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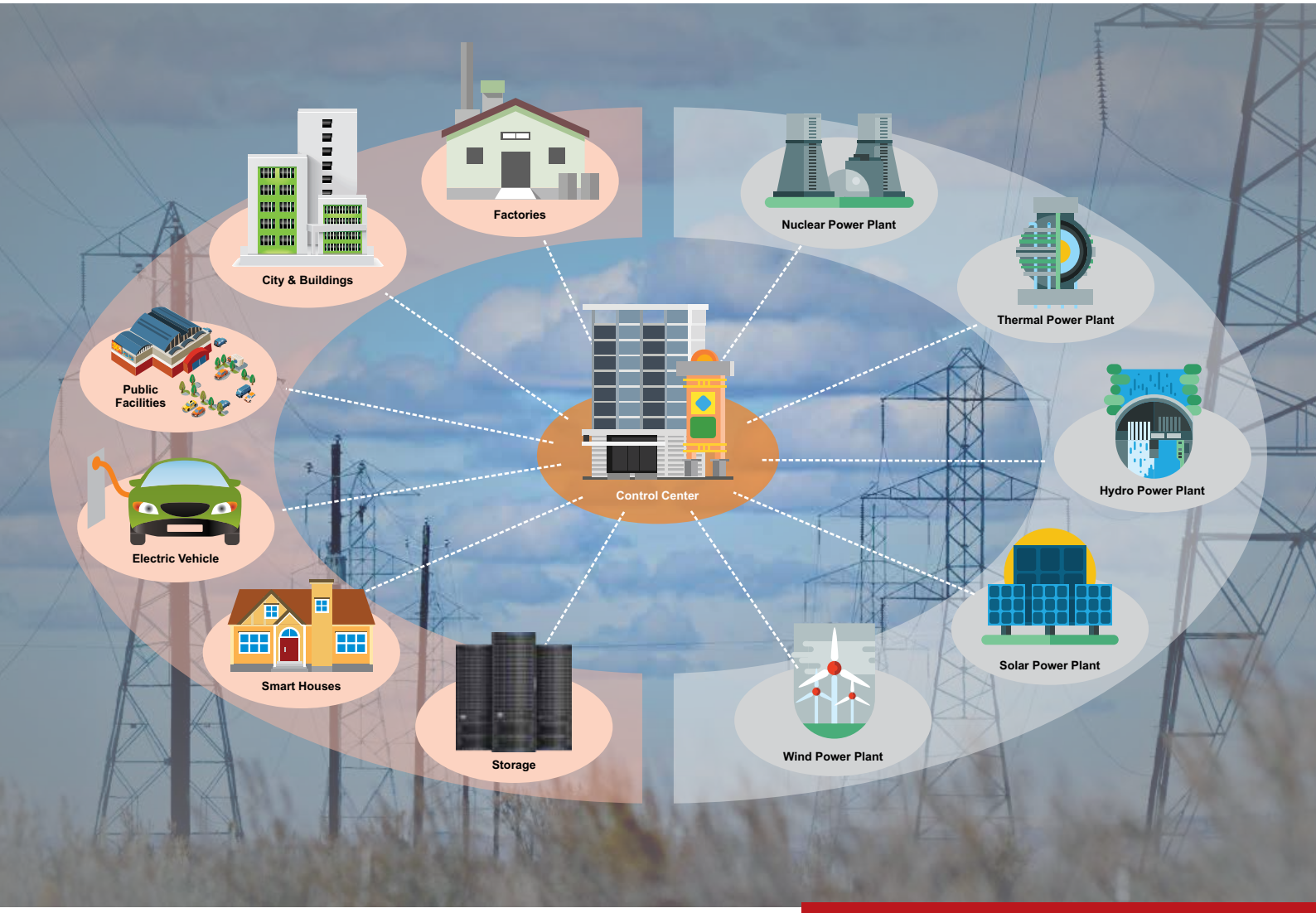

Opportunities for Virtual Power Plants in India

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AGC	Automatic Gain Control
AI	Artificial Intelligence
APR	Active Power Reserve
BE	Backend
BMS	Battery Management System
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CCU	Central Control Unit
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CHP	Combined Head and Power
CVPP	Commercial Virtual Power Plant
DB	Database
DER	Distributed Energy Resource
DMZ	Demilitarized Zone
DSI	Demand Side Integration
DSM	Deviation Settlement Mechanism
DSO	Distribution System Operator
DT	Distribution Transformer
EESL	Energy Efficiency Services Limited
EMS	Energy Management System
EPEX	European Power Exchange
EV	Electric Vehicle
FCR	Frequency Control Reserve
FE	Frontend
FoR	Forum of Regulators
FY	Financial Year
GUI	Graphical User Interface
GW	Giga Watt
HTML	Hypertext Markup Language
HV	High Voltage
ICT	Information and Communication Technology
INR	Indian Rupee
IoT	Internet of Things
IPDS	Integrated Power Development Scheme
KPI	Key Performance Indicator

LSVPP	Large Scale Virtual Power Plant
LVPP	Local Virtual Power Plant
ML	Machine Learning
MVA	Mega Volt Ampere
MW	Mega Watt
NA	Not Applicable
NTP	Network Time Protocol
OPEX	Operating Expenditure
OTC	Over the Counter
PCC	Point of Common Coupling
PCR	Primary Control Reserve
PLC	Programmable Logic Controller
PV	Photo Voltaic
QCA	Qualified Coordinating Agency
RE	Renewable Energy
RES	Renewable Energy Source
RVPP	Regional Virtual Power Plant
SCADA	Supervisory Control and Data Acquisition
SCR	Secondary Control Reserve
SLDC	State Load Dispatch Centre
SMNP	Smart Meter National Program
STU	State Transmission Unit
TANGEDCO	Tamil Nadu Generation and Distribution Corporation
TCP/IP	Transmission Control Protocol/Internet Protocol
TCR	Tertiary Control Reserve
TCS	Trade, Commerce and Service
TNERC	Tamil Nadu Electricity Regulatory Commission
TSO	Transmission System Operator
TVPP	Technical Virtual Power Plant
TWh	Tera Watt hour
UDAY	Ujjwal DISCOM Assurance Yojana
UI	Unscheduled Interchange
UMTS	Universal Mobile Telecommunications System
USD	US Dollar ($)
VPN	Virtual Private Network
VPP	Virtual Power Plant

Executive Summary

Energy sector across the globe is witnessing a paradigm shift from conventional fuels to cleaner sources of energy. The shift is also being seen from a large-centralized power system to a much diverse and localized power supply system. India, lying at par with the global scenario, is making rapid steps in the energy sector and seeing a similar trend where the built environment of energy is shifting from macro to micro scale.

Changing energy system architecture of India is driving the need for an innovative solution to manage the new system.

Installed capacity of Renewable Energy Sources (RES)* has grown at a CAGR of 14.5% from FY 2014-15 to FY 2018-19 in India (Figure 1).

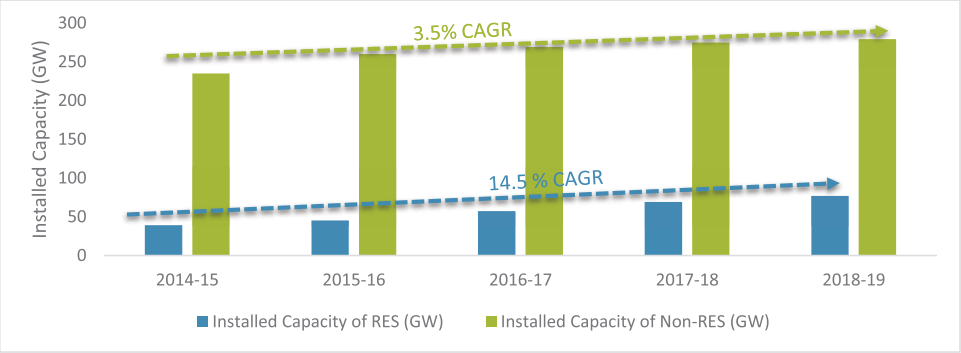


Figure 1: Installed Capacity of RES and Non-RES in India

In terms of energy generation, generation from RES has grown at a CAGR of 15.5% for the same period, while generation from Non-RES* has grown at a CAGR of meagre 4% (Figure 2).

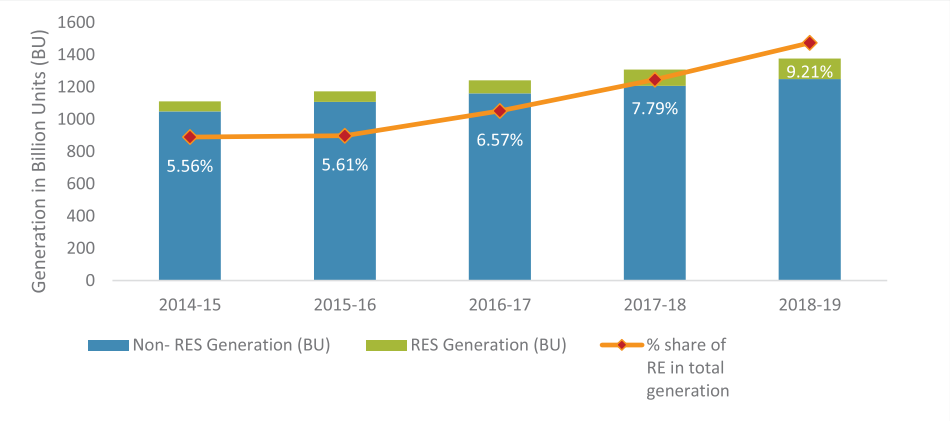


Figure 2: Generation Capacity of RES and Non-RES in India

In addition, Decentralized Energy Resources (DER), Smart devices, Energy Storage, and Electric Vehicles are also increasing in India. This transition is driving the need of a solution which can ensure controllability and visibility of these resources in the power system.

Virtual Power Plants coming to the rescue

Increased RE and DER penetration is leading to various technical and economical issues in the energy system. Varying power quality due to fluctuating RE generation, grid congestion, non-predictability, and no market visibility are some of the issues arising with increasing RE and DER. A plausible solution to address these challenges is through a Virtual Power Plant (VPP). A virtual power plant is a cluster of dispersed generator units, controllable loads and storages systems, aggregated to operate as a unique power plant. Various research institutes define and classify the technology in different ways. VPP may be classified as Technical and Commercial VPP based on the end-use application, or local, regional and large scale based on the area catered.

VPP can basically be considered as "software-as-a-solution", whose architecture and cost depends on the use case applicable. The cost of a medium sized VPP having aggregated control functionality can be expected in the range of 20.000 $ – 300.000 $. The high cost of VPP may be attributed to the need for infrastructure (communication hardware) and license model for selling VPP software. This cost may differ with varying licenses and varying number and type of consumers. However, since the technology is at an initial phase, giving an exact cost of the solution may be difficult.

One solution for all

There are numerous benefits associated with a VPP. For instance, VPP can help increase DERs' visibility to all energy participants due to metering installations on site and facilitate remote control capabilities of DERs due to strong communication network, which is currently missing in the power system.

- For Load Dispatch Centers: VPP can help in improving scheduling of RE plants, automated network monitoring and accurate accounting of electricity transmitted. It can also provide ancillary services from aggregated DERs.
- For transmission companies: VPP can help in providing relief in the transmission congestion and transmission upgrade deferral.
- For distribution companies: VPP can help in providing accurate forecasting of net load and thus, efficient planning of power purchase. Aggregated and visible DER in a VPP can also help discoms in reducing the quantum of power purchased.
- For customers having DER: VPP can provide market visibility to the customers and can help in improving their supply capacity to grid. For off-grid customers, aggregation of DER in a VPP can help them in performing peer-to-peer transactions in future.

North America, China, Australia and Europe are the front runners in deployment of VPP

Development of "VPP as a solution" is speeding up in many countries. North America, China, Australia, and Europe are proactively working in this direction and have deployed VPP for various end-usages

(Figure 3).

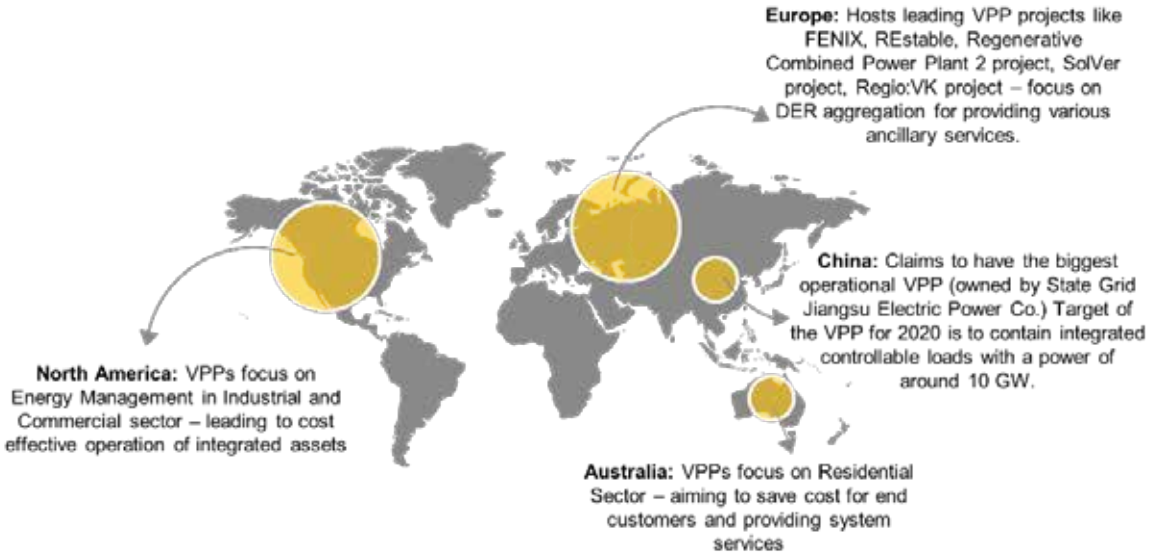


Figure 3: VPP Projects implemented across globe

Pool of companies providing end-to-end VPP solution

Considering the changing power scenario and requirement of a RE-supporting technology, many firms are now venturing into VPP and providing custom made solutions depending on the type of consumer, and the desired end-use/application of VPP (Table 1).

Table 1: Active VPP solution providers with solutions offered

Next Kraftwerke	NEMOCS™
AutoGrid	AutoGrid VPP™
ABB	ABB Ability™
GreenSync	GreenSync VPP™
Limejump	Various Products: The Balancing Mechanism (BM) ™, Frequency Response – FR ™, The Capacity Market – CM ™
cyberGRID	cyberNOC™
Enbala	Concerto™
Schneider Electric	EcoStruxure™
Siemens	Decentralized Energy Management System™
EnergyHub	Mercury Distributed Energy Resources Management System™
REstore	FlexPond™
Opus One Solutions	GridOS™
GE	Advanced Distribution Management Solutions™
Lockheed Martin	Smart Energy Enterprise Suite (SEEsuite)™
Spirae	Spirae Wave™
Smarter Grid Solutions	Active Network Management™
Itron	
OATI	OATI webSmartEnergy™ Distributed Energy Resource Management System
Indra (ACS)	Centrix DERMS™
Doosan GridTech	Intelligent Controller (IC)™ and DER Optimizer (DERO)™
Energy & Meteo systems	The Virtual Power Plant Software

Changing technology, evolving energy market and stricter regulations showcase the relevance of VPP in India

The Indian power sector is progressing towards adopting advanced technologies and new regulations. Figure 4 illustrates the key developments taking place in India, which are demanding a strengthened and modernized grid, and forming a base for deploying VPP solutions in India.

Figure 4: Key developments in India establishing the relevance of VPP

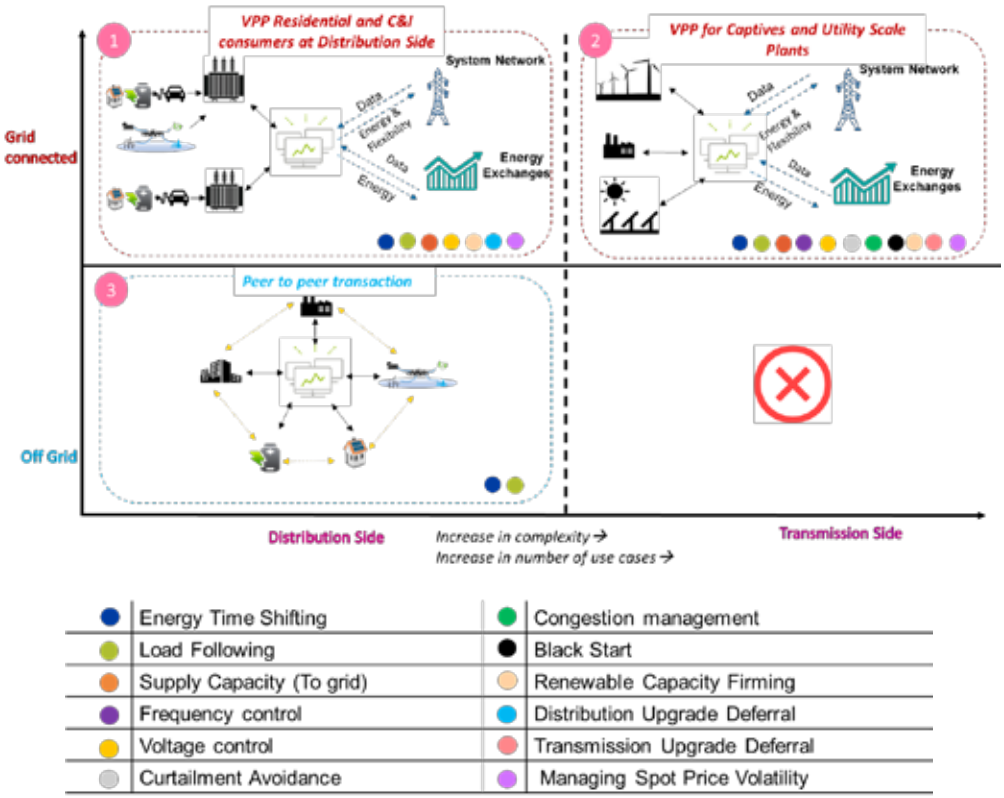
Existing Policies and Regulations indirectly supporting the adoption of VPP in India

- Sub-Group report by Forum of Regulators on '**Introduction of Five-Minute Scheduling, Metering, Accounting and Settlement in Indian Electricity Market**' (February 2018) has set the target date for migration to 5-minute scheduling, metering accounting and settlement as 1st April 2020. VPPs in India can prove to be a supporting system for implementing 5-minute bidding and moving to "fast" markets though DERs.
- Discussion paper by CERC on '**Re-designing Real Time Electricity Markets in India**' (July 2018) focuses on Real-Time Pricing to introduce a demarcation between 'energy trade' and 'system imbalance' handling. The shift to Real-Time Markets is possible only when there is controllability and certainty in the energy generation from resources. VPPs can help in addressing this issue by making RE/DER more controllable.
- Discussion paper by CERC on '**Re-designing Ancillary Services Mechanism in India**' (September 2018) focuses on designing of reserve market which can bid at regional and national levels. Also, the paper identifies DERs (including behind-the-meter resources) as potential ancillary service provider for future. VPPs can support this transition and in re-designing of ancillary service market by aggregating DERs and making them controllable and visible to the market.
- Draft regulation on '**Deviation Settlement Mechanism and related matters 2013**' and Latest (Fifth) Amendment, 2019 issued by CERC aims at enforcing accurate RE generation, forecasting and scheduling by levying penalty on RE generators for deviating from the scheduled generation. VPPs can help in the reduction of power curtailment and/or deviation charges through its enhanced forecasting and optimization tools, along with the ability to control generating sources real-time.
- Regulation by APERC on **'Forecasting, Scheduling and Deviation Settlement of Solar and Wind Generation Regulation**' Andhra Pradesh, 2017, has the provision for virtual pooling of different pooling stations to avail the benefit of larger geographical areas and diversity. VPP can help in virtual pooling by performing all the required functionalities to bring coordination among various generators.
- **'Net Metering Policy of Uttar Pradesh'** issued by UPERC has the provision for group net metering and peer-to-peer transaction. VPPs can play an important role in the adoption of these technologies in future.

- **'Demand Side Management Regulations'** issued by DERC in 2014, defines 'Demand Response programs' as part of Load Management. Alongside, Energy Service Companies defined in the regulation has left the door open for third parties to achieve desired load reduction. These third parties can make use of VPP as a solution to achieve the resultant load reduction. Also, various functionalities of VPP can be leveraged to enable the demand response programs for achieving load reduction.

Plausible VPP Configurations in India to cater to different customer type at different grid levels

VPPs can provide various technical and economic services depending on the designing and target of VPP. If the target is to reduce DSM penalty, then the VPP must have an accurate forecasting tool. If the target is to manage spot price volatility, then VPP must have a tool for optimizing generation during peak prices. Figure 5 gives a brief overview of various plausible configurations of VPP along with suitable use cases which may be provided by VPP, depending on its connectivity to the grid and the customer type.



Connectivity Type	Configuration-1	Configuration-2	Configuration-3
	Grid Connected	Grid Connected	Off-Grid
Customer Category	• Customers (operational at 230V, 400V, 11kV or 33kV) having DERs • Flexible loads at distribution side and EVs • Grid connected microgrids	• Large captives • Large customers (operational at 66kV, 132kV or 220kV) having DERs • RE Generating Companies • Utility Scale RE Plants	• Off-grid customers having DERs • Off-grid microgrids

Figure 5: Plausible configurations of VPP suitable for India along with expected use cases

Specific use cases gaining relevance in India with increasing RE penetration and supporting regulations

The study identifies few VPP use cases which are expected to gain relevance with increasing RE in medium to long-term. These use-cases have been mapped with various VPP configurations in Figure 6.

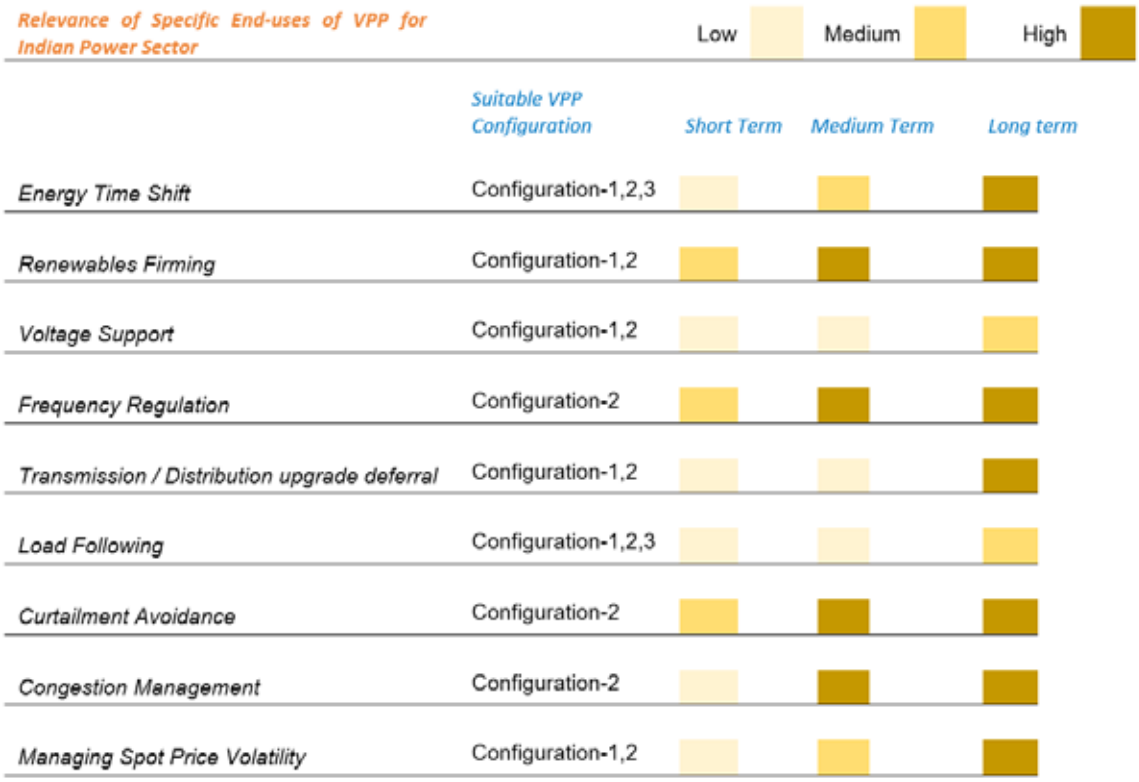


Figure 6: Expected VPP end uses in India

Deviation settlement penalty paid by RE generators – an opportunity for VPP in India

The study identifies an opportunity for VPP through an illustrative example of deviation settlement penalty paid by RE generators. The analysis shows that viability of a VPP solution for RE generators depend upon the following mentioned criteria:

Project or site-specific criteria:

- Level of deviation – high or low

State regulation specific criteria:

- Penalty levied by different states on the generators for the deviation
- Exemption or tolerance for forecasting error
- Maturity stage for commercialization of VPP solution

Participants' specific criteria:

- Number of Generators pooled
- Size of the generating plant

Efficacy of the solution deployed

- Improvement in Forecasting Error

Pilot demonstration, new regulations, evolving energy markets, and modern technologies are the pre-requisites for promoting VPP uptake in India

To promote this technology in the country, India should begin with implementation of pilots at various scale and at various locations. The proof of concept needs to be designed and implemented to weigh the feasibility and understand the system functionalities – both at technical level and regulatory level. Figure 7 proposes few such recommendations for Indian market, which will help in increased penetration of VPP in India.

