Virtual Power Plants - Renewable Energy Production of the Future

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***Abstract*— Virtual power plants (VPPs) have been developed due to the needs of a changing energy system. The growing shares of electrical power production from decentralized and renewable power plants raise the need for efficient management systems to control these sources and to optimize the benefit for the energy system. This paper summarizes the background of the concepts regarding virtual power plants and describes experiences which were gathered in the context of research and development as well as commercial solutions.**

I. The German Power System

A. Transmission and Distribution

The German power grid is the largest one in Europe with around 1,816,857 km of power lines on the distribution and transmission level. In the year 2015 around 628.8 TWh of net energy was transported [1]. The transmission system operators (TSOs) TenneT, 50Hertz Transmission, Amprion, Transnet BW, are responsible for the transport of power on the transmission level and for keeping the power system stable.

Figure 1. Map of the German network operators at high voltage in February 2017 [2]

To transport the energy in Germany four different levels of voltage are used by TSOs and distribution system operators (DSOs):

- In the transmission grid: Connection of large conventional power plants, cross border connections and offshore wind farms , extra high voltage: 220 kV and 380 kV
- In the distribution grid: Typically used to connect onshore wind and solar farms, High voltage: < 60 kV until < 220 kV
- Medium voltage: 6 kV to 60 kV
- Low voltage: distribution grid: lower than 6 kV

To operate a power system in a safe manner so-called ancillary services are required. They include maintaining frequency and voltage stability, the restoration of supply and system operations such as grid congestion management [3].

B. Electricity market

Germany's electricity market is in general based on a one-price zone system. This means that the same market clearing price applies to each trading party participating in the German market, independent of its location within the country. The assumption thereby is a "copper plate" that allows indefinite transport capacity to allow free and competitive trading of electrical energy. There are several ways to trade electrical energy [4]:

- future-market - allows long term products to be concluded years before the agreed period of delivery
- day-ahead market - characterized by the highest liquidity, highest trading volume and greatest number of participants. Energy is traded here for each hour of the corresponding day of delivery
- intra-day market - continuous market of 15-minute products to adjust e.g. schedules of power plants according to more precise short-term forecasts

Besides the strongly regulated and transparent exchange process a second market access exists, the "over-the-counter" (OTC) market. At this market bilateral agreements of power delivery are negotiated.

C. Trading renewables

In the context of renewable energies (REs) and their market integration, the German instrument of direct marketing should be recognized. Since the implementation of the German Renewable Energy Source Act of 2014[5] all RE sources must directly sell their produced energy in the power market instead of only receiving a fixed feed-in-tariff like before. Only installations with less than 100 kW are exempted from this regulation. With the earnings at the power exchange, additional gains received from flexibility provisions, like the control reserve market, and combined with a fixed paid market premium ("Marktprämie" in German) the bandwidth of all RE sources' potential business opportunities under the RES Act are covered. The greatest share of all revenues is usually the fixed market premium which is calculated as follows: The awarded theoretical feed-in-tariff at the time of construction/auction minus the monthly-average of EPEX's day-ahead market results. It is common for a RE operator to assign a market aggregator for trading the generated power on its behalf.

D. German power production and power plants

In the year 2016 the share of renewables in the yearly consumption of electrical energy in Germany was roughly 30%. This energy is produced in decentralized, renewable power plants with a total installed capacity of 109GW (wind farms 51.5GW, PV-farms 40GW, biomass plants 7.4GW, hydro 9.4 and others 0.9). Additional conventional power plants with a total capacity of 105GW are installed [6]. This installed capacity meets an average demand of 55GW to 80 GW.

E. Challenges

As can be inferred from the paragraph above, Germany is in a challenging situation regarding the balance of power production and demand and meeting the climate protection goals which means the usage of as much renewable energy as possible. Some of the specific challenges that Germany faces include:

- Majority of wind power is installed in the northern parts of Germany whereas most of PV is in the south. This requires ' horizontal, geographical transport of energy to the centers of demand.
- In the past the German power system consisted of larger thermal power plants providing power on higher voltage levels. Nowadays a significant share is produced on low voltage level (rooftop-solar) resulting in vertical bottom-up transport from low voltage levels to high voltage.
- Majority of renewables is based on fluctuating sources (wind approx. 2,000 to 4,000 full-load hours, solar approx. 900 full-load hours) leading to variable, intermittent production.
- Total installed production capacity (215GW) exceeds average demand (55GW to 80GW) by a factor of 2.7 to 3.9. This necessitates flexibility of renewable and conventional power production as well as on the demand side.
- Curtailment of renewable power in times of high power feed-in due to grid restrictions may be negative for reaching climate protection goals, even though curtailed power is paid.
- Conventional power plants provide ancillary services. With growing share of renewable power production, wind and PV generators will need to provide these services as well.

