant research names autogrid as #1 virtual power plant platform provider in 2020 — autogrid, https://www.auto-grid.com/products/virtual-power-plant/, (Accessed on 10/21/2020).

[101] e2m announces strategic partnership with swytch to collaborate on proof of concept pilot - with e2m, https://www.e2m.energy/en/news-entry/Strategic-Partnership-with-Swytch.html, (Accessed on 10/21/2020).

[102] Storage and the rise of the virtual power plant — energy storage news, https://www.energy-storage.news/blogs/storage-and-the-rise-of-the-virtual-power-plant, (Accessed on 10/21/2020).

[103] Next kraftwerke records strong portfolio growth in 2017, https://www.next-kraftwerke.com/news/next-kraftwerke-records-strong-portfolio-growth-in-2017, (Accessed on 10/21/2020).

[104] Building a battery power plant wemag — aggreko, https://www.aggreko.com/en-pg/case-studies/utilities/building-a-battery-power-plant-wemag#challenge, (Accessed on 10/21/2020).

[105] What is a virtual power plant?, https://www.solarpowerworldonline.com/2017/09/virtual-power-plant/, (Accessed on 10/21/2020).

[106] Simply energy virtual power plant - australian renewable energy agency, https://arena.gov.au/projects/simply-energy-virtual-power-plant-vpp/, (Accessed on 10/21/2020).

[107] Sa virtual power plant — tesla australia, https://www.tesla.com/en_au/sa-virtual-power-plant, (Accessed on 10/21/2020).

[108] First 5mw virtual power plant from major utility origin gets funding in victoria, australia, https://www.energy-storage.news, (Accessed on 10/21/2020).

[109] W.a. community virtual power plant confirms $50m swiss investment — one step off the grid, https://onestepoffthegrid.com.au/w-a-community-virtual-power-plant-confirms-50m-swiss-investment/, (Accessed on 10/21/2020).

[110] Evegen virtual power plant, https://www.evergen.com.au/, (Accessed on 10/21/2020).

[111] Engie, kiwi power partner on virtual power plants in us — s&p global market intelligence, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/engie-kiwi-power-partner-on-virtual-power-plants-in-us-59480758, (Accessed on 10/21/2020).

[112] Enel increases 'virtual power plant' to 157mw — vermont business magazine, https://vermontbiz.com/news/2018/march/01/enel-increases-virtual-power-plant-157mw, (Accessed on 10/21/2020).

[113] Vpp.pdf, https://www.enbala.com/wp-content/uploads/2018/01/VPP.pdf, (Accessed on 10/21/2020).

[114] repowering-clean-sunrun.pdf, https://www.sunrun.com/sites/default/files/repowering-clean-sunrun.pdf, (Accessed on 10/21/2020).

[115] Pge program will transform hundreds of homes into a virtual power plant - news releases — pge, https://www.portlandgeneral.com, (Accessed on 10/21/2020).

[116] O. Sadeghian, A. Oshnoei, R. Khezri, S. Muyeen, Risk-constrained stochastic optimal allocation of energy storage system in virtual power plants, Journal of Energy Storage 31 (2020) 101732.

[117] J. T. Johnson, Design and evaluation of a secure virtual power plant., Tech. rep., Sandia National Lab.(SNL-NM), Albuquerque, NM (United States) (2017).

[118] S. K. Venkatachary, J. Prasad, R. Samikannu, A. Alagappan, L. J. B. Andrews, Cybersecurity infrastructure challenges in iot based virtual power plants, Journal of Statistics and Management Systems 23 (2) (2020) 263–276.

[119] P. Li, Y. Liu, H. Xin, X. Jiang, A robust distributed economic dispatch strategy of virtual power plant under cyber-attacks, IEEE Transactions on Industrial Informatics 14 (10) (2018) 4343–4352.

[120] T. Pavleska, H. Aranha, M. Masi, G. P. Sellitto, Drafting a cybersecurity framework profile for smart grids in eu: A goal-based methodology, in: European Dependable Computing Conference, Springer, 2020, pp. 143–155.

[121] M. Sony, Lean six sigma in the power sector: frog into prince, Benchmarking: An International Journal.

[122] J. Lu, X. Zheng, A. Gharaei, K. Kalaboukas, D. Kiritsis, Cognitive twins for supporting decision-makings of internet of things systems, in: Proceedings of 5th International Conference on the Industry 4.0 Model for Advanced Manufacturing, Springer, 2020, pp. 105–115.

[123] J. M. Rozanec, L. Jinzhi, Towards actionable cognitive digital twins for manufacturing, in: International Workshop On Semantic Digital Twins (SeDiT 2020), SeDiT 2020, Greece, 2020.

[124] Z. Zhai, J. F. Martínez, N. L. Martínez, V. H. Díaz, Applying case-based reasoning and a learning-based adaptation strategy to irrigation scheduling in grape farming, Computers and Electronics in Agriculture 178 (2020) 105741.