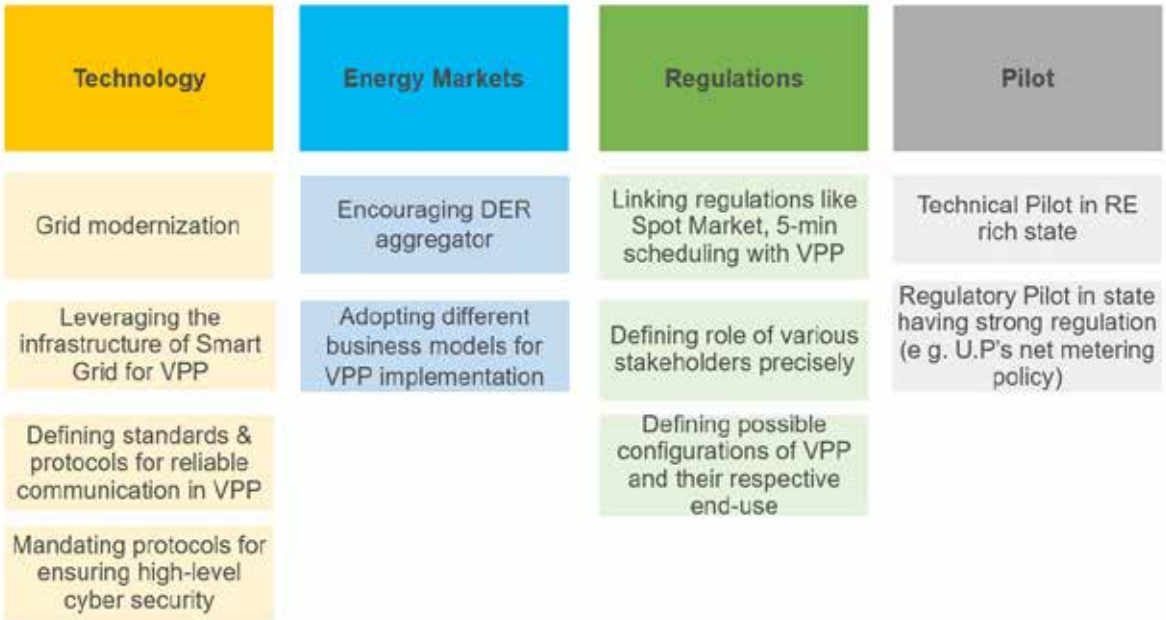


Figure 7: Recommendations for promoting VPP adoption in India

01

Change of the energy system architecture

The world's electric economy is currently witnessing transition from a large-centralized power system to a much diverse and distributed power supply system. Lack of energy access, unexpected utility power outages, power quality problems, and increase in power costs are the reasons majorly attributing to the localization of energy generation and growth of Distributed Energy Resources (DERs) across globe. Renewables are deeply penetrating the power sector and are replacing the fossil fuel-based generation.

India, lying at par with the global scenario, is witnessing a similar trend where the built environment of energy is shifting from macro to micro scale. Generation through Renewable Energy Sources (RES)[1] are increasing and generating points are becoming more diffused and decentralized to meet the ever expanding and diversified energy needs. In 2018, the renewable based generation in India grew at a rate of 10.6% (291 TWh) from the previous year, making India as one of the leading country to absorb RE in its energy system [1].

This section will bring forward similar trends and changing architecture of the energy system in India.

1.1. Conventional fossil fuel-based energy to renewable energy generation

It is a known fact that there is an unprecedented interest in Renewable Energy (RE) in India. The commitments made by India under the Paris Agreement has largely pushed the adoption of cleaner energy in India. Under the Paris agreement, India pledged to reduce its carbon emission intensity by 33-35% from 2005 level, and to obtain 40% of its installed power capacity from non-fossil fuel sources, both by 2030 [2]. This commitment brought forth the ambitious goal of achieving 175 GW of RES by March 2022 in India.

Installed capacity of RES has grown at a CAGR 14.5% from FY 2014-15 to FY 2018-19 [3]. Figure 8 illustrates that as compared to the installed capacity of RES, Non-RES[2] has observed a sluggish growth for the same period.

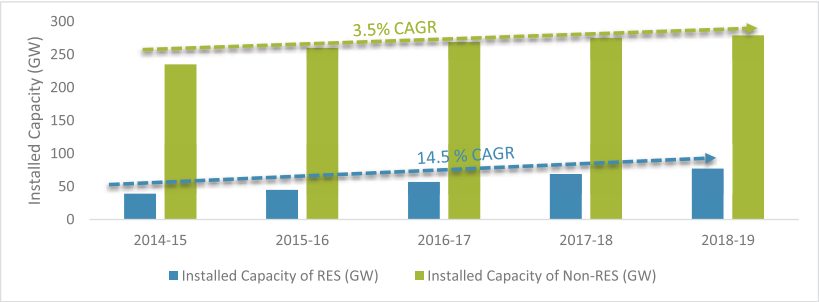


Figure 8: Growth in Installed Capacity of RES in India as compared to Non-RES [3]

1 RES here refers to solar, wind, biomass, waste to energy, and small hydro

2 Non-RES here refers to large hydro, nuclear and fossil fuel based energy sources

In terms of power generation, generation from RES has grown tremendously over the years witnessing a CAGR of 15.5% from 2014-15 to 2018-19 [3]. Comparatively, generation from Non-RES witnessed a sluggish growth at a CAGR of meagre 4% for the same period. Figure 9 illustrates the percentage increase in the energy generation from RE in India over last four years.

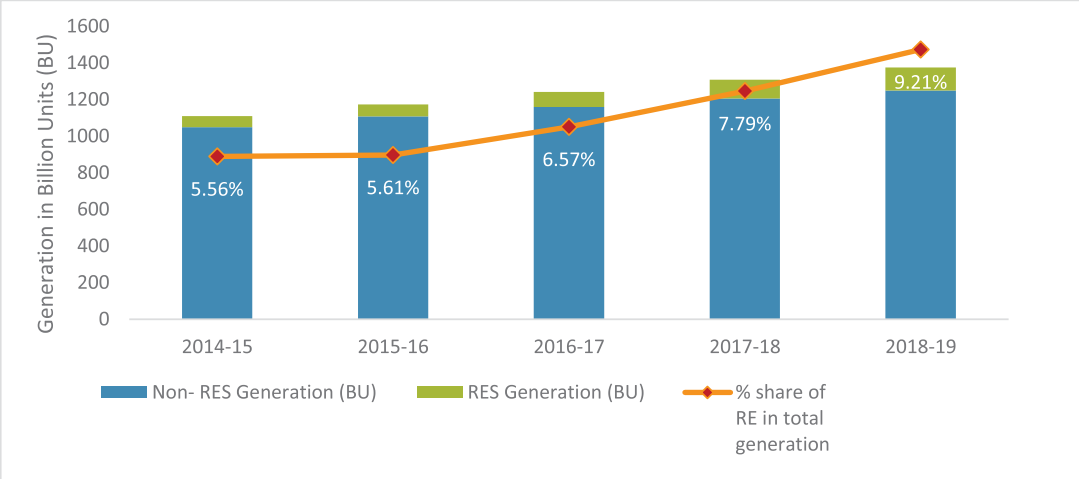


Figure 9: Increasing penetration of energy generated through RES w.r.t. Non-RES [3]

As on 28th February 2019, the Installed capacity of India was 350 GW, out of which renewables accounted for 21% (75 GW) [4]. Figure 10 illustrates the segregation of installed capacity of India on the basis of various energy sources.

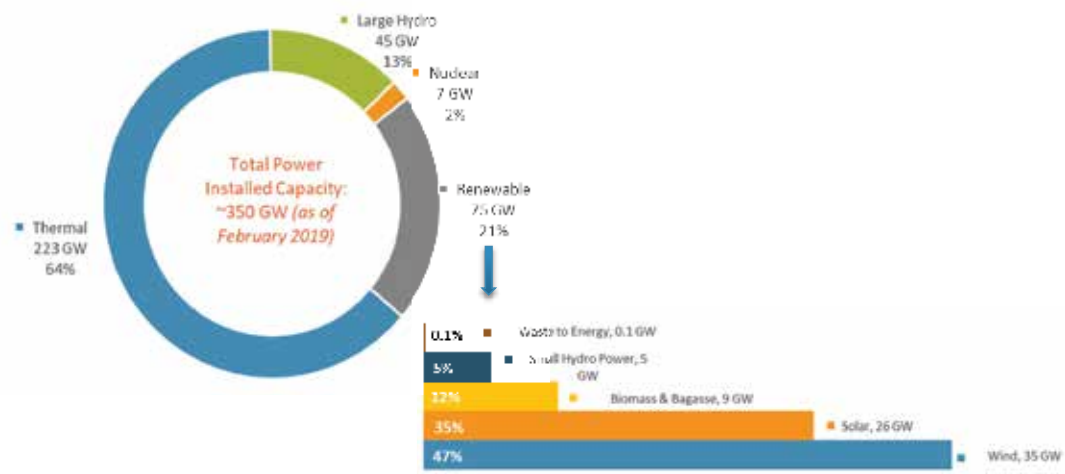


Figure 10: Installed Capacity of various energy sources in India (as on 28.02.2019) [4]

1.2. Central to decentralized and distributed power generation

Decentralized Energy Generation in India has grown and is poised to grow further with government's initiative like "24 x 7 Power for All by 2022". As on 31st July 2018, cumulative achievement of off-grid solar systems deployed by government was about 762 MW.[3] As per a report published by Clean Energy Access Network (CLEAN), DER in India has an estimated

3 This represents total of all off-grid solar systems deployed (lamps, home lighting systems, pumps, standalone power plants, etc.)

market potential of more than INR 6.71 lakh crores (USD 103.3 billion) with solar pumps and solar thermal segments alone having a potential of INR 4.27 lakh crores (USD 65 billion) [5].

Table 2 provides a snapshot of the DER systems deployed in India under various government programs. The table clearly illustrates that the capacity additions in the government-driven off-grid sector are increasing across all segments. In future, we are likely to see a flood of technologies which will further accelerate the rate of capacity addition of DERs.

Table 2: Increasing penetration of off-grid systems deployed under Government Schemes (cumulative until 31st December of respective year) [5]

Technology		2015	2016	2017
Off-grid solar				
	Lamps (million)	0.98	1.00	2.33
	Solar Home System (million)	1.25	1.40	1.48
	Streetlights (million)	0.38	0.44	0.47
	Pumps (million)	0.04	0.10	0.15
	Standalone Power Plants (MW)	120	172.46	182
Biogas				
	Biogas Plants (million)	4.87	4.95	4.99

Rise in the sale and installation of biogas plants, solar home systems, solar pumps, solar lamps and standalone solar power plants, shows that the off-grid market in India is witnessing a change and will undergo a major transition in future for providing energy access and to all.

In terms of captive plants, a larger shift has been observed to distributed renewable generation, mostly in the form of rooftop solar. With falling prices of solar panels and supporting policies coming into action; industries, commercial buildings, parking lots, bus/ railway stations, schools etc. are utilizing their unused rooftops to install solar panels. Many of the institutions have already gone for such installations and with the Government's aim to achieve 40 GW of solar rooftop by 2022, the installation capacity is yet to increase further. Figure 11 illustrates the increasing share of solar rooftop in India (which is more decentralized in nature), in the overall solar capacity addition [6]. This gives a clear indication of the transition towards decentralized power generation.

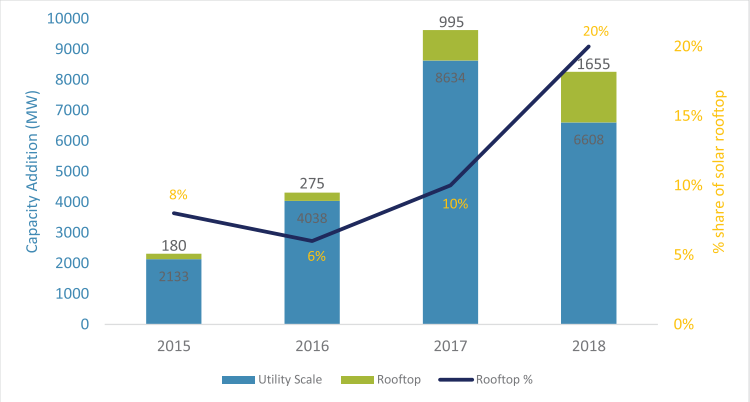


Figure 11: Year-on-Year Addition of Solar Capacity with increasing share of solar rooftop (in MWs)

Electric Vehicle (EV) uptake in India is also increasing and is expected to grow in the forthcoming years. As shown in Figure 12, 2-Wheelers in this segment are outnumbering 4-Wheelers in terms of sale and adoption in India. This in turn is making EVs more distributed and dispersed in residential area.

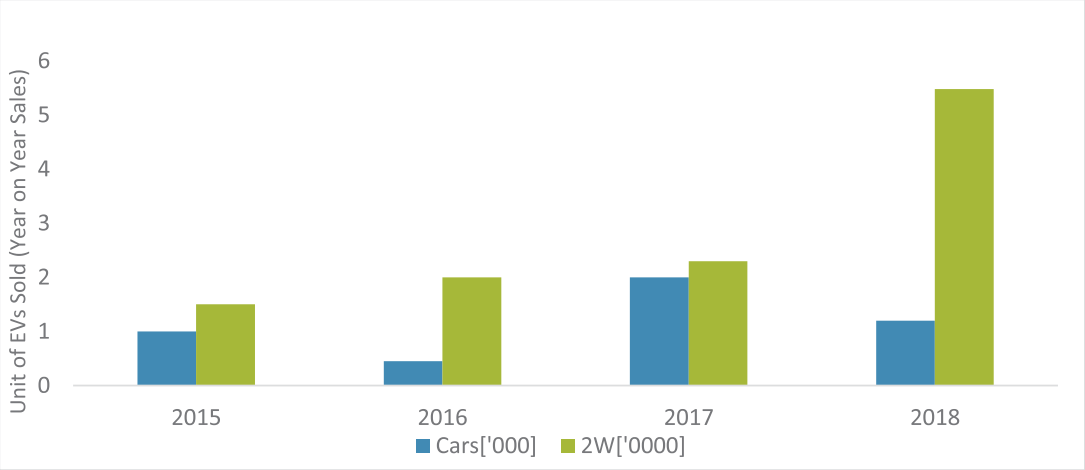


Figure 12: Increasing penetration of Electric Vehicles- majorly dominated by 2-Wheelers

1.3. Transition from central system to swarm intelligence

Today, swarm intelligence in Indian power system is mainly dominant in the form of centrally located intelligence system which can forecast, schedule, and run the optimization algorithms. However, as the new technologies evolve, the need has arrived for having the intelligence at the device level.

> Swarm intelligence refers to distributed devises with computational, communicational and controllable abilities working together to create a systemic effect.

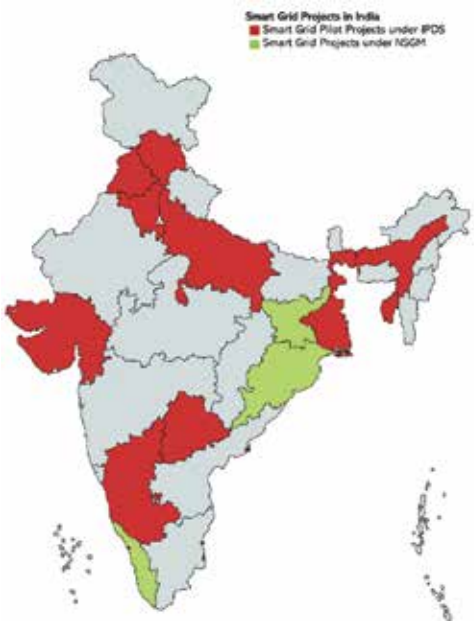


Figure 13: Smart Grid Pilots Projects being implemented in India

> EESL's Smart Meter National Program (SMNP) is targeting to replace 25 Crore conventional meters with smart meters across India. In this context, EESL has signed MoUs with state governments to supply 17 Lakh smart meters to Andhra Pradesh, 10 Lakh smart meters to Haryana and 18 Lakh smart meters to Bihar.

India is paving its way to adopt intelligent systems in its power system at device level also. Smart meters, smart inverters, battery management systems (BMS) are few developments in this area. Inclusion of smart metering investments in IPDS (Integrated Power Development Scheme), UDAY (Ujjwal DISCOM Assurance Yojana), other schemes and mandates of Government of India are means to accelerate the pace of this adoption. Various Smart Grid projects in India, as shown in Figure 13 are

also being implemented at a fast pace to make the power system intelligent.

Swarm intelligence is also gaining momentum in the form of smart inverters. Smart Inverters, which are deployed at solar plant are capable of making an informed decision for lowering down their outputs in situation where it is critical to maintain the system frequency.

Another "smart" trend which is expected to grow in future is self-controlled and smart charging of electric vehicle. The smart electric vehicle charging stations will be capable of providing the demand response by altering their charging rate as required by the grid.

In addition, rather than a Discom trying to forecast its load, based on a central weather forecast, it may collect the data at the DT level. Through this form of localized swarm intelligence, discoms may be able to better analyse the prevailing micro climatic conditions and forecast the load in a more precise manner using high resolution data. This is a probable form of swarm intelligence which is yet to pace up.

Table 3 summarizes few technical and economic challenges which are currently being faced by Indian power system due to the change in the energy system architecture and energy transitions observed.

Table 3: List of technical and economic challenges being faced by Indian Power System today

	Challenges due to increased RE penetration	Challenges due to increased DERs	Challenges due to swarm intelligence
Technical Challenges	Power Quality • Harmonics • Frequency and Voltage Regulation	Non-Controllable	Cyber Security
	Interrupted Power Supply • Small time power fluctuations • Long time or seasonal power fluctuations	Uncertain and therefore difficult to predict the grid injection	Technical challenges in monitoring devices and data
	Non-Dispatchable Energy Resources	Non-Dispatchable Energy Resources (if grid connected)	Analysis of the abundant data available
	Grid Congestion in case of excess RE generation		
Economic Challenges	Reduction of average spot price level	Non-Observable in the Energy Market	High Investment required
	Deviation Settlement Penalties	Under-utilization of assets	

Next section will describe in detail one of the probable solutions VPP, which may help in addressing these challenges, its implementation across globe and how internationally it has been able to benefit the electrical grid.

02

VPP as the power plant of the future

As described in the previous section, increasing decentralization and RE is urging the need of a solution which can control these sources at various levels. A solution to this uncontrollability is the so-called Virtual Power Plant (VPP).

This section gives an outline about the several views and definitions of Virtual Power Plants (VPPs). Besides that, it describes benefits of VPPs, which are underpinned with concrete examples. Furthermore, there will be an overview about the VPP market worldwide.

In this report, the term DER is used for energy producers, for example photovoltaic (PV) or wind parks as well as not strictly regenerative energy like combined heat and power. DERs can also be consumer-producer combinations as electrical storages. Flexible loads and Electric Vehicles will also be considered as DER.

2.1. Introduction to VPPs

The general idea of VPPs was developed in the early years of the century. In the German context, the fast growing share of RE sources such as wind and PV, compare Figure 27, which became possible because of the RES Act, led to the question of how to integrate these sources efficiently into the power supply system.

This led to research and development projects done by applied research institutes like the Fraunhofer IWES, now Fraunhofer IEE, as well as commercial activities. Several solutions for virtual power plant management systems were developed by small companies like energy2market GmbH or Next-Kraftwerke GmbH who acted as new players in the energy market. These "in house solutions" addressed commercial questions like energy trade or providing control reserve power with distributed energy sources using virtual power plant structures. Established technology providers like Siemens AG began to develop more or less generic applications to provide management systems for distributed energies as an addition to their power plant control software portfolio.

Virtual power plants today can provide services for:

- Aggregation of electrical power production on macro scale for energy trading
- Aggregation of electrical power production on micro scale for the purpose of local power supply
- Provision of system services like control reserve power (frequency) or voltage stability
- Aggregation of electrical demand or demand response activities
- Increase of efficiency by synchronizing electrical power production/demand and heat.

2.2. Various definitions of a VPP

Till date, no uniform and unambiguous definition has been found for the term VPP, see [7] and [8]. In [8] it is stated, "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".

In [7] a VPP is generally defined as "A portfolio of DERs, which are connected by a control system based on information and communication technology (ICT). The VPP acts as a single visible entity in the power system, is always grid-tied and can be either static or dynamic." Another definition "Virtual Power Plants rely upon software systems to remotely and automatically dispatch and optimize generation-or demand side or storage resources in a single, secure web-connected system" by [9] also underlines the central and integral component of an energy management system.

Probably the most widely accepted definition determines a VPP as "a flexible representation of a portfolio of DERs, not only aggregating the capacity of many diverse DERs, but also creating a single operating profile from a composite of the parameters characterizing each DER and incorporating spatial constraints", given by [10].

There are also numerous synonyms for a VPP in general. For example, there are the terms swarm intelligence ("Schwarmansatz") or swarm power plant ("Schwarmkraftwerk") [11].

For VPPs, several dependent technological components are crucial for their functionality. The following systems are to be regarded as part of a VPP [12] [13]:

- The central supervisory control and data acquisition (**SCADA**) system as the central control instance,
- The **remote-control units / control boxes** (usually with a programmable logic controller with a communication interface to the power plant, plus a communication unit for remote communication) on site at the plants for the realization of remote metering and remote control,
- The **communication link** via satellite or Internet, where appropriate, as a closed user group (for example, in the case of balancing service provision),
- The **database systems** for the storage of various data sets, e.g. measurement data, schedules or forecasts with a data management system to manage the data records,
- Control center based on a **graphical user interface** (GUI), which serves as an interface between the control personnel and the VPP system, and;
- Optional further software components such as an **energy management system (EMS)** for the plant optimization or forecasting modules that use externally provided information, such as weather forecasts, to create a load/generation or electricity price forecast.