II. VIRTUAL POWER PLANT - AGGREGATED POWER PRODUCTION AND CONSUMPTION

With the concept of VPP it will be possible to meet these challenges. For this it is necessary to combine power production/consumption with intelligent management systems in order to treat portfolios of decentralized sources as one unit:

> *A virtual power plant is a cluster of* ***dispersed generator units, controllable loads and storages systems****, aggregated in order to* ***operate as a unique power plant****. The generators can use both fossil and renewable energy source. The heart of a VPP is an* ***energy management system (EMS)*** *which coordinates the power flows coming from the generators, controllable loads and storages. The* ***communication is bidirectional****, so that the VPP can not only receive information about the current status of each unit, but it can also send the signals to control the objects.* [7]

A. Principle of virtual power plants

VPPs can serve different goals in the energy system. On a commercial level, aggregation of decentralized energy sources can act as one unit in analogy to thermal power plants in the energy markets. On a technical level, virtual power plants are able to stabilize the power system by providing system services. These two concepts, called Commercial VPP (CVPP) and Technical VPP (TVPP), vary in the optimization goals for the generation portfolio and can be combined. These two types act on macro or energy system scale and can include distributed generation, flexible loads and energy storages. The objective is either to maximize revenues or system stability.

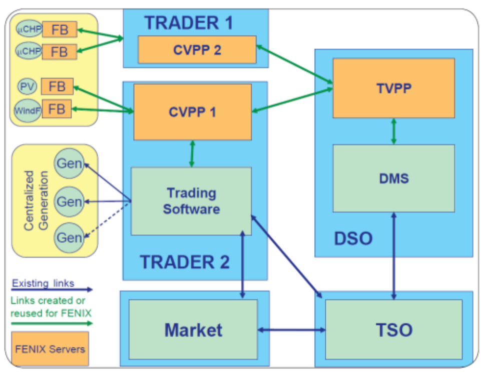

Figure 2: "General Fenix architecture" (figure 2.3.1 in [8])

For further understanding of the differences between CVPPs and TVPPs, the general concept will be explained according to Figure 2. Its structure has been introduced by the European research project FENIX. As shown in the figure, initially multiple DERs like CHPs or PV are connected via a so-called "FENIX box" to the CVPP. This box allows metering and control functionalities at site. Then the central Energy Management System coordinates the flow of information from DERs to form a single aggregated profile of all pooled resources. Imperative is the data about cost curves to participate on different markets with one associated cost curve for the entire VPP that feeds the trading software of a CVPP's operator, e.g. an energy supplier or market aggregator. A further input can be data from centralized conventional power plants. As a result a CVPP participates similar to a conventional power plant on the energy market or procures ancillary services for a TSO with the same primary objective of maximizing its profitability.

B. Architecture

VPP consist of three main levels of implementation. The third or lower level consists of communication structures in order to aggregate the portfolio and secure the connection between the central control unit (CCU) and the distributed energy resources (DERs), energy storages or loads. Main tasks at the aggregating level are metering power feed-in of DER and further values like storage levels, flexibility and ability to provide reactive power. On the other hand, the bidirectional communication channel is used for sending schedules or operating points (in the case the unit is not able to compute schedules).

The second level consists of the backend software that is the core component of the plant. Here the logical unit is located. The main task here is to process the business case and to find an optimal schedule for the whole portfolio. The process for this calculation depends on the business case. For example, for day-ahead trading the calculation follows these steps:

- The feed-in forecast for the portfolio and market price forecast for the next day are acquired
- The offer on the day-ahead market is calculated and placed
- On the next day the metering values of the portfolio is aggregated
- In the case of energy shortage storage can be activated, demand can be shifted or energy can be traded intraday (depending on cost functions)
- In the case of energy surplus DER can be rescheduled, energy can be stored, demand raised or energy can be traded intraday

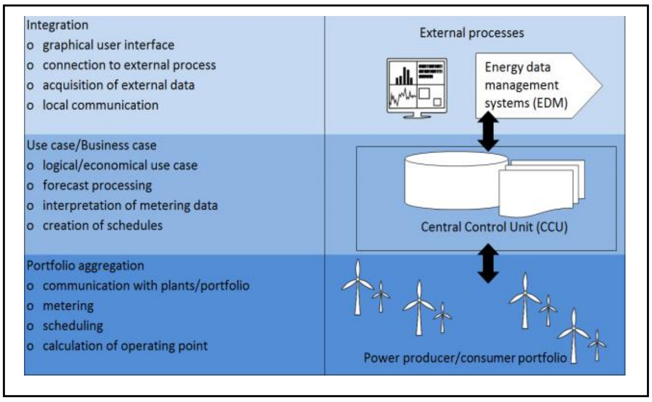

Figure 3: Virtual power plant architecture

The first level includes communications to other systems such as automatic trading systems, grid operation systems, and graphical user interfaces (GUI). Usually the VPP keeps its own data internally and provides interfaces to external systems. For communication with external systems as well as DERs, standardized interfaces and protocols are common. The following table shows some interface technologies:

Wind	OPC-XML-DA
	IEC 61400-25
	SOAP (Depending on Manufacturer spec.)
PV	MODBUS/TCP
	OPC-XML-DA
CHP	VHPready 3.0
	OPC-XML-DA CHP
Storage	SMA Sunny Island
Loads	IWES OGEMA

Table 1: Interface technologies for integration of DER, storage and loads

The graphical user interface gives the operator the opportunity to control the plant, integrate further components like DER, and to define boundary conditions related to the business cases.

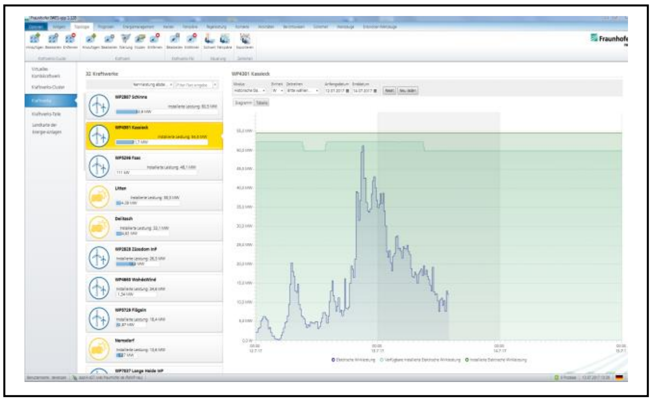

Figure 4: Graphical user interface of a VPP solution (Here the GUI of IWES.vpp – a software that is used in several research and industrial projects – is shown)

III. BUSINESS CASES AND BENEFITS FROM VPP

Several general aspects can be concluded in relation to benefits from VPP solutions. Therefore it is crucial to recognize the main technical capabilities that come along with a VPP. First important change is the option of DERs' visibility to all energy participants due to metering installations on site. And if, in the sense of a VPP, remote control capabilities of DERs are added on top, access is granted as well. Needed elements are a strong communication network and an efficient central control unit. Besides the options of visibility and access to DERs the technology shift from synchronous generators to inverter-based systems should be noted. From this change arises the possibility of great flexibility, in relation to active and reactive power flows, even though resulting challenges shouldn't be underestimated.

With these two essential technical requirements of visibility and controllability of DERs several benefits can be realized. In the following section, possible advantages of VPPs will be listed from the point of view of different entities interacting with the power system: The network operators (TSO and DNO), DER operators, market aggregators, and the regulators.

A. Benefits for TSOs

With the TSO's system-wide responsibility of ensuring the security and quality of supply, the need for compensating the phase-out of large conventional generation becomes increasingly important. By filling the gap caused by loss of generation that provides frequency response, voltage support and black start capability with large VPPs of decentralized DERs, acting in their entirety at the transmission level, an even better service can be achieved due to the higher flexibility and redundancy of a VPP.

B. Benefits for DSOs

In the process of increasing numbers of DERs connected to distribution grids, a fundamental change occurs - the responsibility of system stability gets inverted in comparison to the current situation. For a renewable driven energy system the DSO's actions are essential to maintaining security, due to the majority of DERs installations being on the distribution level, in comparison to the strong TSO's influence in centralized grids of today. And with the implemented remote controls at DERs' a DNO can optimize their operation without non-essential expansion of the grid while keeping the system secure.

C. Benefits for DER operators

Besides advantageous consequences of VPPs' introduction in relation to system security, various discussed business opportunities can be enabled for DERs. The requirement therefore is of a route to the market that is created by DERs' pooling in a VPP. Subsequently DER owners can generate higher profits that wouldn't be possible due to market regulations, e.g. a minimum offer limit or too extended product lengths, as well as high transaction costs for trading only as a single unit. In particular high profitable markets, in the context of Germany and similar countries, such as the control reserve and spot market are of major interest.

D. Benefits for Market aggregators (German market)

Acting as the link between a VPP operator and the electricity market in Germany, aggregators benefit from increasing amounts of commitments at the energy market and their corresponding transaction fees. With VPPs additional trading and tendering processes are to be expected on top of current direct marketing of larger DERs. Simultaneously VPPs facilitate cost reductions for acquiring balancing energy, e.g. as a result of internal balancing in a VPP pool by its own flexibility possibilities or increased short-term market liquidity.