Beyond that, the following should be noted, the English term VPP must be distinguished from the virtual auctions of power plant generation slices, see [14]. In addition, the English term is used in the context of power plant simulations [15].

2.3. Classification of VPPs

Two different definitions of VPP (Figure 14) can be found in context of the Fenix project [12], [8]: **Technical VPP** (TVPP) and **Commercial VPP** (CVPP).

- Technical VPP (TVPP) [10] focuses on the connection of decentralized energy plants at the distribution grid level due to grid supporting reasons.
- Contrary to this, the so-called commercial VPP (CVPP) is to be understood as an equivalent to the market-based behavior of large power plants whose main target markets are electricity wholesale centers [10].

Figure 14: Classification of VPP

In order to understand the differences between CVPPs and TVPPs more accurately, the general concept has been explained below. Its structure has been introduced by the FENIX project (for project details about FENIX see section 3.1).

CVPP

The CVPP component of the FENIX Project has a "FENIX box" which connects multiple DERs like CHPs or PV to the CVPP. This box allows metering and is responsible for controlling functionalities at site. Central energy management system of CVPP 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.

CVPP allows the participation of a pooled DER 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.

TVPP

On the opposite site is a TVPP, which is usually operated by the DSO. This VPP connects only DERs in close proximity, which may be part of one or more CVPPs. In this case, their operation is orientated towards system stability. As part of the structure, a TVPP interfaces with the DSO's distribution management system (DMS), an active central solution to optimize the safe power flow within the distribution grid.

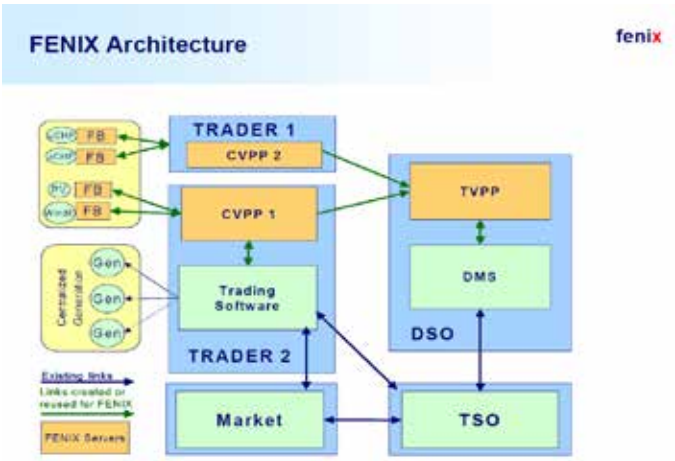


Figure 15: FENIX architecture, source [30]

One integrated option of a DMS is another interface to the TSO to grant a TVPP access for supporting the transmission grid by providing further ancillary services to the TSO. This last connection finalizes the concept of FENIX within the existing energy system.

As a second dimension, different control mechanisms are used for integration. Classical VPPs have a distributed generation portfolio but the aggregation and optimization are organized in a central solution (e.g. FENIX concept). This means generation is monitored. Subsequently the metered values are transmitted to the central control unit (CCU). Based on this data, optimization schedules for the single units are calculated and sent to the technical units. A further concept for VPPs is a more reactive control mechanism. Here the single unit acts on a local optimization based on external inputs like variable energy prices or metered technical values.

Figure 15 illustrates the architecture of TVPP and CVPP in FENIX Project.

Differentiation of further terms

In addition, there are a large number of conceptual subdivisions of a VPP. On one hand, there are definitions, which permit certain types of decentralized plants in the VPP, such as the so-called "Kombikraftwerk", which exclusively combines renewable energies on the generation side. On the other hand, there are sub types where the structure depends on the voltage level of the connected energy plants, as in the case of Bakari [16]. Their subdivision starts on the low voltage as local VPP up to the transmission level as large scale VPPs. This classification is described in more detail in section 2.4. An example of a corresponding subdivision can be found in [17] or as a single variant in [18] in the area of multi-agent systems.

Another view on VPPs is that it does not include the individual DERs, but only the prepending information and communication technology (ICT) infrastructure, which is necessary for the technical implementation of the plant network [11].

2.4. Differences of VPPs due to location on the grid

There are different views on VPPs with respect to generation, transmission and distribution level. For example, in [16] there is differentiation between so-called local VPPs (LVPP), regional VPPs (RVPP) and large scale VPPs (LSVPP). Figure 16 illustrates the operational architecture of the Bakari Project depending on the location of VPP. The architecture is a general approach and is abstracted from country-specific features.

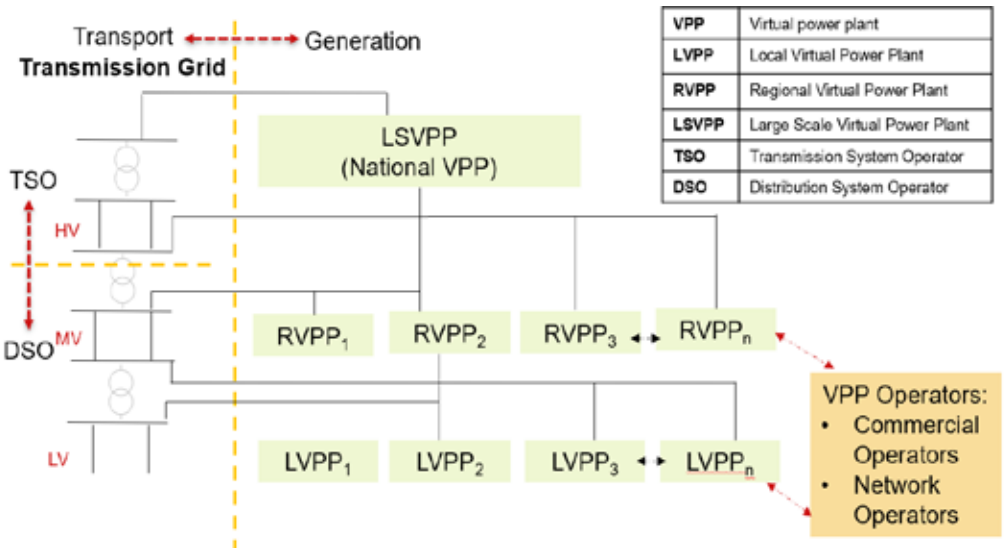


Figure 16: Integration of VPPs in deregulated power market

The different types LVPP, RVPP and LSVPP can be seen as consecutives.

- The operation of a LVPP is done by a local energy company or some other local energy market participant. The intended purpose of a LVPP is an optimal usage within an electricity market (for example EPEX/EEX SPOT) as well as different kinds of network support (congestion management, voltage support) or system services like balancing services.
- On the next level, RVPPs consist of an aggregation of LVPPs and are operated by the DSO or other commercial parties. They are used to manage the power flows in the regional distribution network.
- Pooling these RVPPs in a LSVPP leads to a VPP, which is operated at the transmission level and is therefore in responsibility of the TSO.

2.5. Generic benefits from VPPs

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:

- DERs' visibility to all energy participants due to metering installations on site.
- Remote control capabilities of DERs due to strong communication network, which grants access to DERs.

With these two essential technical requirements of visibility and controllability of DERs several benefits can be realized. Following section brings out the possible enabled advantages of VPP for different parties interacting in the power system, viz. the network operators (TSO and DSO), DER operators, market aggregators and the regulators.

Benefits for TSOs

TSOs has a system-wide responsibility of up-keeping the security of supply and its high quality. This forces a need for compensating the large conventional generation phase-out. By filling the gap, large VPPs of decentralized DERs can help in providing frequency response, voltage support and black start capability, by acting in its entirety at the transmission level.

Benefits for DSOs

In the process of increasing numbers of DERs connected to distribution grid, 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 for maintaining security, due to the majority of DERs installations being on the distribution level. Also, with the implemented remote controls at DERs' a DSO can optimize their operation without non-essential expansion of the grid while keeping the system secure.

Benefits for DER operators

Besides advantageous consequences of VPPs' introduction in relation to system security, various discussed business opportunities can be enabled for DERs. DER owners can generate higher profits that would not 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 a single unit.

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, an increasing cost position with higher penetration of wind and solar energy without counter measures like the introduction of VPPs.

Benefits for Regulators

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 [19]. Primary, for an improved cost-competitiveness of energy supply, the general reduction of end user electricity prices thanks to lower grid expansion costs and less system flexibility expenses, as a result of a 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 enables the positive national cost effect. Secondly, regarding a secure supply, it provides 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, facilitate the tackling of climate change, fulfilling finally the last objective of the energy triangle.

2.6. Overview of the worldwide VPP market

This section gives a short overview of VPP developments and an estimation of the worldwide VPP market. Additionally, it should be noted to take the section 2.7 into consideration while it describes some of the use cases worldwide in more detail.

Worldwide VPP market estimates

According to [20] the global VPP market in 2017 had a volume of $193.4 million (USD). It is expected to grow to a size of about $709.2 million (USD) in 2021. One of the biggest challenges are cybersecurity issues associated with the energy sector. The key players considered in the analysis of the virtual power plant market were ABB Ltd (Switzerland), Siemens AG (Germany), Schneider Electric SE (France), EnerNOC, Inc. (U.S.), Comverge (U.S.), Limejump (U.K.) and Flexitricity (U.K.). Other key players are illustrated in Figure 17.

Figure 17: List of aggregators per country (selection), source [21]

The report [20] divides the worldwide VPP market into four major segments. These are North America, Europe, Asia-Pacific, and Rest of the world (RoW), which includes Latin America, the

Middle East, and Africa. Figure 18 illustrates the VPP market participation ratios by region as expected in 2021.

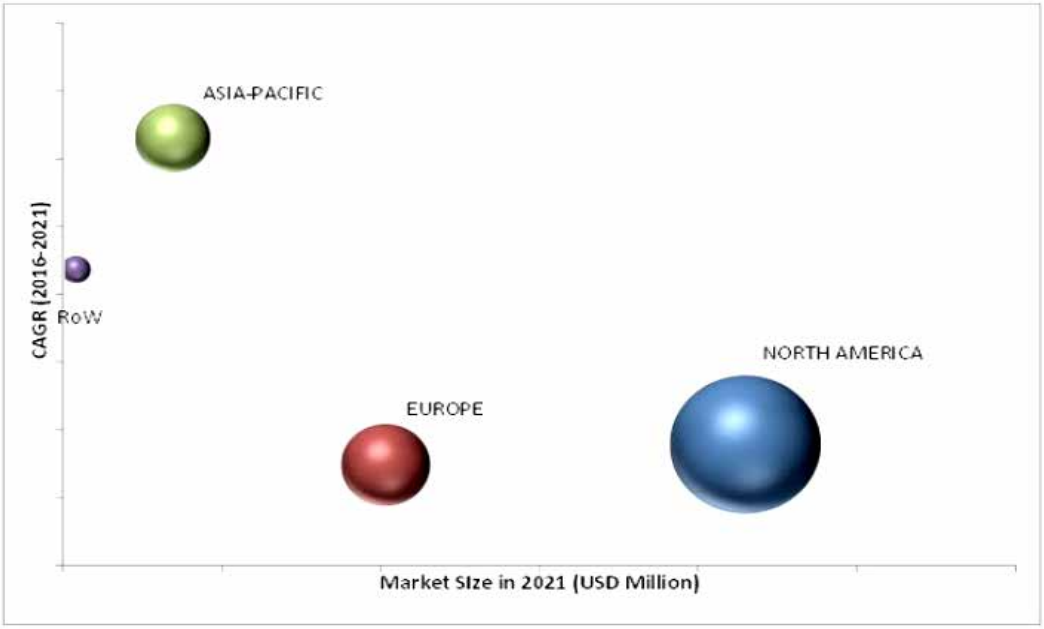


Figure 18: Expected VPP market participation ratios by region, 2021 (USD Million), source [20]

According to Markets-and-Markets "North America is expected to dominate the global virtual power plant market … owing to the extensive use of these solutions in commercial & industrial as well as residential sector" [20].

For the Asia-Pacific market, it is expected to have the "Highest Compound Annual Growth Rate (CAGR) from 2016 to 2021" [20]. This is due to the fact that this region is the "largest market for the infrastructure sector and industrial sector and is taking various steps to reduce carbon footprint and produce clean energy which includes renewable energy such as hydro energy, wind energy and solar energy generation".

Regarding this estimation other analysts like Allied Market Research came to the same conclusions [22] (Figure 19). Furthermore, based on the technology, the global VPP market can be categorized into distribution generation, demand response, and mixed asset, such as mainly battery and storage technologies. The most promising investment options were investigated by Allied Market Research, regarded to these categories [22]. They stated, "in 2016, the demand response segment, accounted for around five-eighths of the global market share. This segment is highly lucrative for investment due to long-term benefits for end users and improving the energy efficiency of the grid. Thus, demand response is anticipated to show high growth rate along with significant return on investment for the stakeholders, owing to its notable revenue contribution and high growth rate." Another result is that storages and batteries are expected to have the highest market growth while demand response hast the highest market attractiveness.

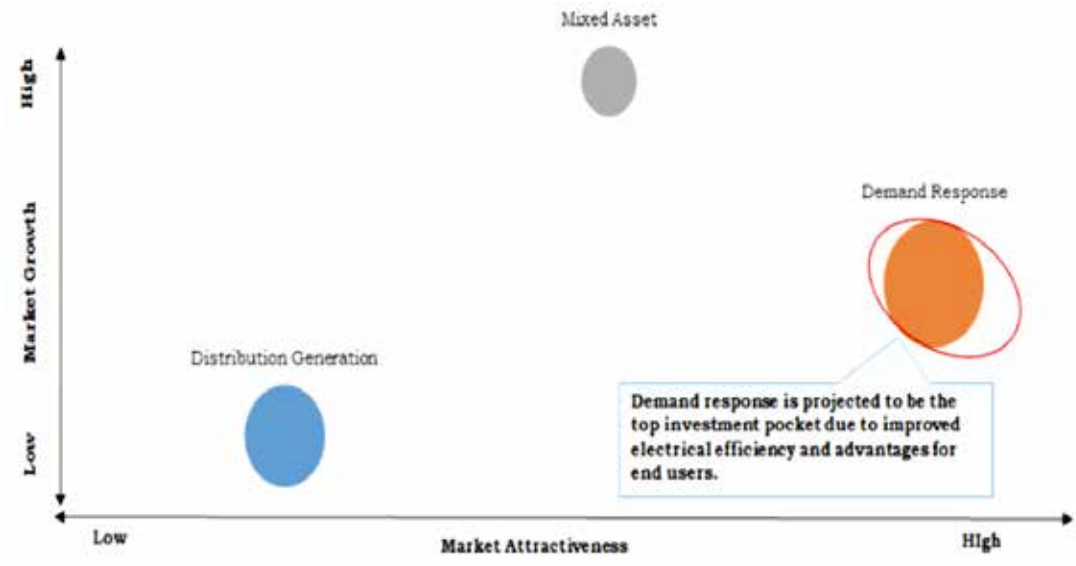


Figure 19: Top investment pockets, source [22]

2.7. VPP Examples

In relation to the worldwide development of VPPs, the North American market needs to be named. In recent year further states, besides California and Hawaii, like New York or the mid-Atlantic ones implemented regulations and incentives to back VPP developments in the field to allow a renewable driven system without sacrificing economic viability. Similar motivations back current developments in Australia, where power shortages require modern solutions as combined PV-battery systems. Another country is also starting to increase its efforts of VPP trials. After the Fukushima incident in Japan, a feed-in-tariff has been introduced in 2012. Thanks to its success, the capacity of renewable energies increased until the end of 2015 around 3.5 times up to around 40 GW in relation to the period without a tariff scheme [23]. Due to fears about stability issues, the government supported seven VPPs development projects in the financial year 2016 with a total controllable pool of 19.1 MW [23]. However further funding, for at least 50 MW, is planned by officials until 2020 [23].

In this section, few examples on existing VPPs are provided. The examples cover the regions North America, China, Australia and Europe and give short summaries of the associated use cases.

North America – Enbala VPP solutions

In the Navigant Research Leaderboard Report, the Canadian company Enbala Power Networks is ranked #1 of the global VPP software market [24]. Enbala's focus is the software behind the VPP, which is designed to fit customer needs. The following use cases are some examples listed on Enbalas website [25].

Pennsylvania American Water

Pennsylvania American Water is the largest water utility in the state. Enbala implemented a VPP at site integrating water pumps with a capacity of 400 kW in the first phase. The goal for Pennsylvania American Water was a cost-optimized use of the pumps with simultaneous various obligations to energy traders and without affecting the operating process. Enbala managed to integrate the water pumps into their VPP software solution, noting their existing experience with water pumps. The final implementation integrated these water pumps into the VPP. The VPP

ensures all obligatory commitments (regular operation, energy sales) and with the remaining flexibility, the VPP participates on the grid balance market. Overall, the system led to additional earns of $35,000 - $50,000 (USD) per MW per year for Pennsylvania American Water.

Four Seasons Whistler Resort

In 2006 the Four Seasons hotel group decided to implement a local VPP powered by Enbala at one Four Seasons Resort at Whistler, British Colombia in Canada. The resort is one of the biggest luxury resorts of Four Seasons located in the biggest ski resort in North America. The VPP is a hybrid system integrating propane-heating systems controlling the type of fuel and an optimal use of the components. This means it mainly optimizes supply and demand while using cleaner electricity if possible. This system was the start of the public visibility of Enbala. This is due to the fact because the system achieved far more energy cost reductions than the expectations. In the first implementation phase, the system led to $185,000 (USD) savings and reduced greenhouse gas emissions by over 40%. The system was extended in 2007.

Summary: The picked use cases mainly highlights the energy management capability of a VPP leading to cost effective operation of the integrated assets. However, Enbala is broadly positioned and its solution is an example of the predominant evolving type of VPPs in North America, namely "software only VPPs".

China – Stategrids VPP at Jiangsu

In China's eastern province of Jiangsu it is claimed to have the biggest VPP in operation [26]. The VPP was set to operation in May of 2017 and is operated by State Grid Jiangsu Electric Power Co. and implements Chinas Internet Plus Grid strategy. The idea behind this, in the context of power supply, is to equip producers, consumers and all kind of energy related components with rich Internet-of-Things (IoT) technology to use it within the developments to lead to the Smart Grid. The main goal of this VPP is to keep consumption and demand in balance but with the possibility to intervene in the energy system with harder means if necessary. For the VPP in Jiangsu this means for example to integrate lights and cooling systems such as air conditioners as single entities in the VPP system. Depending on the situation and the associated criticality, lights can stay enabled, but air condition systems may be deactivated. Another option to keep the balance is of course the possibility to downregulate integrated DERs, such as PV parks or wind power plants. The target of the Jiangsu VPP for 2020 is to contain integrated controllable loads with a power of around 10 GW.

Summary: China has one of the most aggressive approaches, consciously considering controlled power outages. Additionally, China's VPP are one of the biggest VPP implementations worldwide. Due to China's political structure and the resulting central state energy system, it is possible to have a vertical integrated VPP and optimize usage of the assets in a macro-economic way.

Australia – Ausgrid and Reposit VPP

The Australian government perceived the potential of the concept of VPPs. The Ausgrid Power2U initiative together with Reposit Power built up a VPP consisting of batteries in around 233 private households across 170 suburbs across Sydney, the Central Coast, and the Hunter region of New South Wales [27]. Reposit Power has experience with intelligent demand side management and offers the needed ICT which is needed to include the DERs in the VPP. Customers participating on the program earn money via Reposit on active calls of the flexibility.

Furthermore, the clean energy initiatives of the government of New South Wales (NSW Government) has programs aiming to build up a big VPP on the scale of 200 MW installed power [27]. The program mainly addresses private households with installed PV or storage systems.

Other VPP trials initiated by Tesla, Sonnen, SA Power Networks and AGL [27] are ongoing. Tesla aims to build up the biggest VPP in Australia integrating about 50,000 homes with an installed capacity of 250 MW. In fact, this ambitious goal of Tesla has not been achieved by now. In the first phase, Tesla started to integrate 100 households. In the second phase, which is now ongoing, another 1,000 public housing properties shell be equipped with solar panels and Tesla's Powerwall [28]. Sonnen aims to install a VPP similar to the concept they already implemented in Germany in the middle of 2019. Similar to the other VPPs in Australia this VPP mainly consists of residential battery storage systems from Sonnen their self.

To sum it up, the predominant VPP in Australia is a residential VPP, mainly consisting of PV plants, batteries in the private sector or public institutions, such as state schools and hospitals. Some VPPs intent to include various controllable consumers, for example cooling equipment. Therefore, the main goals of these VPPs and the goals of the funding programs behind them are as follows:

- offering possibilities reducing customer payments for electricity power
- the way to 100% clean energy production
- stabilizing the grid (frequency stability, voltage support, congestion management) having a centralized VPP system with control to a significant amount of active power.

Summary: Australia's VPPs are mainly residential VPPs. The implementations of VPPs in Australia are mainly pushed by governmental programs. These programs aim to save costs for end customers, providing system services and supporting the full penetration of green energy.

Europe – Comprehensive German French-Portuguese VPP in REstable

The synchronous grid of Continental Europe (formerly known as the UCTE grid) is the largest synchronous electrical grid (by connected power) in the world (Figure 20). Grid stabilizing coordination has therefore been a European task rather than a state-only responsibility since a long time. However, there are still many state specific regulations regarding the general network operation. It was the primary goal of the German French-Portuguese project REstable to improve regenerative-based electricity grid system services by improving cooperation between the European control areas. The project started in 2016 and just ended in 2019. The aim is to secure grid stability in the European electricity grid network while expanding fluctuating electricity generation with renewable energies. With regard to the European 100% renewable energy scenario, the transferability to the entire European entso-e grid was investigated in order to derive milestones for the conversion of the European energy supply to renewable energies.

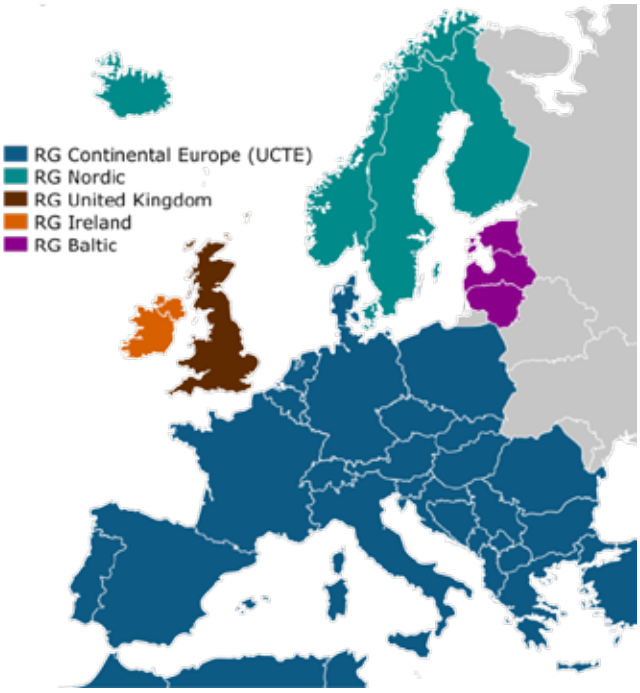


Figure 20: Map of European Transmission System Operators Organizations [54].

More precisely, methods and concepts for the provision of control power by renewable energies were developed in the European context and tested in a field trial. Based on representative scenarios, a VPP was designed and realized, which can control many DERs and supports the automatic retrieval of primary control power in the event of frequency fluctuations as a Europe-wide system service as well as the retrieval of secondary control power and minute reserve in individual control zones for TSOs. The fulfilment of the availability requirements of the TSOs and the cost-efficient distribution of the control power called up to the connected systems are important requirements. This VPP then was evaluated during a Europe-wide demonstration.

The project REstable received a very high visibility in its lifetime by winning the German French Innovation Award for Renewable Energies from the Deutsche Energie-Agentur (dena) in June 2016.

For the evaluation of the demonstrations a complex requirements analysis for the active power reserve (APR) was carried out before. Based on this analysis, evaluation formulas and a key performance indicator (KPI) system was designed to evaluate the field tests as comprehensively and realistically as possible. The field tests have shown that an international VPP, based on renewable energy sources, can achieve a similar quality in comparison to operational conventional pools and is even able to exceed them. In one test, a quality of even 100.0 % was achieved with regard to the frequency control reserve (FCR) requirements (see Figure 21). Finally, it shows how the requirements of the APR are likely to evolve in the coming periods.

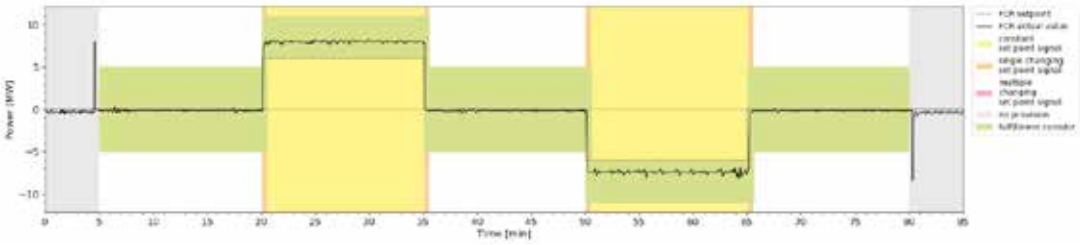


Figure 21: Activation and reaction of the REstable VPP based on renewables showing the FCR fulfillment corridor, source Fraunhofer IEE.

For the future of VPPs Arthur D. Little stated "Our research and project experience in this area highlight the attractiveness of Europe, especially the French and UK markets, for their maturity and continuous willingness to improve conditions for DSR to participate in the flexibility market." [21]. The project REstable can be seen as an example to underscore this statement.

Summary: REstable is a representative example where the development of VPPs in Europe is heading. In order to get to the politically aimed goal of 100% clean energy, it is crucial that assets like wind parks, photovoltaic parks and batteries are systemically useful. This means that the assets or at least some kind of superordinate system needs to able to manage the energy system stability. This can be achieved by VPPs and because the grid and therefore grid stability in Europe is a cross-national concern it is important doing research in this area.

03

German Experience in VPP

This section gives an overview of some representative VPP projects in Germany. In order to get a good understanding of these examples, the German power system is described briefly before that. On top of the listed projects the project REstable, which is described in section 2.7, should be noted because the VPP contributions are led by Germany.

For readers who have not been in contact with the German electricity system, Annexure-1 provides an overview on the main characteristics: Beginning with the general structure of the power grid, followed by the different types of ancillary services, and finalized by an introduction into the German electricity market.

3.1. Existing and future use cases

PwC analyzed following possible use-cases in the German market primarily in the context of CVPPs' applications [29].

- Direct marketing of renewable generation under the German Renewable Energy Source Act (RES Act, 2014)
- Balancing services
- Peak generation. The favorable cost side of renewable generation like wind and PV farms, low marginal operating costs, allows them to provide power during peak load times. For instance, solar farms are able to substitute other peak generation, e.g. gas-fired power plants, around noon. These periods enable usually higher profits in comparison to low-load situations in a conventional generation dominated power system.
- Substitution of large conventional power plants
- Power flow optimization.

A different option, in relation to the RES Act, is the use of funding under the flexibility premium scheme (so called "Flexibilitätsprämie") (RES Act, 2014): By increasing the installed controllable power of a VPP higher governmental financial support is granted (paid per kW of new installed power). A typical example is a biogas power plant with an additional installed generation unit.

The next sections list successful projects of VPPs in Europe. They will be summarized with regard to their main objectives, field test design and finally their main findings. Due to overlapping of CVPP and TVPP related use cases in the listed projects in most of the cases, a clear structural separation will not be realized.

FENIX project

The fundamental concepts of virtual power plants were elaborated in the **European project "FENIX"** ("Flexible Electricity Network to Integrate the eXpected energy evolution", see

http://www.fenix-project.org/). The objective of FENIX was to maximize the contribution of decentralized energy sources to the electric power system, through aggregation into "large scale virtual power plants" and decentralized management [30]. To achieve this the FENIX consortium incorporated: Research Centers like the Fraunhofer IEE (formerly ISET – Institute for Solar Energy Technology) and Universities with high involvement in previous and current EU projects in this area (CRISP, DISPOWER, MICROGRIDS, EUDEEP); Transmission and Distribution Utilities, which today hold the responsibility of the networks where DERs are being integrated; equipment and ICT manufacturers, with large presence in the energy sector; DER owners, that bring to the project their business view; and finally organizations responsible for regulation, standardization, etc., that will be managed in the project through a Stakeholders Advisory Group, absolutely needed for the future effective widespread exploitation of the project results.

For the duration of four years, from October 2005 to September 2009, the project covered three different phases. At first, the impacts of DERs on the European electricity grid were analyzed for a "Southern" and a "Northern" scenario (details see below). Afterwards the development of a multi-level communication system together with control systems followed. Both ended up in recommendations for revision of international power standards. At last, the concept's validation took place with the help of two large field tests in Spain and in the United Kingdom (UK).

As part of the first project phase the general situation of the grid was described as in the following: In Europe a shift occurs from some hundred-large centralized conventional power plants to millions of small renewable generators distributed over the entire grid, especially on the distribution level. The conventional approach "fit and forget" of connecting DERs to the grid raises issues in the context of system safety and overall costs. The FENIX approach should tackle it by converting the current passive networks to active ones that incorporate decentralized VPPs to cope with the increasing risks of non-visible and non-controllable DERs.

For achieving these objectives, VPPs are required to take over the services of large power plants. According to the FENIX group the following ancillary services should be provided by DERs:

- Frequency control
- Voltage control
- Congestion management
- Reduction of power losses
- Improvement of power quality
- Black start capabilities / islanded operation

Due to lack of a harmonized definition and conceptualization of VPP, an adapted one to the project has been introduced. It is the separation between commercial VPP and technical VPP, as already explained in section 2.3.

Subsequently to the definition of the FENIX concept its validation took place. For the "Northern"-scenario the UK's "Woking Borough Council" supported the first field test. Around 3 MW of small scale DERs like CHPs, PVs, fuel cells or fridges were supervised by a central supervisory control and data acquisition system (SCADA), in majority connected to the low-voltage grid, and, due to the absence of further clusters of DERs within the region, the Imperial College of London embedded a simulated cluster into the test VPP ("FENIX city simulation"), see Figure 22.

Priorities of the system were CVPP applications like wholesale market participation and provision of energy to the UK's Balancing Mechanism. Its operational architecture is shown in Figure

22. It was designed as a "multi-agent system" [30]. Beginning at the DERs, they used FENIX boxes, which were combined with specific agents like "freezer agent" or "PV agent" to provide a DER characteristic, most importantly a cost curve with "bid-offer prices", to the "matcher agent" [30]. At this point all single DERs' characteristics were combined to one profile, like one price curve for the entire CVPP. On this basis, it was possible to control the DERs with one specific price signal. As a result of this signal only DERs with a lower or equal price were activated. The corresponding price signal depended on the required amount of DERs. The demand of energy was calculated based on the simulated market results of the "e-terraTrade" system (project's industry partner Areva) that allowed optimized trading e.g. at the energy stock exchanges. For the communication between the "matcher agent" and the market platform another agent was introduced, the "VPP agent". Finally, this agent exchanged the planned CVPP's schedules from the trader to the CVPP, and CVPP's main status information to "e-terraTrade" [30]. Further insights into the functionalities of the "PowerMatcher" system are provided in Table 4.

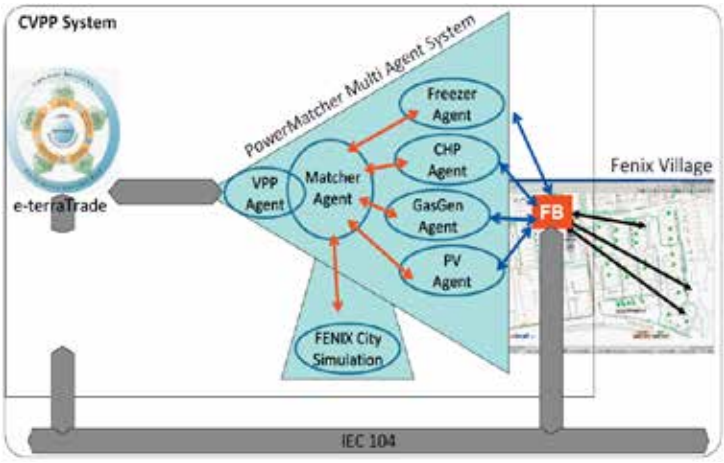


Figure 22: Components of the "Northern"-scenario's field test in the UK (figure 3.1.1 in Kieny, et al., 2009)

Table 4: Main functionalities and characteristic of the "PowerMatcher Multi Agent System" components (architecture shown in Figure 16) [30]

Components of the "PowerMatcher"	Main functionalities / characteristics
FENIX box	• Metering and optional remote-control device for DERs • Allows the "PowerMatcher" to receive data about the current state of the supervised DER (like the CHP or freezer temperature)
DER agents ("Freezer Agent", "CHP Agent", "GasGen Agent" and "PV Agent")	• Calculation of each DER's characteristics of operation • General parameters of the characteristic: "generation/ load capability, minimum and maximum 'on' and 'off' times, ramp rates, and cost curves" (e.g. a step function to [30] -> additional parameters for specific DER types
"Matcher Agent"	• Creates Composition of all single characteristics to form one CVPP characteristic • Most important: multi-step function of the price curve • Recipient of the CVPP's schedules created by the trading platform "e-terratrade" • Follows the overall schedule by sending out a price signal in relation to the aggregated price curve of the controlled VPP to trigger the required amount of power

"VPP Agent"	• Creates bid/offer prices (in price per MWh) for max. the next five days for the entire CVPP in dependence of the general CVPP characteristics (especially the price curve) • Sends bids and offers plus the CVPP characteristics to the trading platform "e-terratrade" • Receives schedules from "e-terratrade" and passes them along to the "Matcher Agent"
"e-terratrade" (external system)	• Optimized energy trading: Organizes notification processes with the energy market and/or the TSO for ancillary services • According to the market situation and tender results, as well as the CVPP's state itself, the CVPP's schedules will be altered and transmitted back to the "VPP Agent" • DERs' SCADA-system • Provides control access for the CVPP operator
"FENIX City Simulation"	• DER emulator (combined use of real and simulated devices) • Represented multiple loads and generators • Included FENIX boxes capable of metering and remote-control access

Substantial learnings of this field test were in the area of overcoming technical issues, which appeared in the context of metering and communication:

- ICT requirements and limitations should be validated in an early stage
- Complicated process of establishing VPN
- Connecting smart meters requires detailed information of the power plant and close contact with the DER owner for installation because a full shutdown is necessary
- Smart metering devices should not be accessible by the public
- Separation of research and development activities from the operational business to avoid disturbances of supply

Nevertheless, it could be demonstrated that it was possible to monitor, aggregate and procure simulated market offers with DERs.

The second field test, as the representation for the "Southern"-scenario, was conducted in the Alava distribution network in Northern Spain operated by the DSO Iberdrola Distribución with 169,000 low-voltage customers (70% urban, 12% suburban and 17% rural). At the time of the project around 170 MVA of DERs like wind farms, PVs, CHPs, hydro and biomass plants were connected to the 30kV high voltage (HV) - grid. From this number ca. 104 MVA of DERs joined the demonstration project with a broad technology mix (detailed numbers in Table 5).

Table 5: Field test portfolio of the "Southern"-scenario: DER participants in the Alava distribution grid (data sourced from Marti, 2009)

Type of generation	Total number	Total rated power
CHP	5	70.86 MVA
Wind farm	1	32.3 MVA

Hydro power plant	1	0.44 MVA
PV	1	0.1 MVA
Total	***8***	***103.7 MVA***

With this pool of eight DERs three different services were conducted for demonstration. In particular:

1) **Day ahead trading**

   The objective was the aggregation of DERs to form one VPP within a greater portfolio to allow DERs market access. This process included the unconventional step of DSO's validation of VPP's proposed DERs' schedules against the network's projected constraints.

2) **Ancillary service: tertiary reserve**

   The corresponding TSO modifies the VPP's submitted offers if required. Thereby it was advantageous that these offers were already validated according to the distribution grid's predicted capacities by the DSO. Consequently, a stable operation of the grid was ensured.

3) **Voltage control support for the TSO and DSO**

   With the implemented framework a direct provision and sale of reactive power to the system operators (SOs) could be achieved. SOs' actions within the developed approach were planned with the assistance of an optimal power flow algorithm that focused on voltage control with the assistance of changing transformer taps, switching capacitor banks and modifying the reactive power output of DERs. In the case of the VPP the DERs received set points by the VPP's central control, previously determined and submitted to the VPP by the related SO.

From an overall perspective the Spanish field test has shown that the in-depth integration of the DSO within all relevant processes could enable a high penetration of DERs. Even the first step of DERs' visibility was seen as "a great step ahead" to stop adverse developments within the distribution network [30].

After the two field tests, which have shown the technical feasibility of the FENIX concept, its financial implications were analyzed with a cost benefit analysis (CBA). As representative scenarios, "Northern" and "Southern" were chosen with adaptations according to considered generation in comparison to the field tests' portfolios: in the case of the "Northern"-scenario only CHP units (around 2.5 MW).

For the different business cases the following assumption were made. For the UK ("Northern") the business-as-usual scenario was a solely commercial aggregation of distributed generation. Alternative options, enabled by the FENIX approach, were wholesale market optimization, flexible instead of fixed operating schedules of CHPs, intra-day balancing services for the energy supplier, and two services for the TSO, balancing services as well as tertiary reserve.

In the "Southern"-scenario the CBA's reference scenario was assumed as solely the trading of each DER unit. Alternatively, like for the "Northern"-scenario, four other use cases existed. At first the "(non-operational) commercial aggregation" that implies the need for pooling to reduce imbalance penalties and administrative costs [30]. In addition, like in the UK, wholesale market optimization and imbalance management within the pool along with balancing services for the TSO. Thereby, it should be noted that all these studied market opportunities depend highly on the countries' market design.

On this background three CBAs were conducted: One for a "Today"-scenario (2006/2007), and

two for the future in 2020, divided into a low spread of the FENIX concept ("Future") as well as its large-scale application ("Upscaling") [30]. With regard to different levels or parts of the system the main findings are the following:

- Business level
  - Increased benefits were predicted for DERs in 2006/2007, the "Today"-scenario, but also for 2020 with a further rise in most of the considered applications
  - Benefits are cut down by ICT-investments to create a FENIX infrastructure
  - A wide-spread-application of the FENIX-concept in the future would decrease the possible revenue of a flexible DER due to increased competition
- System level
  - Replacement of central power plants, characterized by low efficiency, mainly during peak-times that lead to lower system costs due to more competition in the market and reduced fuel expenses
- Use of a TVPP
  - Qualitative analysis because its benefits rely upon multiple local factors in comparison to system-wide issues
  - General advantages
    - Less energy losses
    - Deferment of new investments in the network
    - Reduced penalty payments for loss of quality of service and non-supplied energy
    - Extended options for network operators to cope with higher levels of DER penetration by applying an active instead of an passive network management
- Socio-economic results
  - Higher use of CHP units results in an improved system efficiency with e.g. a lower consumption of gas and therefore reduced carbon dioxide emissions
  - Integration of higher numbers of DERs at reduced costs
  - Higher market competition leads to a lower price level, which in the end facilitates lower end consumer expenses for energy

"Kombikraftwerk 2" / Regenerative Combined Power Plant 2 project

One major VPP project with the focus on Germany, named as "**Kombikraftwerk 2**" or translated "Regenerative Combined Power Plant (RCPP) 2", carried out by ten project partners of the service, industry and research sector including the Fraunhofer IWES [31], now Frauhofer IEE. The project was a follow-up to "RCPP 1", which was concluded in 2007. It has proven the feasibility of a purely renewable energy driven electricity system in Germany. Main aspect of RCPP 1 was a field test representing the future German energy system with a ratio of 1:10,000, and consisted of different renewable energy resources, distributed over the country, as well as a virtually integrated pumped hydro storage. In conclusion, the project has shown that a renewable energy system can cover the energy and power demand of Germany over an entire year, which finally stands for an ensured security of supply.

However, a stable energy supply is not only characterized by power balance, further issues are frequency and voltage stability in addition to black start capability. For keeping these factors in stable conditions especially ancillary services such as frequency response or voltage support are

required to maintain a high quality of supply. Accordingly, RCPP 2 highlighted this side of the power system during its three-year period from 2010 to 2013.

The underlying examination of frequency and voltage stability required the development of a simulation tool with high spatial resolution to locate extreme situations with regard to frequency and voltage instability (resolution of 10 x10 km). Depending on the simulated deviations the demand for balancing power and reactive power was calculated and checked against the available capacities to compensate them safely.

Main input data of the 100%-renewable scenario were consumer and weather series data of 2007 in combination with 100x100 meters spatial data sourced from the land cover data system "CORINE Land Cover" [31]. In addition, topographical data was used to identify future sites of Res, especially wind, PV and bioenergy power plants. Besides future generation, current sites of renewable power generation and energy storages were added to the simulation's input stream. To determine the energy flows the grid development plans (on-/offshore) were used as the basis for the future grid expansion, as well as time series of REs in an entirely RE-powered Europe, to calculate the in- and export of excess energy. For additional details about the underlying scenario data check chapter 2 in Knorr, et al., 2014.

In this context, rotor stability was of less importance due to the fact that synchronous generators in a future energy system are predicted to be not abundant anymore. They will be substituted in majority by converter-coupled systems and therefore a new stability criterion in the sense of rotor angle stability is required. However, this future aspect was not in the scope of RCPP 2.

Beyond the simulation, a large field test took place during the time of the project. Around 80 MW installed capacity of widely distributed wind farms, PV and biomass plants were aggregated as one centrally controlled RCPP (detailed portfolio in Table 6). In the project's context, the meaning of RCPP is a VPP that composes entirely of a renewable energy mix, coordinated by a central management system.

Table 6: Portfolio of the field test's VPP for providing control reserve (data from section 3.1.2.2 in Knorr, et al., 2014)

Type of Generation	Rated power	Location
Wind farm	37.2 MW	East Germany, Brandenburg
Wind farm	39.2 MW	East Germany, Brandenburg
PV (residential & large-scale)	1 MW (in total)	Central Germany, Hesse
Biogas CHP	1.2 MW	Central Germany, Hesse
Biogas CHPs	0.5 MW (in total)	West Germany, Rhineland-Palatinate
Biogas CHPs	1.4 MW (in total)	West Germany, Rhineland-Palatinate
Biogas CHPs	0.5 MW (in total)	West Germany, Rhineland-Palatinate
Total	***80 MW***	

Beginning with frequency stability, it should be noted that biomass plants were already partially prequalified for the control reserve market in Germany, not like wind and PV plants, which were not participating in the reserve market. Due to their intermediate behavior a curtailment approach is required to provide positive reserve power. Requirement thereby is sufficient available solar or wind energy.

Another issue of wind and solar DERs' fluctuations is the validation of a procured reserve. Therefore, two methods of power delivery were analyzed [31]:

1) "Schedule method" (shown in Figure 23)

Constant curtailment of a PV or wind power unit depending on the forecasted amount of available power (compare blue line, compliance with a probability of 99.9%, and red line, forecasted maximum output, in Figure 23), determined for each 15 minutes period, enables the unit to provide positive and negative power reserve in relation to the probabilistic forecast (99.9%). This method is comparable to the current control scheme of conventional power plants in the reserve market: Running a conventional power plant under part load to allow ramping up and down if called up on.

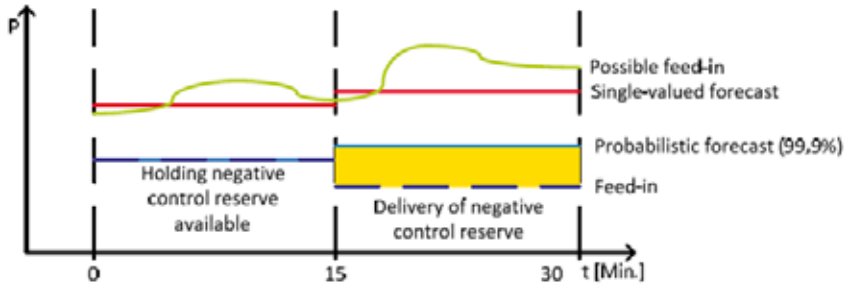


Figure 23: Illustration of the 'schedule method' (sourced from Knorr, et al., 2014, figure 62)

2) "Available active power" (see Figure 24)

During a request for reserve power delivery the actual curtailment is in relation to the possible feed-in, or the available active power, which is calculated live (compare green-colored line in Figure 24). Consequently, the concept allows a variable instead of a constant feed-in.

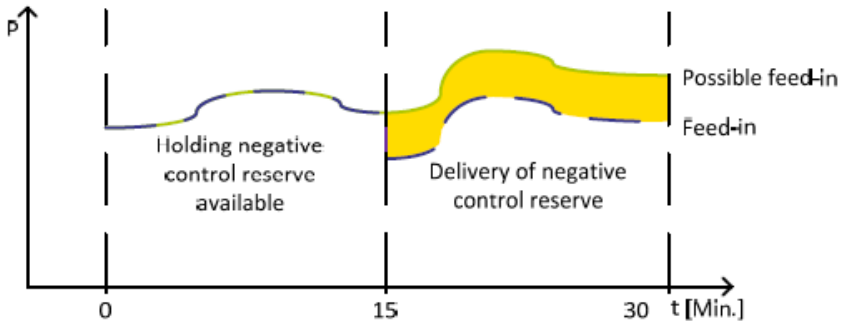


Figure 24: Illustration of the method 'available active power' (sourced from Knorr, et al., 2014, figure 64)

Available active power scheme was chosen as the preferable one, primarily for the reason that it is associated with fewer losses, thanks to the variable feed-in, hence lower costs. Still further issues could be identified with regard to the accuracy of control. During the trials tolerance violations occurred as a result of too low precision. However these technical issues could be overcome in a recent project, named "**ReWP**" ("Control Reserve by Wind and Photovoltaic plants") for distributed wind and solar generation units controlled by Fraunhofer IWES VPP software solution "IWES.vpp", now "IEE.vpp". The project was led by Fraunhofer IWES, now Fraunhofer IEE, took about 2 years, and was finished at the end of 2016.

The greatest challenge of procuring such a concept is lack of corresponding market conditions. In particular short-term products for only 15 minutes, procured one day ahead instead of a week, made possible by next day demand forecasting ("dynamic demand dimensioning"), that could be used for calculating a daily total reserve capacity [31]. Its accurate calculation requires high visibility of DERs within the VPP, providing a detailed data basis, to improve forecast errors

significantly. These two aspects of a short product time and a short lead-time, in combination with a large widely distributed VPP pool that gives the opportunity of spatial generation balancing of wind and PV plants, increase considerably the potential of RCPPs to procure reserve power.

In the case of voltage stability, a TVPP issue, the developed simulation tool came to use. For the highest voltage network, at each voltage node, the resulting voltage levels were evaluated and requirements for reactive power derived upon for the 100%-RE-scenario. Outcomes of the simulation were frequently appearing high capacitive demands as a result of the future use of large direct current lines in the north-south axis of Germany. Moreover, it could be concluded that new voltage strategies will be required to sustain safe voltage ranges. For example, in the higher voltage grids the operation of decommissioned plants' generators as phase shifter, or four-quadrant inverters to provide further reactive power as a replacement for the disappearing large conventional power plants.