E. Benefits for Regulators

And at last, for the regulators, three main benefits can be stated in the sense of the "energy triangle": economical profitability, security of supply and sustainability [9]. Firstly, the general reduction of end user electricity prices thanks to lower grid expansion costs and less system flexibility expenses, which in turn are a result of reduced number of congestion management activities, less expenses for reserves and short-term electricity products caused by increased market offers, improved forecasts and internal balancing, enable the positive national cost effect and lead to an improved cost-competiveness of energy supply,. And secondly, regarding a secure supply, VPPs provide the regulator with an option to increase the quantity of flexibility in the power system and thereby its stability. This flexibility of controllable and renewable DERs, interconnected in a VPP, facilitates the tackling of climate change, thereby fulfilling finally the last objective of the energy triangle.

IV. CONCLUSION AND OUTLOOK

The main reason and common business case why VPPs are used today is trading renewable energies. For this, aggregated portfolios consisting of several DERs are used for example by German energy traders like Energy2market GmbH, Next Kraftwerke GmbH or others. But with the detailed knowledge and abilities to control these portfolios further business cases are possible. One already established is provision of control reserve power in order to keep frequency stable. Since several years energy traders have been providing secondary and tertiary control reserve power as well by using pool of flexible units like CHP. At the end of 2015, German TSOs published prequalification rules for negative tertiary reserve power from wind farms. Due to low prices on the market for tertiary reserve power, there is still very little participation from wind farm operators in this market. For this reason the Regulator changed the submission process of the secondary control reserve power from weekly to day-ahead submission [10]. This is one step to raise the share of fluctuating – which means forecast based for day-ahead – renewables in the control reserve power markets.

Another future option will be the provision of reactive power from DERs. Modern wind farms for example have the ability to provide reactive power more or less independently from the active power feed in. Due to the fact that there is no market for this at present, provision of reactive power is still no business case for wind and PV.

Currently in northern Germany wind power is curtailed on the demand of the grid operators. In actual research projects market based redispatch mechanisms related to the state of the electrical grids (transmission and distribution) were developed in order to create specific markets and products to meet grid restrictions. This might be a further possible business case for operators of VPP as well.

Curtailment and redispatch are ways to deal with situations of high feed-in and low demand or grid restrictions. A further opportunity is the use of demand side management mechanisms like power-to-heat, -to-cool or -to-transport as a direct use of electricity in other demand sectors or the generation of renewable gas or fuels. To address these opportunities the regulatory side has to be examined from a national economic point of view.

In the end the operation of a VPP and the new role of the aggregator or operator of the VPP show by example the change which happens to the energy system under the influence of rising shares of renewable and intermittent energy producers like wind and PV. The greater this share the higher is the demand for flexible units and structures for their aggregation like VPPs. Fluctuating power production has to be met by flexible consumption. So for the operator of the VPP new business cases arise – including provision of detailed knowledge of actual and future behavior of the portfolio.

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Biographical Information

Dr. Reinhard Mackensen finished his studies of civil engineering with the focus on computer science at the University of Kassel in 2001. Subsequently he gained professional experience in the field of software development and software architecture in different companies.

Since his admission to the ISET (Institute for Solar Energy Supply Technology which was changed into FhG-IWES in 2009) in April 2005 he is working in the R&D division "Energy Economy and Grid Operation". His main responsibilities included the development and enhancement of various applications in particular the project management of the wind power management system, an application to forecast the time response of the wind power generation as well as the leading of various research projects amongst others the research project "Regenerative Combined Power Plant". After having completed his dissertation "Challenges and solutions for renewable electricity power supply in Germany" Dr. Mackensen attended for the establishment of the department "Energy Informatics and Information Systems". Since early 2012 he is the head of this department.

Mr. Sagun Tripathi is currently working as a Senior Associate in the Energy Practice of ICF’s New Delhi office. ICF is a US-headquartered global consulting firm with offices across the Americas, Europe, Asia, and Africa. Sagun has a cumulative experience of about 5 years in industry and academia. At ICF, Sagun has been involved in a wide variety of projects covering areas of data analytics, capacity building and institutional strengthening, demand and market size estimation, regulatory/policy research and market analysis for investment decision making support, business model development, pilot project feasibility analysis and implementation support, policy advocacy amongst others. Sagun coordinated ICF’s activities in the space of renewable energy grid integration as part of the Clean Energy Grid Integration Network (CEGIN), a joint initiative of NREL, Low Emission Development Strategies (LEDS) Partnership and the Clean Energy Ministerial. Sagun has also co-authored several knowledge papers and white papers on the RE sector in India highlighting the key challenges and way forward.