On the distribution level, on lower voltages, novel approaches for voltage support like DERs injecting reactive power even without active power output, or the application of flexible tap-changers in transformers are required. However, especially in the distribution grid, individual solutions should be developed due to the local phenomena of voltage stability with a dependency on the conditions on site.

Regarding the last central aspect of the project, restoration of supply, a laboratory test at the University of Kassel and Fraunhofer IWES, now Fraunhhofer IEE, supported the research activities. Its theoretical background was a grid recovery in a system-wide blackout situation by forming small island grids. Such a restart requires grid-forming units, e.g. gas generators, pumped hydro storages or batteries, which are capable to supply themselves with auxiliary power during the starting process. Main challenge during this operation of grid restoration is the coordination of reconnecting loads as well as generators while keeping the voltage and frequency in acceptable ranges. Currently this process is organized on a "top-down" approach in Germany [31]. This means that large power stations resupply at first the highest voltage level and afterwards the lower ones. With a more decentralized system, as expected with an increasing number of DERs in the grid, this approach is not feasible anymore due to the resulting opt-out of large conventional power plants. Consequently, a "bottom-up" solution, beginning at the low voltage level, seems to be more suitable in the future [31].

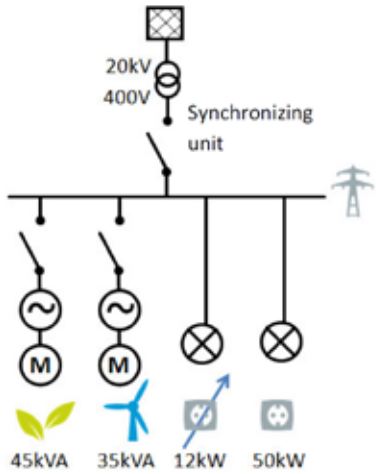


Figure 25: Fraunhofer IWES laboratory test's set-up to simulate a restoration of supply at the low voltage level (figure 125 in Knorr, et al., 2014)

Such a decentralized approach was tested in a simplified environment at Fraunhofer IWES. Main parts of the trial were a grid-forming diesel unit, representing a biogas unit, a synchronous generator as a wind turbine in connection with two loads. The smaller load was partially controllable. All components were connected to the interconnected grid via a 400 V low voltage network (compare Figure 25).

In the test, the following steps were covered: At the start, the disconnection of the LV-grid from the MV-grid caused an outage. With the assistance of a battery the diesel unit created a grid that supported the connection of the wind turbine and the loads until the voltage and frequency of the island grid were in acceptable limits to finally reconnect to the interconnected grid. All steps were

achieved with full success. From the trial it could be concluded that a black start requires more generation capacities than the expected demand, as well as one independent grid-forming unit, which is further supported by other units to keep the frequency and voltage steady. On top of this a crucial learning was the necessity of a full reliable and strong communication infrastructure to cope with the intensive exchange of information and control signals during a black start situation.

In the overall conclusion of RCPP 2, four essential findings can be named.

- At first, the fundamental proof of preserving the high quality of service, within a 100%-renewable energy system in Germany, could be achieved.
- Secondly, aggregated DERs are already capable to provide ancillary services, but the obstacles are lacking adjustments in the German market and energy system design.
- The third one concerns the infrastructure of VPPs: Secured, efficient and standardized monitoring and controlling of DERs must be implemented.
- And at last, it can be stated that the aggregation of DERs is the key in enabling the shift to a stable renewable energy system.

Regio:VK project

Derived from the question, how to adapt the presented futuristic approach of a RCPP to the current energy system, the project "**Regio:VK**" evolved [32]. During the period November 2013 to December 2015 a regional consortium from North Hesse in Germany, led by CUBE Engineering GmbH, Fraunhofer IWES, now Fraunhofer IEE, as a research partner and the North Hessian public utility union SUN ("Stadtwerke Union Nordhessen") investigated the following generic issue: "Optimization of daily processes within a regional VPP integrating renewable energy generation" [33].

The economical drivers behind the project were very diverse, but always in the context of CVPP applications: Primarily the optimized market participation at the day-ahead spot market was examined in depth. Enabler, comparable to the FENIX project, was the ability to monitor and control each DER unit within the VPP's bidirectional network. With the assistance of simulations, potential earnings for CHP units at the spot market could be calculated for the reference year 2014. The results varied depending on the CHP's equipment configuration. In some cases the second business scenario, the procurement of secondary control reserve, revealed higher benefits. For the instance of multiple available CHP units, it could be proven that it can be more profitable to use one unit on the spot market, and another one for the provision of control reserve. Nevertheless, a confirmation of the simulated results is still in progress.

Additional business cases were seen in the field of improved direct marketing of renewable energy generation on the energy market, as well as selling electricity in the corresponding region, in this case North Hesse. Anyhow, a viable possibility to sell electric energy to nearby citizens is currently prevented by inadequate regulations. But a different scenario seems more promising, the improvement of the plants' availability as a result of reduced deviations from the prognosis thanks to, for e.g. optimized maintenance scheduling.

From the technical standpoint the further development of optimization tools is a central aspect of the project. CUBE Engineering has developed a product named "FlexTOP". It is an operation optimization tool for a single unit that takes into account heat demand and market price prognosis along with live data from the CHP units, like the motor status (e.g. warm or cold start possible), and information about the gas and heat storage on site. By applying this system optimization solely, market participation can be achieved. If the corresponding CHP unit is pooled in a VPP, like in Regio:VK, the VPP's central intelligence unit incorporates the FlexTOP schedule: In the

case that the unit's schedule, according to the pool optimization, enables higher profits than the FlexTOP's outcome, the pool optimization will be applied, or vice versa in the opposite case.

For testing the FlexTOP solution, CUBE Engineering used its own in-house small-scale CHP unit. The trials showed the following: The degree of compliance, with regard to the planned CHPs' schedules, was low if e.g. the price forecasts were inaccurate or in times of random peak heat demands. Nevertheless, the results of CUBE's optimization were promising under multiple other circumstances.

The central VPP optimization tool for spot market participation at the EPEX, developed by Fraunhofer IWES, now Fraunhofer IEE, as part of their VPP/RCPP solution "IWES.vpp", now "IEE.vpp", has been trained as well with a CHP plant to incorporate the heat demand side of a CHP unit into the forecasts. The congruent CHP unit is part of SUN's generation pool. Most of their renewable power plants, as CHPs, ground-mounted PV arrays and a wind farm, have been connected to the Regio:VK VPP (in total around 24 MW rated power output, check Table 7 for specified numbers). Within specific ranges, all pooled units can now be controlled according to the spot market optimization results. Beyond spot market participation, further business applications are planned to be included in the VPP software solution IWES.vpp in cooperation with the public utility network SUN.

Table 7: Overview on the integrated power plants of Regio:VK's VPP (internal IWES data)

Type of generation	Total number	Total rated power
CHP	9	2.589 MW
PV	2	5.900 MW
Wind farm	1	15.375 MW
Total	***12***	***23.864 MW***

With regard to infrastructure design, the underlying information stream requires a simple and cost-effective implementation, as explained above. In this manner, the CHP units' interface is based on the "VHPready" protocol ("Virtual Heat and Power Ready[4]"), which maybe will develop to a future standard for DERs that are projected for VPP integration. If this step of standardization can be reached, significant cost reduction effects should be obtained. Consequently, the option of integrating smaller DER units is more likely viable.

In a nutshell, Regio:VK has enabled multiple solutions to become commercially deployable, in particular CUBE's FlexTOP solution for single unit optimization and IWES spot market optimization tool of IWES.vpp for an entire pool of generation. Moreover, crucial findings concerning the prospective enablers for regional VPPs could be identified:

- Conventional generation still need to be accounted for in the transition phase to a 100%-renewable energy system
- Economical viable solutions to integrate energy storages and demand side management are required
- Low-cost and standardized VPP integration for additional VPP units in the form of e.g. "Plug & Play"-solutions (possibly based on the VHPready protocol)
- And the introduction of incentives for regional power balancing besides adaptations and creation of energy market roles according to unbundling regulations by the governors

4 https://www.vhpready.de/dokumente/

SolVer project

The following project "**SolVer**" ("Storage optimization in distribution grids") has a focus on operating decentralized energy storages in a German distribution grid [34]. From March 2013 to May 2015, three project partners, namely the corresponding distribution network operator (DSO) Entega (formerly HSE), the German storage supplier adstec and the University of Applied Science Darmstadt, analyzed the potential of seven energy storages to provide various services. This connected pool consisted mainly of lithium-ion storages but as well as redox-flow systems. In total 286 kW of rated active power and 450 kWh rated capacity was tested successfully in field on a regional level (detailed numbers in Table 8).

Table 8: Field test portfolio of "SolVer" (data from HSE, 2015)

Battery type (owner)	Total number	Total rated power	Total rated capacity
Li-ion	5	+/- 266 kW	250 kWh
Redox flow	2	+/- 20 kW	200 kWh
Total	*7*	*+/- 286 kW*	*450 kWh*

Focus of their research activities was the development of an independent trading platform that allowed the provision of power storage services. Nevertheless, the tool was designed to provide open access for further storage solutions. For preparing the field tests one main objective was at first the evaluation of theoretical business cases, and secondly the identification of viable ones. In this process, the following services have shown to be suitable for decentralized energy storages (HSE, 2015):

- Primary control reserve
- Secondary control reserve
- Voltage control
- At low voltage level
- At medium voltage level
- Energy trading
- Congestion management
- Purchasing schedule (balancing the schedule's deviation of a directly marketed renewable energy resource on the German market)
- UPS & island grids
- Phase balancing

All these services were further examined with regard to economic viability. As a result, three CVPP applications have been shown to be viable in the German energy market, the scheduling of active power output, and the ancillary services PCR along with SCR. In the case of TVPP applications only one option could have been identified, local voltage stability. All four services were conducted live in the HSE's grid.

A specialty of these tests was the parallel provision of different kinds of services. Two new concepts have been designed to achieve such an approach to improve the former known "time-multiplexed"-system, which simply processes multiple services one after another over time (HSE, 2015). The first new method, called "additive"-operation, is a simultaneous offer of PCR and scheduling. Handicaps of this operation were the High German requirements to achieve a minimum rated

active power of 1 MW, combined with a long offer time of one week and a flexible reserve, which could not be met with the small test portfolio of SolVer.

Secondly the "priority"-method has been introduced (HSE, 2015). According to this mode of operation, two or more services will be marked with a priority that is defined by the possible income of this service. For instance, PCR has the highest priority due to its valuable fast response requirements. Other parallel services can be local voltage control and/or energy trading that requires a specific amount of the energy and power reserve of the storage. These quantities will be reserved and called after their allocated priority if required.

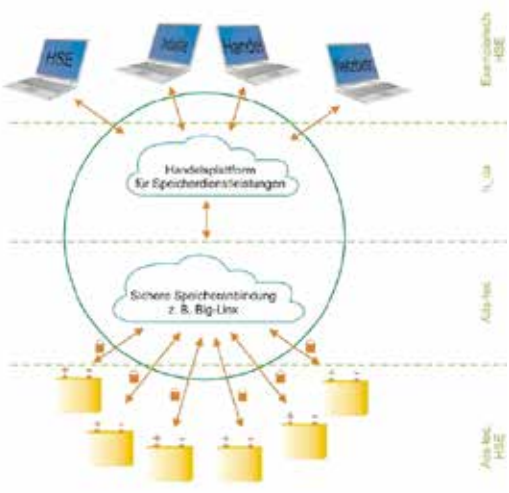


Figure 26: Cloud infrastructure of the "SolVer" project (sourced from Glotzbach & Graf, 2013)

With respect to the SolVer's infrastructure design to allow such an operation, two main cloud services should be noted (compare Figure 26): On the one hand the commercial solution of adstec, the cloud service Big-LinX®, has been applied and further developed for the time of the project. This software solution allows remote access via the Internet. In the case of the project's storages Universal Mobile Telecommunications System (UMTS)-modules were used on site. Its communication was based on the IEC 61850 protocol with individual modifications, in the form of new and excluded control and observation variables, to fit the purpose, as well as the IEC 60780-5-104 standard for non-adstec storages. For securing the cloud system a smart-card encryption system within a virtual private network (VPN)-network was applied which included an "adstec firewall", installed in every storage system, to process the flow of information (HSE, 2015).

On the other hand, the newly introduced trading platform was implemented by the University of Applied Science Darmstadt as the main part of the second cloud service "SolVer-Cloud" (HSE, 2015). Its API-interface allowed a user to overview the storages' states and to control them by assigning a job list to each storage container. Background of each schedule was a former concluded contract on the trading platform. Thereby it was possible to introduce other storages and VPP by using an open interface, based on the industry standard for scheduling at the time (based on CSV-files), to provide them access to the marketplace. The entire process of signing up a contract at the platform until the proof of performance, depending on the storage's job list fulfillment, has been checked for the previously mentioned commercial feasible use cases at full success. However, this approach is still on a research level because there is no regulation in Germany that gives a trading option in a solely distributed way.

In conclusion, the project has shown three key findings. First, the applied smartcard-technology of the adstec cloud has been rated as a secure system. Secondly, it should be noted that the trading platform is capable of upscaling to achieve a multi-cell structure to reach greater grid coverage. This means that parts of the network should be organized by local platforms, which interconnect with each other to fulfill the requirements of the system's flexibility. Of high importance in this process will be a full interoperability according to the existing standards like IEC 61850. How to design such an approach is currently under examination in the follow-up project "Flex4Energy" [35]. Finally, and most importantly, the research project SolVer could enable decentralized

storages the crucial advantage of accessing multi-revenue streams. According to the authors' recommendations a commercial use of distributed power storages would be impossible otherwise.

Future use cases

Due to the last major change in the European power systems – the unbundling of grid operation, generation and sales and distribution – virtual power plant solutions have become possible in theory and practical in several business cases. In future power systems the share of distributed generation will grow further. This opens further opportunities for the concepts of VPPs.

One proposed overlying system design for DERs' integration into the grid is a so-called "smart market" system [36]. It allows regional trading of energy between market participants, including newer ones like prosumers or VPP operators.

One technology, that can enable the implementation of a fully decentralized market platform, like the smart market, is the "blockchain" technology [37]. This technology consists of "peer-to-peer transaction platforms that use decentralized storage to record all transaction data" [37]. Its origin is the financial sector with cryptocurrencies like "Bitcoin".

A basic blockchain process has five steps [37]:

1) "A provider and a customer agree a transaction".
2) "The transaction is combined with other transactions made during the same period to create a data block".
3) The data block gets stored encrypted and verified at each node of the blockchain computer network.
4) After a successful verification the block will be added to the former verified blocks, creating the pre-existing and growing blockchain.
5) The success of the transaction "is confirmed to both parties".

Based on this technology so called "smart contracts" can procure fully automatically business processes between two parties by replacing all the manual work of a third party (e.g. verification, payment organization or data storage). Thereby two types of blockchains can be applied [37]:

1) "Public blockchain" (basic blockchain): a public decentralized data and verification network based on a peer-to-peer network
   - Advantage: no fees for an operator, and if the case requires, anonymous and free access
   - Disadvantages: operating costs are higher, no ex-post modifications possible
2) "Private blockchain": a private centralized data and verification network operated by a central authority
   - Advantages: ex-post modifications are possible, operating costs are lower, and if necessary, the operator is able to invite specific costumers who are known to him
   - Disadvantages: fees for an operator

In future, VPPs can connect millions of new options of DERs of all energy sectors, e.g. heating systems (like heat pumps), cooling units, electric vehicles, industrial processes. Of course, it will be challenging to connect all these different devices, but technologies like artificial intelligence or machine learning can improve forecasting or control strategies of the pooled DERs. In addition, future standards can allow simplified plug-and-play solutions, which enable even smaller DERs to be interconnected in a VPP, and as a result they will be accessible by the flexibility market with

reasonable cost effort. In this way VPPs can act as a "bridge technology" for bringing together the conventional energy market with the uprising decentralized grid structure [38].

3.2. Business models

An analysis of the VPP market participants, described in [39], showed that all German VPP operators offer a combination of technical aggregation of the equipment, as well as their direct marketing. As a result, no external aggregator is required as a key partner to market the so-called energy product on the power exchanges, via OTC or to a TSO. In the case of TSOs, the marketing is mainly the provision of balancing services, such as SCR and TCR, compare explanations at the beginning of Section 3.

In order to account the two market services for the DER operators, in the case of EEG/KWKG (German "Erneuerbare-Energien-Gesetz"/ "Kraft-Wärme-Kopplungsgesetz") direct marketing an individual service charge, adapted to the characteristics of the integrated assets, is demanded from the VPP operator.

The exact customer segments addressed by the VPP operators were also evaluated. The regional energy supply companies / municipal utilities as well as the industrial and Trade, commerce and service (TCS) customers were clear. In addition, most companies operating VPPs use the VPP to bundle their own assets. The same applies to CR 4, which markets its assets in VPPs under its own responsibility. To remember, CR 4 is the concentration ratio of the German energy economy, namely the companies E.ON, EnBW, Vattenfall and RWE (including Innogy).

In order to win the DER operators for participation in the VPP system, the primary focus is on a high level of service that comes from a single source and promises the plant operators a low-risk business. In doing so, the VPP operating company relies on custom-made solutions for the connection and control of the DERs. Additionally, it is stated that the operator is supporting the energy transition and can therefore expect an image gain. Customer service is usually implemented via key account management, telephone/email support and the provision of a customer portal.

In addition, plant operators are provided with the help of lock-in effects, such as the presentation of additional services, held in the ecosystem of the providers. The same supports the offer of company-owned remote-control units (communication boxes) which provides the DER operator with a remote control service over longer contract periods. In the case of DSI customers, there are electricity supply contracts predominant ensuring customer loyalty.

The following key activities of VPP operators are needed to deliver the requested market performance in Germany:

- Integration of the DER with optional installation of a remote-control unit at site,
- Implementation of an energy data management to record the relevant plant data,
- Monitoring the DER to verify operational readiness,
- Consideration of local control strategies, such as peak load management or optimization of own consumption,
- Provision of load, production and/or price forecasts,
- Processing and integration of the generated forecasts,
- Use the available data for shift operational planning,
- as well as the optimization of the entire DER pool

Summary: The prevalent business model for operational VPPs in Germany is the application in the German direct marketing. These commercial VPPs gain from the integration of as many assets as possible. Through the mass of integrated DERs in a central VPP system, it is possible having a global optimization approach regarding all associated profits and costs. The energy is mainly sold on electricity spot markets like EEX/EPEX SPOT. The key enabler for these VPPs in Germany is the market premium in the EEG act, section 20. With exception, it forces electricity producers participating on the electricity market to be read and controlled remotely which is often realized by VPPs. For more information note section "German electricity market" at the beginning of Section 3.

3.3. Estimated and known benefits

First, there will be a summary of existing benefits for the German macroeconomy. Afterwards, based on this analysis, it is given deductions and estimations for further benefits and ongoing trends that are associated to the VPP developments.

Known benefits

The ongoing growth of renewable energies into the German electricity system enforces the need of intelligent systems like VPPs to enable a stable integration of such assets. There is a correlation between the overall renewable energy producer growth and the growth of VPPs in operation in Germany. This relation can be seen in Figure 27. The thesis that VPPs support clean energy penetration in Germany can be set up based on this data.

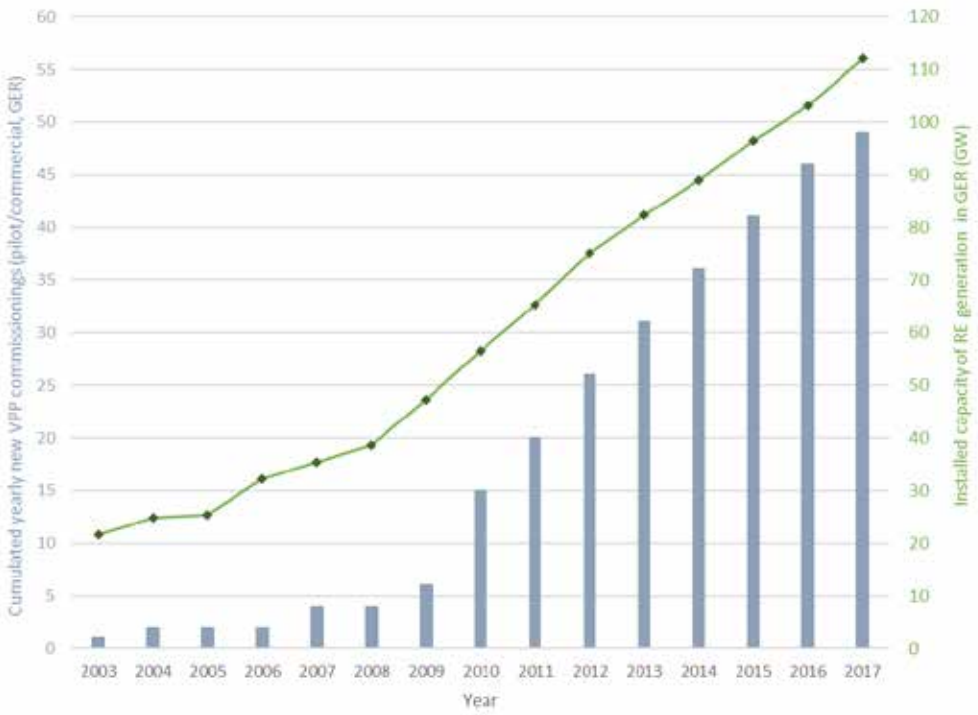


Figure 27: VPP commissioning and renewable energy installations in Germany, source Fraunhofer IEE, Fraunhofer ISE (https://www.energy-charts.de/)

Based on a survey about 93 % of the German population support the German energy transition (Deutsche Energiewende), see Figure 28. As stated in Section 3.2, supporting the German energy transition is also a sales argument for VPPs. One important reason behind this is that VPPs are the central instruments to make this energy transition visible and promote this acceptance.

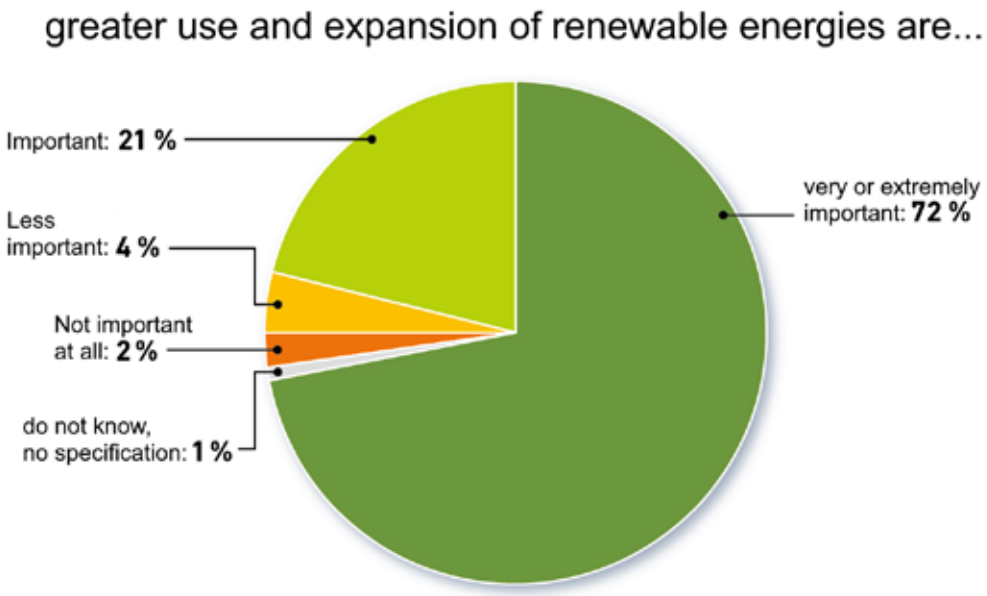


Figure 28: 93% of the German people support the stronger expansion of renewable energies in Germany, source [40]with translation by Fraunhofer IEE

More concrete this means, the growth of renewable energy integration in Germany is abstract and not tangible for the population. Therefore, VPPs can be seen as a marketing tool for the energy transition, because graphical user interfaces (GUI), which are typically a part of a VPP, can show the potential and the behavior of those DERs. Adequate visualizations, as seen in Figure 29, help to transport an understanding for everybody about this topic.

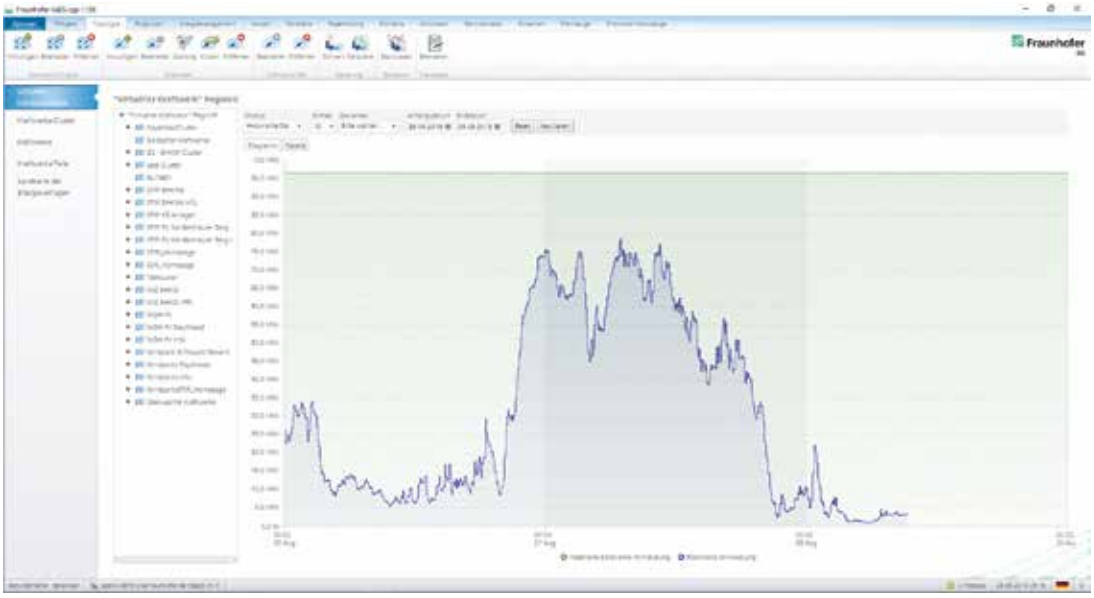


Figure 29: Screenshot of the Fraunhofer IEE VPP, IEE.vpp, source Fraunhofer IEE

Regarding ancillary services, aggregators like VPPs are the basis of integrating DERs like wind or photovoltaic energy into the balancing market. This is due to the fact that a single plant cannot provide reliable balancing energy because of high uncertainties or safe non-availability in certain times, such as photovoltaics in the night. This leads to the need of a bigger portfolio or clusters

of these DERs. Clustering these assets has multiple benefits. The predominant advantage is to be able to provide a much safer energy call of band of the pool than the single plants would have. This is because of compensation effects. The safety of such provisions is given through adequate active power forecasts. The same mechanism of compensation holds true for pool forecasts versus single forecasts, see Figure 30.

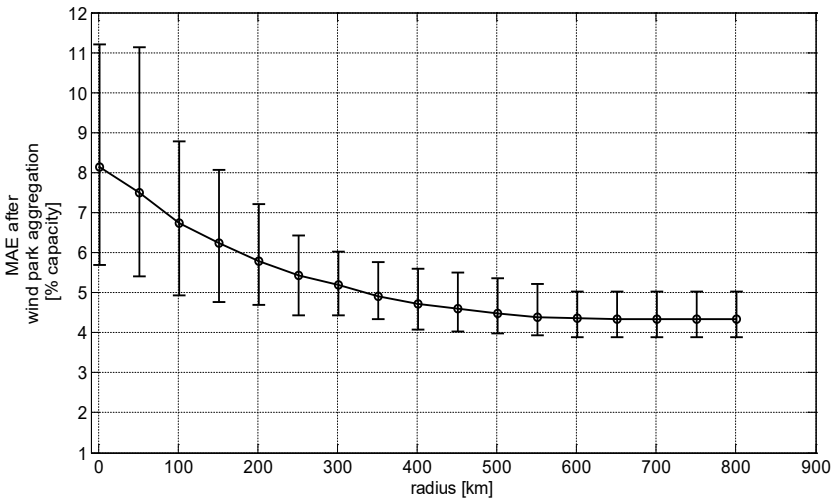


Figure 30: Forecast quality depending on size of the aggregated portfolio of wind parks, source Fraunhofer IEE

Another benefit of pooling DERs is that the risk of failure of the overall system, which is the VPP, is smaller than a single comparable conventional power plant. This is because the single conventional plant is a single point of failure. If it is down, no energy at all can be provided. Compared to this, in a VPP having one or more failure of some DERs usually does not lead to the incapability of the system. This is because a VPPs basis is an intelligent handling of flexibilities and such failures can be considered as a behavior due to this flexible nature. Therefore, the VPP can handle these scenarios in a limited scope.

Estimated benefits

According to the worldwide VPP market trend expectations, the market in Germany is expected to grow in the next years. With the anticipated ongoing continuous increase in VPP operational start-ups, as seen in Figure 27, comes also an increase in competition in direct marketing. Competition in this segment is crucial to lead to better and more elaborated technologies. It can be estimated that this competition will keep on growing and therefore will lead to further steps regarding an optimal integration of renewable energies in the overall energy system.

04

Schemes of VPP in India

4.1. Relevance of VPPs in Indian scenario

As highlighted in section 1, there is a growing penetration of RE sources and DER in India. With these technological changes in the Indian grid, it has become indispensable to incorporate large scale aggregation of RE and DER, which apart from giving us the flexibility to quickly ramp up/ ramp down supply, will also enhance the overall system efficiency.

Figure 31 given below illustrates such market and technological developments happening in India, which are demanding a strengthened and modernized grid.

Figure 31: Developments happening in the Indian Power sector boosting the requirement of VPP in India

The steadily increasing distributed generation (especially in the form of solar rooftop) is bringing in a different set of challenges that need to be addressed. In terms of distribution, there are limits on the total amount of electricity that can be injected in the grid at one-point owing to the transformer capacity at that location. Other grid related issues such as effect on voltage control, quality of power, grid protection issues, forecasting and scheduling issues are other factors that have to be taken care of. Today, even at a minuscule penetration of solar rooftop in the grid (~0.15% of the total power consumption) in various states, Discoms are facing problem in handling the solar generation. This makes VPP a highly relevant solution in the Indian context. Figure 32 illustrates the different penetration levels of solar rooftop as a percentage of overall energy consumption of the states.

In the field of e-mobility in India, more and more electric vehicles are coming on-road. The Government of India has set a goal of 30% electric vehicles by 2030. This is also leading to an

upsurge in the charging infrastructure. With the growing trend of EVs, the connected load and the time of charging is going to severely affect the distribution grid. Also, at a higher penetration, number of charging stations scattered over large geographies need solutions like VPP for effectively managing the grid.

Government has also taken up several initiatives with the vision of upgrading the current electricity grid to future-ready smart grids. From the formation of the Indian Smart Grid Forum (ISGF) and Indian Smart Grid Task Force (ISGTF) to unveiling National Smart Grid Mission and pilot project implementations, India is paving way for a phenomenal transformation. These initiatives aiming to bring automation in the grid can form the base for deploying the VPP solutions in India.

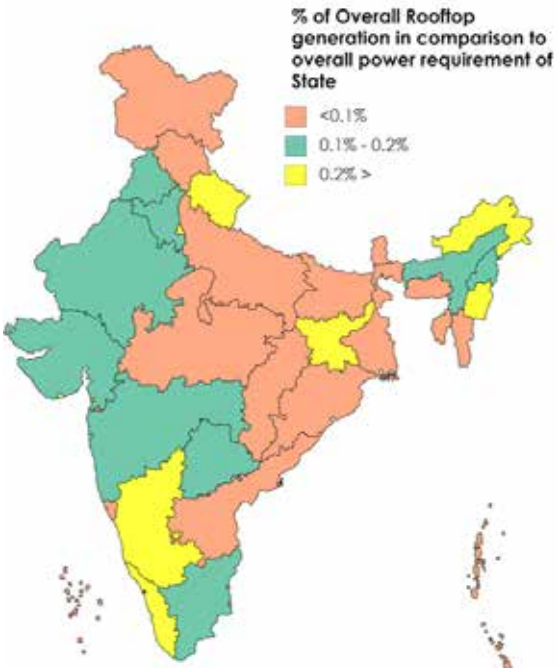


Figure 32: Status of different Indian states in terms of solar rooftop generation vs. total power requirement

Energy markets in India are also evolving parallelly. The electricity market trends (Figure 33) show the growth of volumes served by the short-term markets, which implies the need for the development of the ancillary services for maintaining the system reliability. VPPs are capable of providing the needed ancillary service support like voltage support, frequency support, and black start. Also, the ongoing smart cities and smart grid initiatives, which are majorly focusing at automating the conventional grid, will be strong supporting factors for bringing the VPP solutions to the Indian markets.

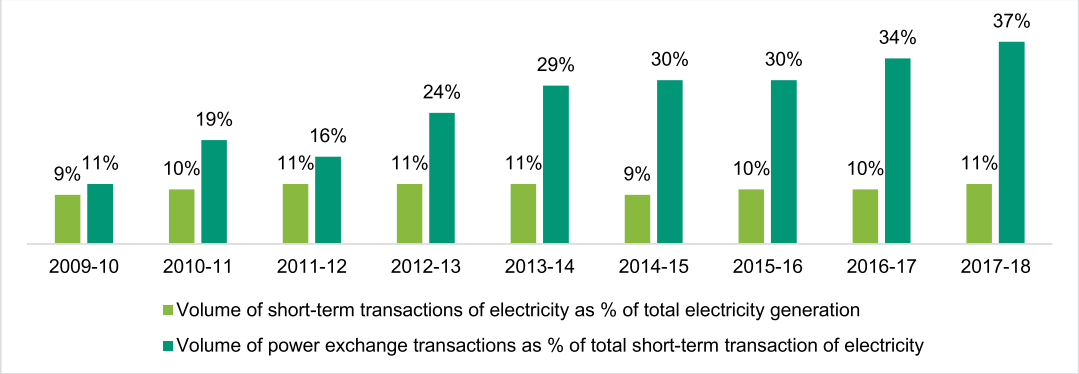


Figure 33: Increasing short-term transactions of electricity in India [41]

In terms of regulatory development, India is striving towards stricter deviation settlement mechanism (DSM) and sub-15-minute markets. The increased penalty with stricter DSM demands highly sophisticated and accurate forecasting and optimization systems, which are currently unavailable in India. Also, moving from the 15-minutes to 5-minutes time block will require better scheduling and settlement services. These required services can be made possible with the implementation of VPP.

The operational and commercial responsibilities of the lead and principal generator defined by CERC in the document 'Implementing of the framework on forecasting, scheduling and imbalance handling', finds several similarities to the functions that a VPP can provide.

From the above discussion it is evident that the Indian power sector is progressing to adopt the advanced technologies, for which VPP can be used as a promising solution. VPP having different functionalities and use cases can help India to leapfrog towards achieving a sustainable and an efficient power system.

4.2. Use cases applicable for India based on regulatory and power market assessment

This section analyzes and evaluates the regulations and market readiness of India to support VPP implementation. Various regulations existing in India were analyzed, based on which various use-cases and VPP configurations were identified. Following is a brief review of Indian policies and regulations that can potentially affect the development of VPPs in India.

i.) Forum of Regulators: Sub-Group Report on Introduction of Five-Minute Scheduling, Metering, Accounting and Settlement in Indian Electricity Market (February 2018)

Target date set for migration to 5-minute scheduling, metering accounting and settlement as 1st April 2020
Key Highlights of the report
Imperatives identified for moving to 5-Minute Scheduling & Settlement: • Increasing RE penetration • Harnessing and Incentivizing Flexibility • Ramp Management • Improved Forecasting, Scheduling and Dispatch • Reduced Requirement of Reserves • Implementation of Primary, Secondary (AGC) and Tertiary Reserves/Control • Facilitating & Enabling Participation of New Technologies • Need for Economic (Price) Signals at Shorter Intervals **Recommendations:** • Move to "Fast" Markets • Development of Forecasting as a Core Area in System Operation • Implementation of Five Minute Scheduling and Dispatch • Implementation of 5-minute bidding in Over-the-counter and Power Exchanges • Five-minute Energy Accounting and Settlement System • Administration and Treatment of the five-minute deviation price. • Pan-India Pilot Project on 5-minute metering • Change in data exchange file structures and other technical issue • Amendments in CEA Metering Standards • Upgradation/Replacement of Metering Infrastructure • Holding workshops, dissemination, stakeholder capacity building

Relevance to VPP
The identified imperatives and recommendations given by FoR in the report are in line with the objectives of a VPP. VPPs in India can prove to be a supporting system for implementing 5-minute bidding and moving to "fast" markets though DERs.

ii.) Discussion Paper by CERC on Re-designing Real Time Electricity Markets in India (July 2018)

Focused on redesigning Real Time Pricing to introduce a demarcation between 'energy trade' and 'system imbalance' handling
Key Highlights of the paper
Identification of need for market reforms: • Increasing penetration of renewable energy with 175 GW target by 2022, causing uncertainty, variability, and increase in the ramp in the net load profile (i.e., demand less renewable output). • Increase in the need for flexible dispatchable resources that can ramp their output up and down quickly to compensate for the renewables, leading to over-generation and thus curtailment of RE plant. • Growing adoption of distributed energy resources by end customers. In addition to the issues of being weather-dependent, uncertain, and variable that utility owned and operated renewable resources do, distributed renewable generators raise an additional 'visibility' issue. • Novel uses of electricity (e.g., for electric vehicles and battery charging) **Recommendations:** • Ancillary services or DSM/UI cannot and should not act as substitute for energy trade at intra-day time horizon. • Moving to an accurate Real Time Pricing to allow for changes in production and consumption schedules, to accommodate differences between day-ahead forecasts of system conditions and actual conditions that are observed in real time • Transitioning from continuous trade (pay-as-bid scheme, where market participants have to anticipate the clearing price and accordingly mark up their bids) to auction based model (where auction participants receive the market clearing price) in the intra-day segment for ensuring greater efficiency in price discovery and increasing the depth of the market. • Introducing the concept of "Gate Closure": The point of time when freeze/finalization occurs for a Delivery/Settlement Period.
Relevance to VPP
The paper focuses on shifting to Real Time Markets, which is possible only when there is a controllability and certainty in the energy generation from resources. VPPs can help addressing this issue by making RE/DER more controllable. Also, paper talks about the "visibility issue" of DER, which again can be solved through VPPs.

iii.) Discussion Paper by CERC on Re-designing Ancillary Services Mechanism in India (September 2018)

CERC enforced Ancillary Services Operations Regulations in 2015 to restore frequency at desired level and relieve congestion in transmission network. This discussion paper aims to assess the performance of the existing framework of frequency support and balancing ancillary services mechanism in India.

Key Highlights of the paper

Key Challenges in Ancillary Services (relevant to VPP enlisted here):

- Need of adequate reserves quantum available for dispatch
- Performance Monitoring of Ancillary Services
- Minimum threshold quantum for Ancillary Services

Recommendations (relevant to VPP enlisted here):

- Addressing adequacy of resources (access to enough power to be able to meet the highest expected level of demand) and system quality is essential to maintain reliability of power at least-cost while the power sector shifts from being dominated by conventional power to renewables.
- Designing of bid-based reserve market model to provide primary and secondary frequency control at regional level as well as national level alongside the day ahead (DA) main market.
- Need to bring in additional machines on bar and maintain spinning reserves to facilitate flexing of generation to meet ramp requirements.
- All technologies and services should be able to compete for ancillary services. Obligation for all providers to ensure the least cost options are developed and all technologies are allowed to compete, regardless of size or type.
- Storage, Inverter Control, and Load control (Behind-the-meter applications) to be utilized as flexible resources for providing ancillary services
- Review of the use of potential from decentralized energy plants and storage facilities to provide frequency control as instantaneous reserve.
- Develop coordinated balancing energy provision from decentralized energy plants in the distribution grid to provide voltage control.

Relevance to VPP

The paper focuses on designing of reserve market which can bid at regional and national level. Also, DERs including behind-the-meter resources have been identified as potential ancillary service provider for future. VPPs can support this transition and re-designing of ancillary market by aggregating DERs and making them controllable and visible to the market.

iv.) Draft Central Electricity Regulatory Commission (Deviation Settlement Mechanism and related matters) Regulations, 2013 and Latest (Fifth) Amendment, 2019

CERC recently issued its fifth amendment to the deviation settlement regulations in May 2019, which came into effect from June 3rd, 2019.

Key Highlights of the regulations

Objectives of the regulation

- To enforce accurate Generation Forecasting and Scheduling
- Intra-State Deviation Settlement

- Forecasting & Scheduling of RE sources
- Regulation on Spinning Reserves and other Ancillary Services within the State
- Process changes to enable frequent and faster intra-day trading at power exchanges
- Cooperation with neighboring States for sharing balancing resources
- Implementation of more iterations of the Electricity Market in Power Exchanges to provide adequate opportunities to the market participants to balance their portfolio
- The fifth amendment also introduced "Daily Base DSM Charge" and "Time Block DSM Charge" to settle for the total deviation occurring in a day and for a specific time block respectively.

Relevance to VPP

Deviation from forecasted generation occurs due to forecasting errors and sudden weather changes. Reducing generation output (curtailment) to minimize deviation charges especially in event of excessive generation is an option. However, it leads to loss of effective utilization of resources. VPP can here help in reduction of power curtailment and/or deviation charges through its enhanced forecasting and optimization tools, along with the ability to control generating sources real-time.

v.) ***Forecasting, Scheduling and Deviation Settlement of Solar and Wind Generation Regulation, Andhra Pradesh, 2017***

Under this regulation forecasting, scheduling and deviation settlement has commenced from 1st January 2018 and deviation charges collection will commence from 1.07.2018

Key Highlights of the regulations

- Mandating the establishment of Forecasting tool for all Wind and Solar generators either by itself or through Qualified Coordinating Agency (QCA)
- Should submit a day-ahead and week-ahead schedule
- Provision for intra-day revision: wind (16 max) and solar (9 max)
- QCA has to be selected for each pooling station
- QCA has the responsibility of coordinating between DISCOM/STU/SLDC and all the generators which it is representing
- Different pool accounts for Inter-state and Intra-state
- Provision for virtual pooling of different pooling stations to avail the benefit of larger geographical area and diversity

Relevance to VPP

VPP has the features to assist the Qualified Coordinating Agency (QCA) by performing all the required functionalities and ensuring virtual pooling to bring coordination among the stakeholders.

vi.) ***Net Metering Policy of Uttar Pradesh***

The policy aimed at increasing the adoption of SPV rooftops in the state

Key Highlights of the regulations

- Peak capacity of the rooftop system shall not exceed 100% of sanctioned load/ connected load/contracted demand of consumer
- Capacity of the rooftop system shall not be less than 1kWp and shall not exceed 2 MWp under this regulation

- Need to pay the system upgradation cost of RS. 1000 per kWp if system size is above 10 kWp
- Provision for the sale and purchase of electricity through peer-to-peer transaction using Block Chain technology
- Enabled provisions for group net metering but not virtual metering

Relevance to VPP

The provision for the group net metering and "peer-to-peer" transaction will enable the VPPs to play an important role to unveil the potential benefits of the technology and enhance the better adoption of the solar rooftop. It is a win-win situation for both utilities and the consumers to reap the benefits and to be able to share them.

vii.) Delhi Electricity Regulatory Commission (Demand Side Management) Regulations, 2014

The overall objective of the regulation is to lower the overall cost of electricity to the consumers of the Distribution Licensee as well as cost of the Distribution Licensee itself.

Key Highlights of the regulations

- DSM is defined as actions taken by Distribution Licensee to facilitate the change in pattern of end use of electricity
- Definition of "Load Management" includes "Demand Response Program" which needs to be carried out for meeting the objectives of DSM.

Relevance to VPP

Energy Service Companies defined in the regulation has left the door open for third parties (VPP solution providers) to make use of VPP as a solution to achieve the resultant load reduction. Also, various functionalities of VPP can be leveraged to enable the demand response programs for acheiving load reduction.

Policies and papers discussed above are indirectly supporting the adoption of VPP technology. Whether it be transitioning to real-time market, adopting DER to provide ancillary services, or to control the penalty due to deviation between scheduled and dispatched generation; VPP can help the power system and act as a backbone for providing all these services - both at regional level (at distribution level) and national level (at transmission level). Based on the above regulatory analysis and use cases deployed across globe, we can conclude that in the present policy framework of India, VPPs may be deployed in India to deliver demand response services and for participating in wholesale and ancillary service markets.

Figure 34 gives a brief overview of various plausible configurations of VPP along with suitable use cases (services) which may be provided by VPP, depending on its connectivity to the grid and the consumer type.

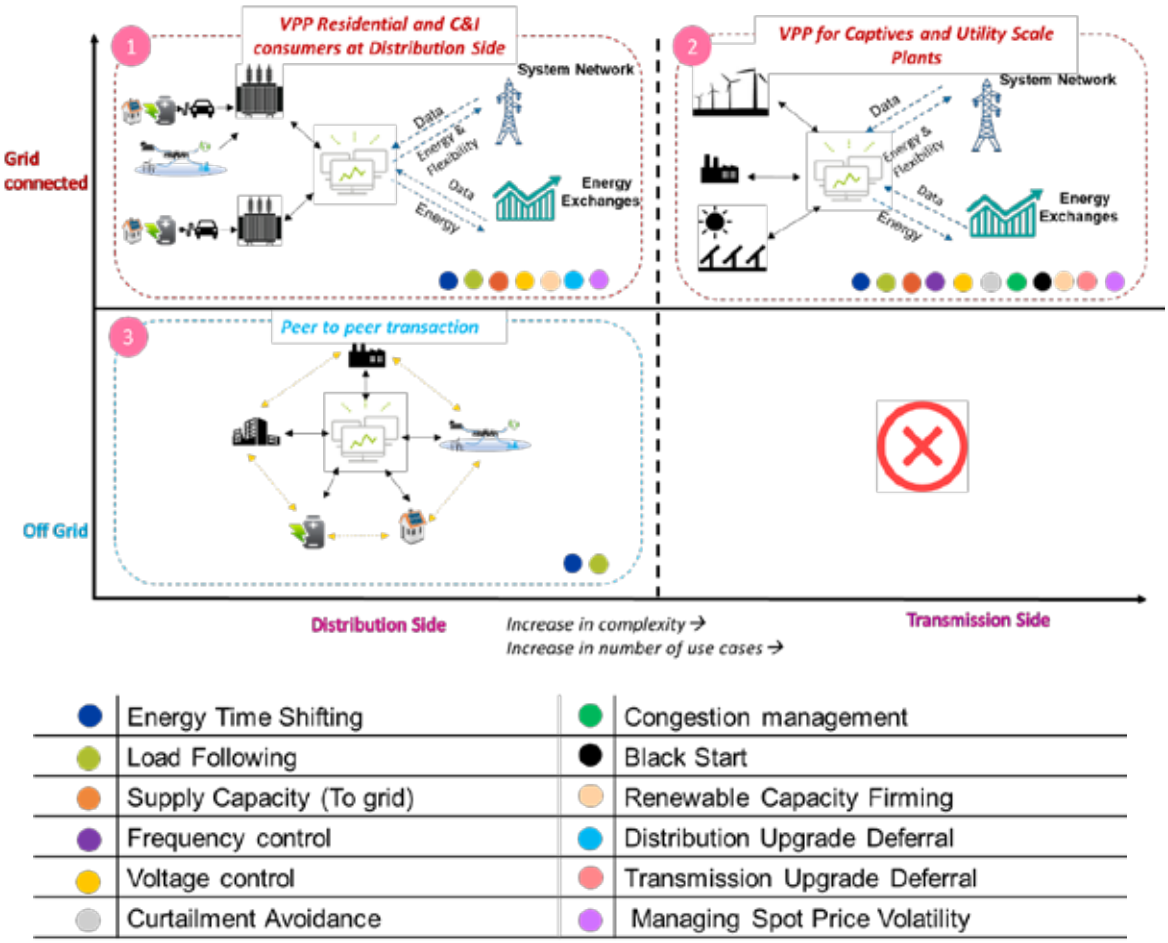


Figure 34: Various plausible configurations of VPP suitable for India along with plausible use cases

Along with technical services, VPPs can also provide economic services such as managing spot-price volatility by controlling and dispatching generation/storage assets during periods of high energy prices. However, designing of the VPP depends on the use cases which an operator desire. VPP can be made to operate - depending on what is the target? If the target is to reduce DSM penalty, then the VPP Control Unit must have an accurate forecasting tool. If the target is to manage spot price volatility, then VPP Control Unit must have an optimization tool for optimizing generation during peak prices. Following sub-section will elaborate on the VPP layouts illustrated earlier in Figure 34.

The ownership of VPP in each of the configuration may lie with Consumer, VPP implementing agency or any Discom, Transco or SLDC, depending upon the business model.

Configuration-1:

Connectivity Type: Grid Connected

Consumer Category: Consumers (operational at 230V, 400V, 11kV or 33kV) having DERs, flexible loads at distribution side and EVs; and grid connected microgrids.

In this layout, a VPP can accommodate various grid connected **domestic consumers along with small industrial and commercial consumers** (having DER, flexible loads, storage, EV chargers), and grid-connected microgrids to allow aggregation of distributed energy sources. Electric

Vehicles, which are expected to grow in future, can be aggregated to perform like a distributed energy storage. This can enable controlled scheduling and dispatching of aggregated EVs as VPP, for supporting the distribution network, and optimal utilization of EV power stored in times of grid balancing at DT level. Through this configuration, it will be easier for Distribution Companies to manage widespread portfolio of DER assets. The generation of the assets can be aggregated at VPP control center and sold to energy exchange as and when required subject to open access regulations. The aggregated output can also be provided to network operator (Distribution Companies in this case) to meet various grid services. Table 9 summarizes the challenges which are being faced by various stakeholders at distribution side, and also brings out the VPP functionalities which are required for addressing those challenges.

Table 9: Existing challenges for stakeholders at distribution side

Distribution Level Consumers*	Distribution Company
No visibility of assets to the energy market	Asset & Load Management
No monetary benefit of installing storage and flexible loads	Continuous Network Monitoring
Power Outage	Load Following
	Unplanned outages and minimizing restoration time
	Procurement of power from different states at high cost during peak demand
	Predicting the quantum of power purchase
	Voltage fluctuation

*Also acting as generators in this case (Prosumers)

These challenges can be addressed by VPP with functionalities of continuous network monitoring, controllability of assets, demand forecast, real-time energy trading

Model involving peer-to-peer energy transaction between prosumers connected to a single distribution line or between prosumers connected to different distribution lines can also become one possible configuration in future.

Configuration-2:

Connectivity Type: Grid Connected

Consumer Category: Large captives and large consumers (operational at 66kV, 132kV or 220kV) having DERs, RE Generating Companies, and Utility Scale RE Plants

In this layout, VPP will aggregate the asset and generation of captive plants and utility scale RE plants, mainly focusing at transmission side of the power system. Through this configuration, it will be easier for Transmission Companies (Transcos) to manage widespread portfolio of assets, both at intra-state and inter-state level, and even inter-country level. Table 10 summarizes the challenges which are being faced by various stakeholders at transmission side, and also brings out the benefit which can be obtained through this configuration of VPP.

Table 10: Existing challenges for stakeholders at transmission side

Captive Plants/Utility Scale RE plants	Load Dispatch Centers	Transmission Company
No visibility of assets in the short-term energy market	Continuous Network Monitoring	Asset Management
Energy Curtailment	Congestion Management	Stressed transmission and Sub-transmission network due to increased RE penetration
Inaccurate Forecasting and Scheduling	Inaccurate Scheduling and Dispatch of electricity within a State	
Deviation settlement mechanism (DSM) charges	Carrying out real time operations for grid control	
	Voltage and frequency fluctuation	

These challenges can be addressed by VPP with functionalities of continuous network monitoring, weather forecasting, accurate generation forecasting and scheduling, real-time energy trading

Configuration-3:

Connectivity Type: Off-Grid

Consumer Category: Off-grid consumers having DERs and off-grid microgrids

Current focus in India is on improving the energy access through DERs/microgrids. However, through virtual power plant, 'quality' of energy access (flexibility, reliability and efficiency) can be improved. In isolated and far-off areas, where not every consumer can afford a DER, there VPPs can be used to trade power amongst consumers. Energy generated from varied and heterogeneous DERs can be aggregated in a VPP and distributed amongst the consumers connected to the VPP in "Pay-as-You-Use" model. In this way, it can be a win-win situation for both - the seller and the buyer. Also, peer-to-peer transaction of energy amongst consumers in a small cluster can solve the problem of providing energy to the 'in-need' consumer without connecting him to the centralized grid.

Table 11 summaries the respective off-takers/beneficiaries of various configurations of VPP at different grid locations:

Table 11:Beneficiaries of different VPP Configurations at different grid location

	Off – Grid consumers with DER	Grid Connected Consumers with DER	Utility scale RE Plants, Captives	Load Dispatch Centers	Transmission Company	Distribution Company
Configuration-1	✗	✓	✗	✗	○	✓
Configuration-2	✗	✗	✓	✓	✓	○
Configuration-3	✓	✗	✗	✗	✗	○

✗ No benefit ✓ Direct Beneficiary ○ Indirect Beneficiary

4.3. System benefits from these use cases

The previous section clearly outlined the purpose of VPPs for different grid participants and illustrated that VPP as a solution can be installed at many points in the grid. Depending on factors such as VPP's location (generator side, transmission side, distribution side, or off-grid), resources utilized (flexible loads, EVs, DERs, energy storage, etc.), and beneficiary involved (Prosumers, Gencos, Transcos and Discoms), VPP can prove to be an ideal solution for beneficiaries to aggregate and control the distributed assets. Benefits gained by each of the beneficiary in different VPP configurations is summarized in Table 12.

Table 12: List of VPP Benefits for various VPP configurations

	Off – Grid consumers with DER	Grid Connected Consumers with DER	Utility scale RE Plants, Captives	Load Dispatch Centers	Transmission Company	Distribution Company
Configuration-1	NA	• Improved supply capacity to grid • Flexible Generation and improved dispatchability • Improved Service Reliability • Improved market visibility	NA	NA	**Indirect Benefits:** Relief in the transmission congestion and transmission upgrade deferral	• Accurate forecasting of net load and planning of power purchase • Reduction in the quantum of power purchase with aggregated DER generation available • Improving Grid Services (Power Quality, Voltage Control, Congestion management)
Configuration-2	NA	NA	• Improved dispatchability of RE Plants • Transparent to Energy Market/ Capacity Markets • Bill savings due to deferred T&D upgrade • Reduced or Zero Energy Curtailment • Better forecasting and scheduling reduced DSM charges	• Improved scheduling of RE plants • Automated network monitoring • Accurate accounting of electricity transmitted • Improved Grid Services (Power Quality, Voltage Control, Congestion management, Black Start)	• Transmission upgrade deferral (controlling single power source is easier than many smaller ones) • Reduced congestion	**Indirect Benefits:** Distribution upgrade deferral

	Off – Grid consumers with DER	Grid Connected Consumers with DER	Utility scale RE Plants, Captives	Load Dispatch Centers	Transmission Company	Distribution Company
Configuration-3	• Better utilization of assets • Peak Load Management • Peer-to- Peer transaction	NA	NA	NA	NA	**Indirect benefits:** Reduction in the burden on distribution grid and grid congestion

In addition to the above-mentioned benefits, VPPs also offer co-benefits. For instance, VPP accelerates the broader adoption of renewable energy and thus acts as a valuable tool to meet emission reductions.

4.4. Design of VPP – identification of actors, concept of operations for regular operation, specific use cases

Based on our international experience (especially that of Germany), and discussion in the previous sections, we have identified few use cases of VPP which are expected to become prevalent with increasing share of RE in medium to long-term. Figure 35 illustrates the specific use cases of VPP identified for India for the different VPP configurations defined in the previous section:

Relevance of Specific End-uses of VPP for Indian Power Sector		Low	Medium	High
	Suitable VPP Configuration	Short TermShort Term	Medium Term	Long term
Energy Time Shift	Configuration-1,2,3			
Renewables Firming	Configuration-1,2			
Voltage Support	Configuration-1,2			
Frequency Regulation	Configuration-2			
Transmission / Distribution upgrade deferral	Configuration-1,2			
Load Following	Configuration-1,2,3			
Curtailment Avoidance	Configuration-2			
Congestion Management	Configuration-2			
Managing Spot Price Volatility	Configuration-1,2			

Figure 35: Growing relevance of VPP end uses in India

To implement these use cases there are various actors which need to be involved. Actors are the major components (hardware and software) that make up the VPP and vary from case to case depending on the end-use served by VPP. This section will highlight the actors involved in VPP implementation. Table 13 given below illustrates the various actors in VPP operation in general:

Table 13: List of key actors involved in a VPP implementation

Actor	*Actor Type*
RE Generating Companies	Grid participant and VPP resource[1]
Prosumers	Grid participant and VPP resource
Distribution Companies	Grid participant
Transmission Companies	Grid participant
Pooling Substation	Grid participant
VPP operator	Grid participant
Battery Energy Storage System	VPP resource
Controllable Loads	VPP resource
Electric Vehicles	VPP resource
Metering system	Hardware and Software

Actor	*Actor Type*
Control Interface between RE portfolio and Central Control Unit	Hardware and Software
Communication system between metering and Control Unit	Hardware and Software
Generation Forecast Module	Software at Central Control Unit
Demand Forecast Module	Software at Central Control Unit
Scheduling and Dispatching Module	Software at Central Control Unit
Weather Forecast Module	Software at Central Control Unit
Real time energy trading Module	Software at Central Control Unit
Continuous network monitoring module	Software at Central Control Unit
Energy data management system (EDMS)	Software at Central Control Unit
Human Operator	Human
Other IT infrastructure (Servers, communication modules, etc.)	Hardware and Software
Graphical user interfaces	Hardware
Actuators, Relays and Circuit Breakers	Hardware
Automatic Transfer Switches	Hardware

It may not be necessary that all the actors participate together for a VPP implementation. The involvement of key actor depends on various factor, which are:

- Size of a VPP (local, regional, national)
- Configuration of a VPP (off-grid, on-grid)
- Location of a VPP (generation, transmission, distribution)
- Target application/End-use of a VPP

Concept of operation of a VPP:

Concept of operation explains the selection of the relevant actors, sequence of steps, and activities followed to achieve a desired target functionality over the range of features offered by the VPP. An example below has been considered for ease of understanding of this concept.

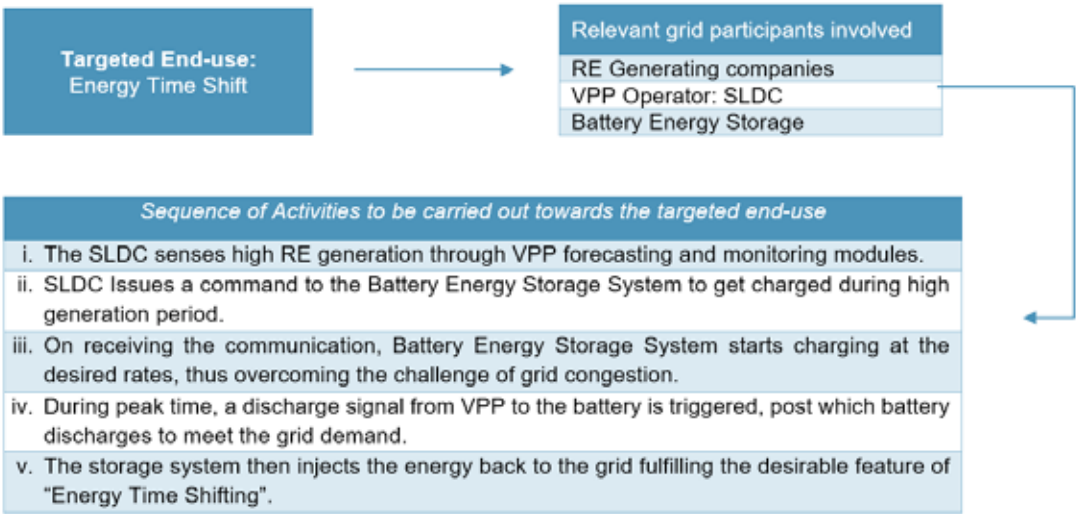


Figure 36 summarizes the above discussion and illustrates the expected concept of operation for Energy Time Shifting by a VPP:

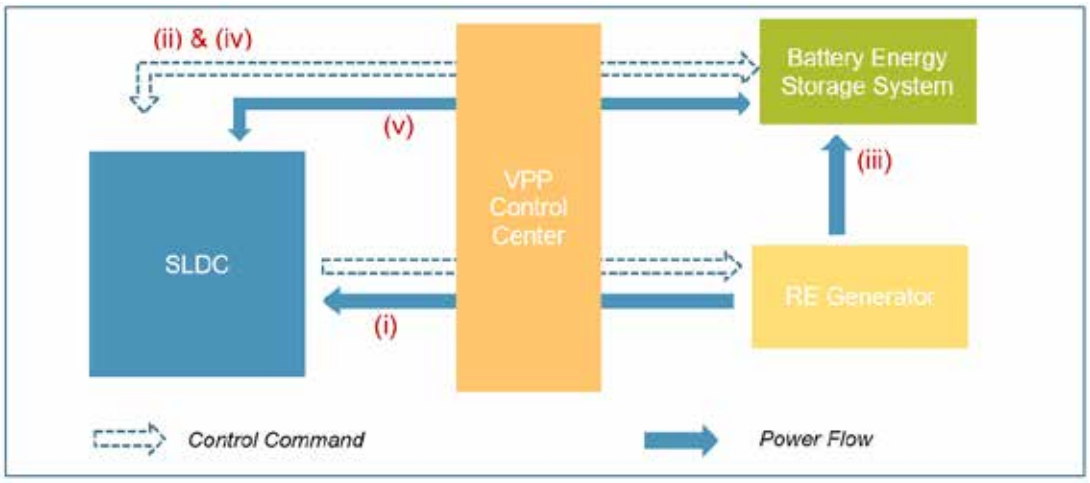


Figure 36: Concept of operation considering time shift as an end-use of VPP

4.5. Opportunities for VPP in India

In this section an opportunity for VPP in India has been identified. A scenario of Deviation Settlement Mechanism (DSM) has been considered, as a part of which wind generators are required to pay huge penalties for variability in RE generation. Readers may please note that the purpose of this section is not presenting a techno-economic feasibility of the solution, rather, presenting an example to highlight the factors on which a VPP solution may depend.

Deviation Settlement Mechanism for RE generators

The total installed capacity of wind energy in India is 36 GW (as of May 2019) [42]; making India one of the largest wind energy producer in the world. For the fiscal year 2018-19, 62 TWh of electricity generated was supplied alone by wind energy [42]. The growing wind power is propelling India towards energy security, but the variable nature of wind generation is creating challenges in accurate forecasting and scheduling.

Wind forecasts typically have 15% to 20% mean absolute error (MAE) for a single wind plant [43]. Due to this variability between expected and actual injection, RE generators are bound to pay **Deviation Settlement Mechanism (DSM)** penalty. States in India like Gujarat, Andhra Pradesh have released their forecasting, scheduling and deviation settlement of solar and wind generation where the exemption limits and penalties are prescribed, which vary from state to state. Generators can appoint Qualified Coordinating Agency (QCA) to manage forecasting and scheduling on their behalf.

The scenario of DSM penalty may be explored as an opportunity for Virtual Power Plant in India, as VPP with functionalities such as weather forecasting, accurate generation forecasting, and scheduling may be used for reducing the forecasting error. This in turn will reduce the penalty to be paid by generators. Described below is an example wherein DSM penalty has been presented as a plausible opportunity for VPP in India.

Example: Aggregation and Pooling of various wind generators in Gujarat

Assumption: For the purpose of the study, an analysis of the expected vs. actual injection has been carried out for a 40 MW wind plant. Figure 37 illustrates the number of time blocks where deviation penalty is applicable due to the difference between the expected and actual injection. If the generator is situated in Gujarat, then, as per the DSM regulation of the state [44], annual penalty to be paid by the wind energy generator is estimated to be **~INR 60 Lakhs.**

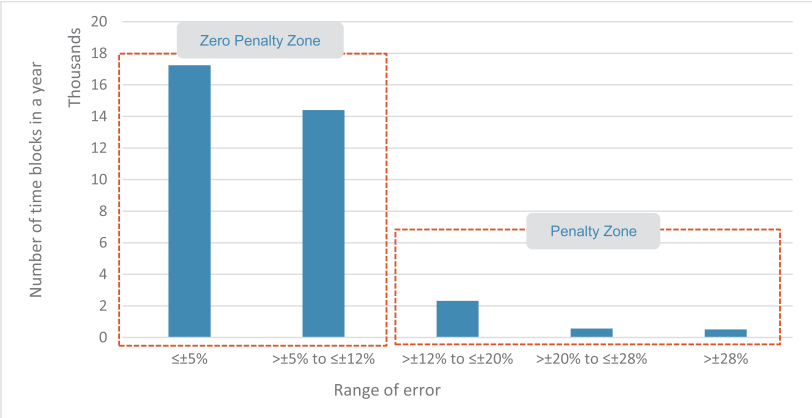


Figure 37: General scenario illustrating number of time blocks lying in penalty zone for a Wind Generator in Gujarat [44]

The penalty incurred by a single generator can be considered as an opportunity cost that VPP can help to recover. Forming a VPP by pooling of wind generators can lead to overall reduction in the forecasting error leading to reduction in the penalty to be paid by generators.

It may be possible that VPP is able to eliminate 100% of the penalty, through highly accurate forecasting, or may be able to reduce the penalty by 50%. This will depend on the accuracy of the forecasting modules used in VPP.

Section 5.3 gives a cost estimate of a medium sized VPP solution in the range of 20,000 $ (14 Lakhs)– 300,000 $ (~2 Crores). However, since the VPP to be set up for this scenario requires accurate forecasting, optimizing tools, and high-end communication technology, hence the cost of VPP here has been assumed as 300,000 $ at the higher end for aggregating upto 6 wind generators. As the number of customers will increase, the cost of VPP will increase.

Figure 38 below summarizes the discussion and illustrates the payback for VPP, based on the assumption that an annual penalty of INR 60 lakhs is paid by a single wind generator. The figure illustrates that for the VPP having 3 participants (generators), the payback period is 1 year if 100% of the penalty is reduced (i.e the VPP is able to perform highly accurate forecasting and scheduling). In case the VPP having 3 generators is able to reduce the penalty by 50%, then the payback period is 2 years. Similarly, for a VPP having 6 participants, the payback is reduced to 1 year even if the VPP is able to reduce penalty by 50% only.

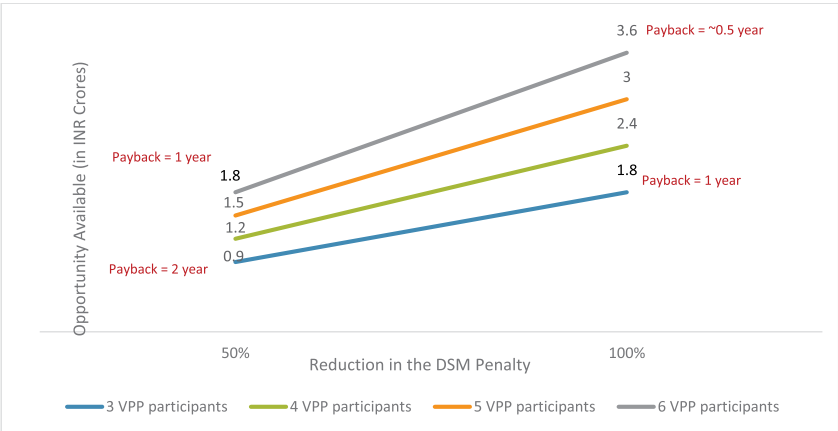


Figure 38: Illustration of the opportunity cost and payback period for VPP solution having different number of participants at generation side

Thus, from the above example, it can be inferred that a VPP solution depends broadly on following four parameters:

Project or site-specific criteria:

- Level of deviation – high or low

State regulation specific criteria:

- Exemption or tolerance for forecasting error
- Penalty levied by different states on the generators for the deviation

Participants' specific criteria:

- Size of the generating plant
- Number of Generators Pooled

Efficacy of the solution deployed

- Improvement in Forecasting Error

05

Steps for implementing a VPP based on a specific use case

This section gives an outline about the technical and organizational steps that need to be done to implement a VPP. More concrete, the section gives an overview about ICT infrastructure needs, human resources needed for operating and maintaining the VPP and general cost estimations. The required steps are highly dependent on the concrete use case and multiple external dependencies may vary quite widely. Therefore, this section is to understand, that it points out these impact factors and gives information about averages based on experiences in the energy economy by Fraunhofer IEE.

Figure 39 shows the basic three levels of an implementation of a VPP. The top level describes the tasks, which are necessary for the integration of the whole plant into workflows and further IT systems. Level two keeps the business case logic and level three the portfolio management.

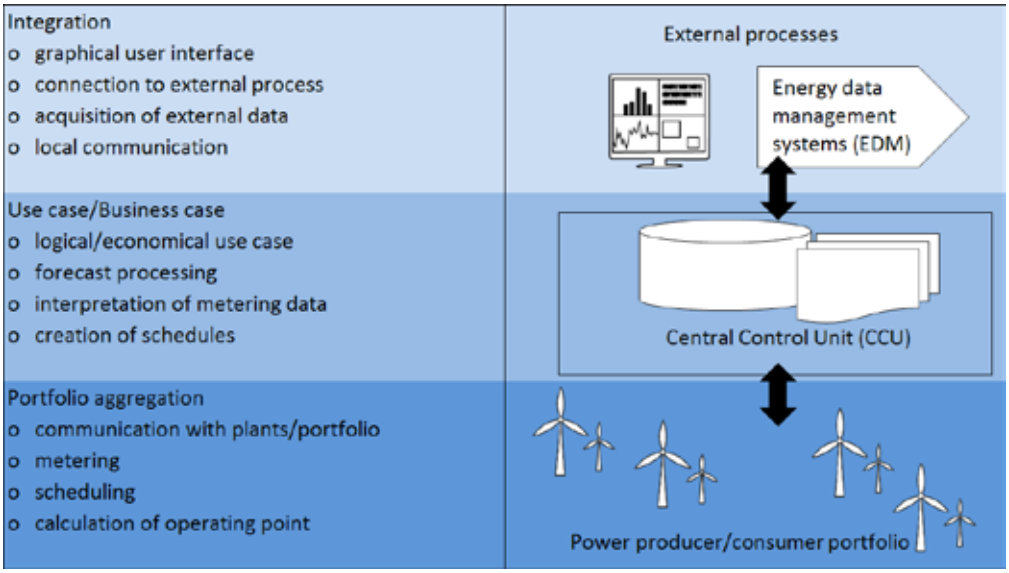


Figure 39: General Architecture of VPP

5.1. ICT infrastructure needs

The ICT infrastructure highly depends on the question how the specific architecture of the VPP solution looks like and the concrete use case. Whether it is a huge countrywide enterprise VPP with multiple thousand producer and consumer or it is a small local VPP managing the optimal energy flow based on the best revenues, the following aspects have a decisive influence regarding this infrastructure question:

- The type of use case realized through the VPP, because the use case can be subject to requirements that need to be ensured. For example, for providing balancing services in Germany, it is necessary to have a completely demarcated communication network all the way up to the plant level. This leads to completely different infrastructure needs because the use of existing ways of communication, for example internet, is not permitted.
- The basic equipment that comes with the power plant itself or other services from the manufacturer that are already in place. As an example, Enercons wind parks, at least in Germany, usually include an OPC XML DA server. This means there is a web service in place to control and monitor the plant with no additional need for a separate communication equipment at site.
- The VPP software basis, meaning the concrete software of the associated vendor, and its system requirements.
- Needed external services crucial for the implementation of the use case, for example external forecasting services. This can possibly lead to additional VPN gateway setups.

DER level

In order to integrate a DER in a VPP there needs to be a remote-control option or at least an option for reading remote data. At least, there needs to be a communication link between the DER and the VPP software system. For realizing this communication link, the following components need to exist:

Communication hardware equipment with adequate software to be able to communicate with from outside needs to be in place. This hardware equipment is often provided by the manufacturer. However, it can be more cost-conscious using other communication devices. There are VPP vendors, for example NEXT-Kraftwerke or Fraunhofer IEE, which prefer to put their own communication devices in place. This has the following advantages:

- The VPP can fully understand the protocol
- System updates and API changes are in the hand of one vendor, cross-system
- The communication box can be delivered with a preconfigured setup, for example with VPN gateway configurations for easy and save integration in the VPP system

Connection to a TCP/IP based communication network, where the VPP has also access, has to exist. If no legal regulatory for the implementation of the use case are contradicting, the local public communication network can be used. In order to do so there needs to be an access to this network, for example via wireless connection with GPRS, 3G, LTE or 5G or with a wired connection like DSL or copper lines. Furthermore, depending on the use case, further security and safety considerations like the need for closed user groups or other network closure aspects need to be considered. Depending on the DER type and the use case, a communication frequency of up to 1 second should be ensured. The communication has to be bidirectional in pull mode to acquire metering data and in push mode for sending control signals. Typical requested data are active and reactive power, storage levels, weather information, and available active/reactive power feed-in.

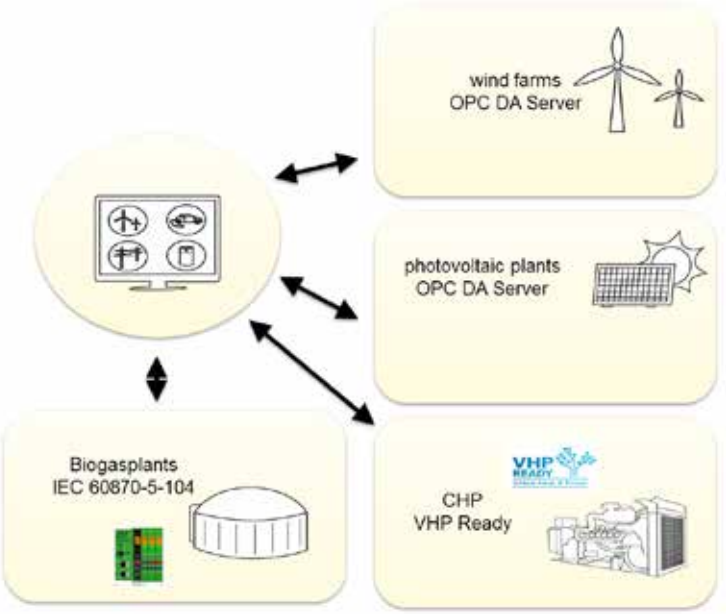


Figure 40: VPP portfolio-aggregation level with examples of communication interface protocols, possibly provided by the plant manufacturer

Grid level

The same as for all other parts the ICT infrastructure requirements holds true, the needs on grid level highly depend on the use case. ICT infrastructure is needed when the use case enforces grid close data to be processed. This could be the case, if measured data from the point of common coupling (PCC) is needed for providing the data because of accounting reasons needed from externals like utilities or the need to use the metered data as a variable in a control loop. If data from the PCC is needed for the use case, analogous to the DER level requirements, the following parts are needed:

Communication hardware equipment with adequate software to be able to communicate with from outside needs to be in place at the PCC. Depending on the location, meaning country, of the implementation of the VPP, this equipment could already be in place and in the control of the utility. If not, similar to the approach at the DER level an installation of such hardware-software combination needs to put in place. An example for such equipment could be a SSV-box (see https://www.ssv-embedded.de) or, if it does not have to be industry-compliant, cheaper solutions like an adapted Rasperry Pi (see https://www.raspberrypi.org/).

Connection to a TCP/IP based communication network, where the VPP has also access, has to exist. Regarding this point, the same requirements as on the DER level apply. It has to be remarked that depending on the use case maybe a unidirectional connection might be sufficient. In most cases, a data reading option is sufficient.

VPP software base system

As expected, ICT infrastructure requirements for the VPP software system also highly depend on the use case. In general, every VPP software system can be classified in three main components; this is a backend (BE), frontend (FE), further IT-systems and a database (DB). The BE hosts the main modules which are necessary to connect to the portfolio, calculate the business cases and to connect to external systems. In detail, the modules are shown in the following figure.

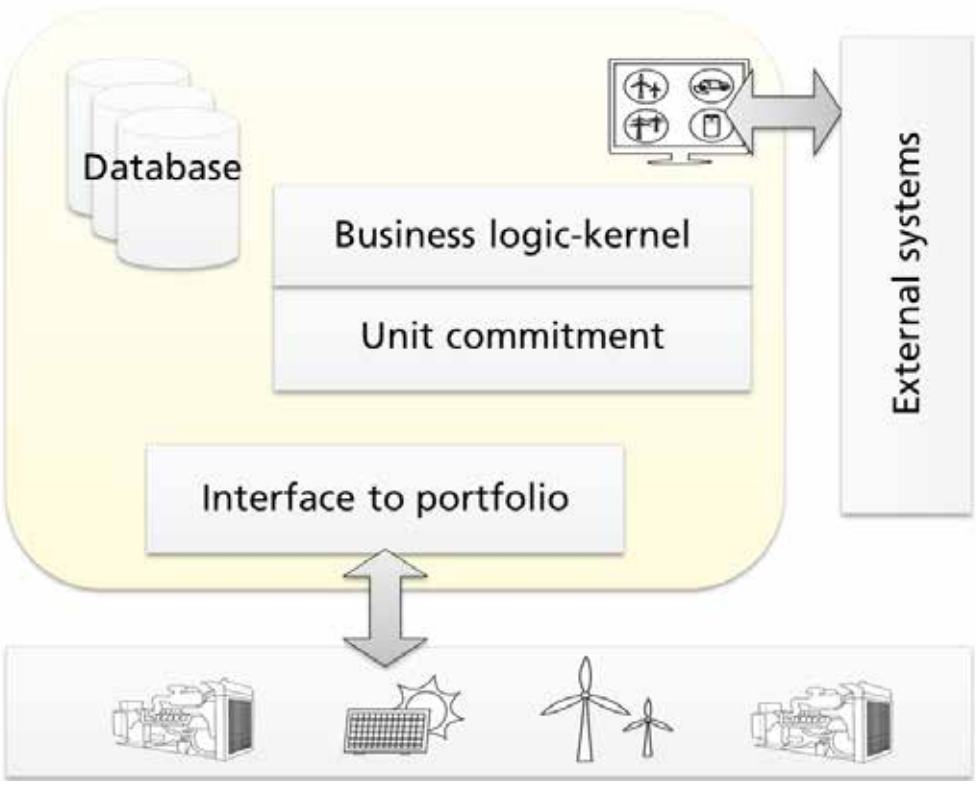


Figure 41: VPP backend modules

The plants, loads, and storages integrated in the portfolio are connected via point-to-point connections to the **VPP BE system**. Internally, a module called **Interface to portfolio**, addresses every single DER with the specific driver software. These drivers can mostly just be used for one manufacturer. In some cases, the same manufacturer has several communication interfaces for single plants. Examples for such drivers were developed for wind turbines from Senvion, Enercon, Vestas, and others. If a new plant type shall be integrated in the portfolio, software development might be necessary. In operation, this module acquires metering values and sends schedules or operating values to the single plants.

The module **Business logic-kernel and unit commitment** is the heart of the VPP BE system. Based on the rules resulting from use or business cases, an optimization algorithm calculates schedules for the portfolio and every single plant. In complex use cases, the optimization based on an intelligent energy management has to be done at every time step.

The **VPP DB system** can be considered as a part of the VPP BE system. However, in most cases the database is installed at one or multiple server that differ from the VPP BE hardware system. The DB is used for storing every kind of data and keeping the overall persistence. Most database implementations include internal redundancy concepts for a reliable data storage.

The combination of all systems is supposed to be the overall VPP system. These systems should run in a safe environment such as a demilitarized zone (DMZ). Figure 42 shows a basic example of a possible infrastructure architecture.

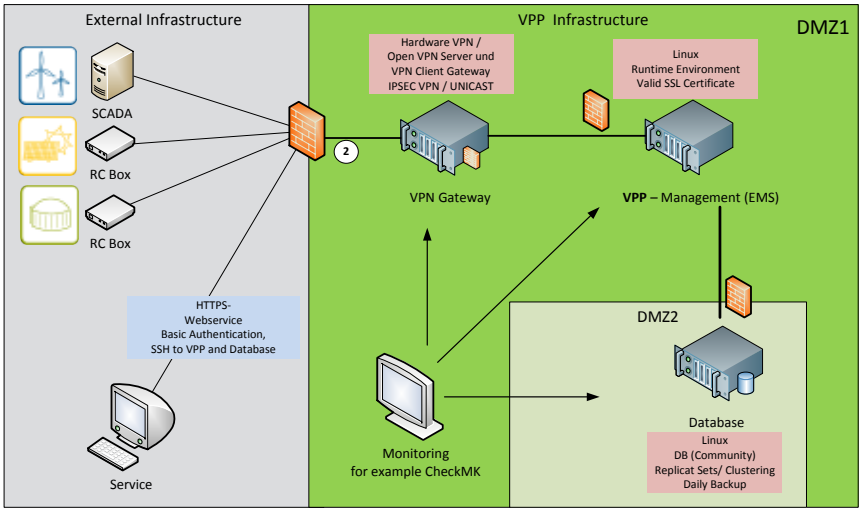


Figure 42: Recommended IT infrastructure for the VPP

In detail, for the overall VPP system the following parts need to be considered:

Sufficient hardware for the operation of the base VPP BE system is needed. Depending on the use case and the VPP software vendor this requirement can vary widely as well. The following influencing factors define the scope:

- Depending on the amount of integrated DERs and the required data resolution, hardware requirements by the VPP vendor may vary widely. An example of system requirements of a basic BE application is as follows:
  - Modern Multi-Core 64Bit-Processor
  - > 8 GB RAM
  - Compact CentOS or other Linux OS (for example CentOS)
  - 100 GB free disk memory (for installation and logging files)
  - Internet access for NTP (Network Time Protocol) time synchronization (UDP Port 123)
  - Unblocking of ports for necessary (web) services
  - Programming Language dependent runtime environment (for example JRE)
  - Valid SSL-Certificate
  - Access via SSH for service reasons
  - Operation in a secure infrastructure (DMZ)
- Depending on the main task of the VPP, there can be legal obligations to enforce redundant hardware. In the case of a software failure or a server breakdown, a second, redundant VPP has to take over the control of the portfolio. On top, there are cases where this redundant hardware needs to be installed on locally different data centers. In Germany for example, in the case where the VPP is participating on the balancing market it is considered being a part of the so-called critical infrastructure. As stated in [45]"Critical infrastructures are organizations or institutions of important importance to the state community whose failure or impairment would result in sustainable supply bottlenecks, significant disruptions to public safety or other dramatic consequences." (Text was translated). This leads to this kind of strictly enforced requirements. Other cases, enforcing redundant BE systems, can be the pure nature of the use case defining a high availability of the VPP.

- Many VPP software vendors offer Software-as-a-Service (SaaS) and/or cloud solutions for their products. If the use case allows this option, usually meaning there are company-specific guidelines or legal concerns forbidding this construct, this can be attractive. With this variant no hardware on site is needed and all ICT infrastructure concerns for the BE system are delegated to the external vendor.

Connection to a TCP/IP based communication network, where all DERs, needed PCC communication devices and required external IT systems have access, has to exist. Examples for external data are forecasts, metered power values, and external requests like the activation of control power. Further, external IT structures may be systems at the stakeholders' premises such as SAP systems for accounting and contracting. The same requirements as listed for DERs and grid level can be applied.

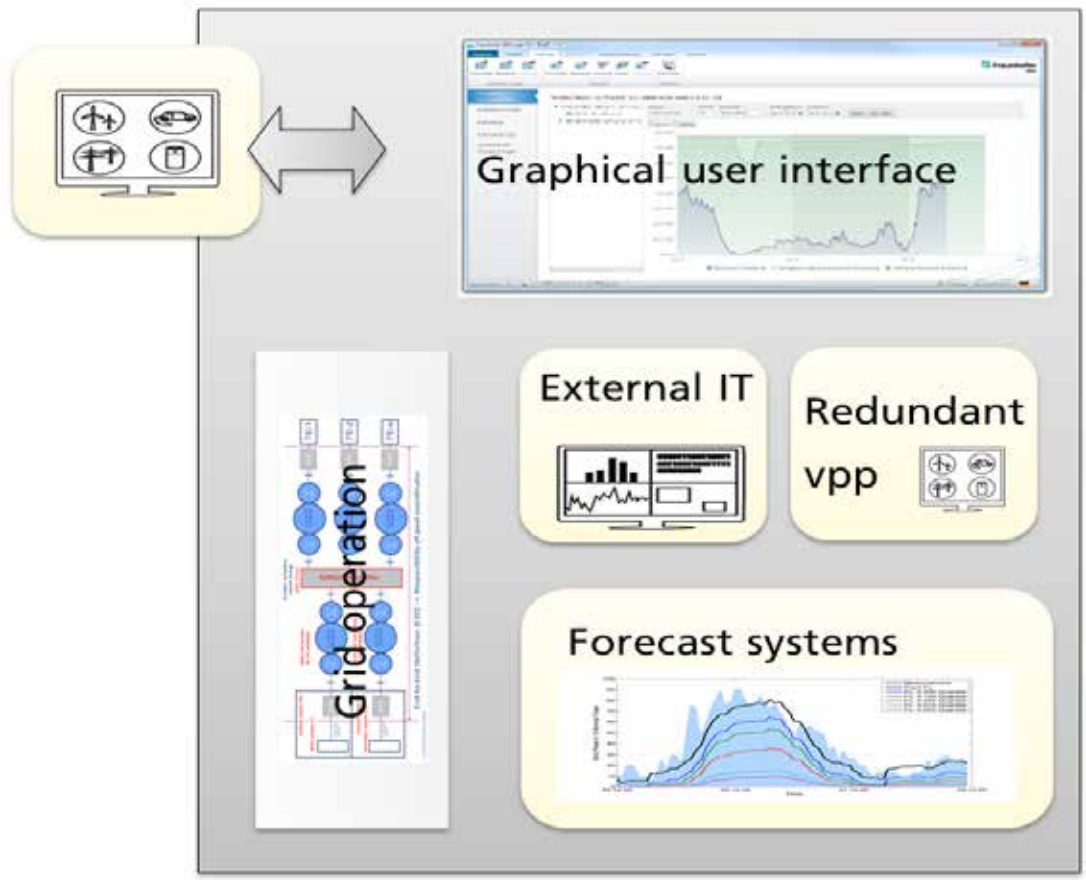


Figure 43: VPP - Connection do external IT systems

Sufficient hardware for the operation of the base VPP FE system is needed. Depending on the use case, a FE might not be necessary. However usually a VPP is shipped with a graphical user interface (GUI), which is considered the FE system. The GUI displays information, which is needed to setup and monitor every plant and the whole portfolio. Secondly, control functionalities are implemented as well as access to optimization tools.

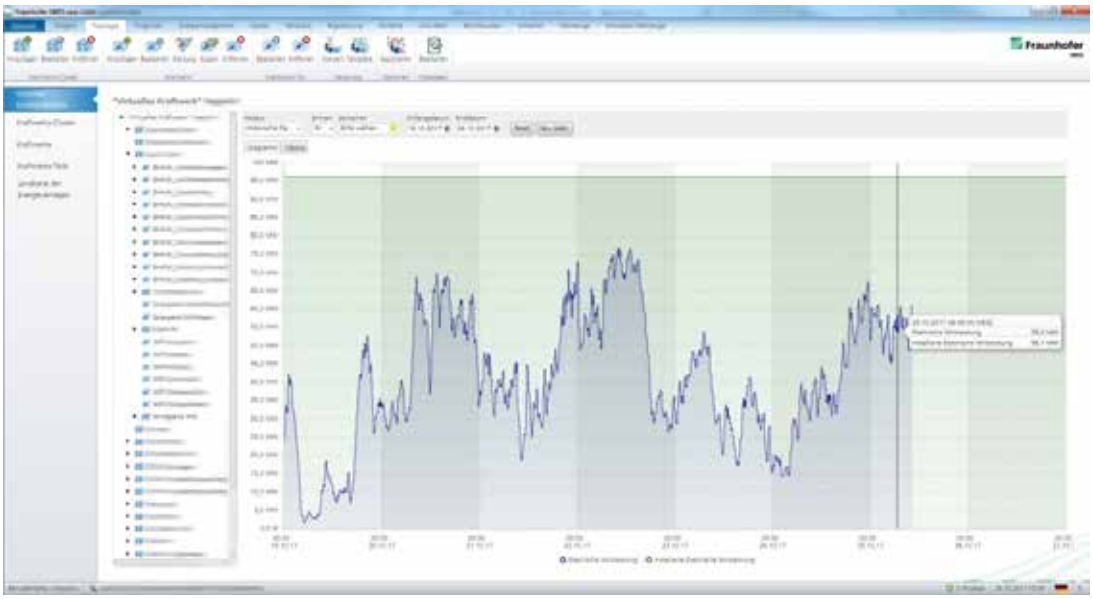


Figure 44: Example of a Graphical User Interface (GUI) of a VPP, source Fraunhofer IEE

Most VPPs are using rich client applications as a FE software because they are historically grown. This means there is a separate software to be installed on each client machine. This client connects to the VPP BE system. An example of hardware requirements or configurations for such a client machine are the following:

- Modern Quad-Core 64Bit-Processor
- > 4 GB RAM
- 1 GB free disk memory for mostly logging purposes
- Installed OS supported (usually MacOS, Linux or Windows)
- Internet access for NTP (Network Time Protocol) time synchronization (UDP Port 123)
- Access to the backend server system via specific TCP port
- Appropriate privileges for installation

Newer VPP software systems bet on web applications as their frontend. This means the frontend is based on HTML and runs in a web browser, for example Chrome, Firefox, Safari or Edge. This has multiple advantages:

- The FE system is kind of OS independent because most web browser are supported for all popular OS (MacOS, Linux or Windows).
- System requirements are only those of the browser.
- No install routine with adequate privileges is necessary because usually a typical client OS has a web browser already installed.

Sufficient hardware for the operation of the base VPP DB system is needed. It is possible to put the database on the same hardware as the VPP BE system. However, usually it is required and recommended to put the database software system to different hardware. Analogous to the considerations of the VPP BE system, the need for redundancy concepts follows the requirements of the use case.

Older VPP systems use SQL databases as Oracle or other vendors. In order to control the amount of data reliably and quickly, modern VPP software solutions use NoSQL databases. For example,

a solid NoSQL database is MongoDB. MongoDB is highly scalable, has transaction support close to conventional SQL databases and has a solid redundancy concept via so-called Replica Sets.

Regarding basic system requirements of a single database server, the same points as listed for the BE system can be referenced, except that, mainly depending on the portfolio size and data resolutions, the free disk memory size should be at least 1 TB or more.

Sufficient hardware for the operation of further IT systems is needed. Depending on the use case, further systems need to run in order to ensure the functioning of the entire system. In order to secure a reliable operation of the VPP, monitoring systems are needed to observe the status of the application and the database. Examples are CheckMK, Grafana via influxDB, ELK (Elasticsearch, Logstash, Kibana) for central logging purposes or database vendor specific monitoring systems.

The same remarks as given for the VPP BE system hold true, the systems mentioned could possibly supplied via SaaS or cloud solutions by an external vendor.

5.2. Organization of human infrastructure

As written in Section 5.1, the ICT infrastructure highly depends on the use case. Therefore, the setup of this infrastructure and the responsibilities of the IT systems define most of the need and the organization of the human infrastructure. Additionally, the use case itself defines the need and type of people working with the VPP system.

To implement, maintain and operate a VPP, different skills are needed. The following main roles are relevant:

- **VPP operators**: A VPP operator is someone that can work with the VPP software with the associated GUI. This is usually some kind of control room staff. For example, these people are able to configure connection data of plants, start optimization runs, edit schedules or answer requests from other stakeholders. A set of VPP operators are required for an operational VPP. The amount of needed VPP operator depends on the use case and the size of needed manual interactions.
- **Connectors**: With connectors, personnel who integrates plant technically in the field is meant. The amount of connectors depends on the use case and maybe zero if the tasks are done by an external service provider.
- **Database administrator:** A database administrator setups and maintains the database of the VPP system. The amount of database admins depends on the use case and maybe zero if the VPP software is used as a SaaS or cloud solution or the task is delegated to a third party.
- **System integrators**: System integrators can maintain software components, data flows, and other associated server structures. System integrators are also able to automate restarts of the VPP BE system or executing restarts as a simple approach fixing certain failures. The amount of system integrators depends on the use case and maybe zero if these tasks are delegated to an external service provider.

Depending on the VPP software vendor and the ability moving more administration and maintenance to the VPP operating institution more human infrastructure and more roles are needed. Further possible roles are software developers for maintaining VPP software components or software developers for PLCs.

5.3. Cost estimations

This section gives a basic overview of expected costs to implement a VPP. The cost estimations are based on existing DERs. This means that the costs for real power plants, their self or other flexibilities are excluded from the considerations. The cost estimations are divided into four sections. First, hardware costs are listed, then software costs are listed. After this, some cost estimations for wind, solar and load forecasts are listed. In the end, further possible development costs are listed.

Hardware

Table 14 tries to give an idea of expected costs related to hardware components for implementing a VPP.

Table 14: Hardware cost estimations for setting up a VPP

Entity	Unit Cost ($)	Amount	Sum ($)	Remarks
Application Server	10,000 – 15,000	0 – 3	0 – 45,000	Fulfilling requirements of the VPP BE system from section 5.1. The amount depends redundancy aspects and if a SaaS solution is chosen.
Database Server	10,000 – 15,000	0 – 3	0 – 45,000	Fulfilling requirements of the VPP BE system from section 5.1. The amount depends redundancy aspects and if a SaaS solution is chosen.
Monitoring Server	4,000 – 6,000	0 – 1	0 – 6,000	Useless if already in place or a SaaS solution is chosen.
Optimizer Server	10,000 – 15,000	0 – 1	0 – 15,000	Useless if no optimizer core (for example for MILP) is needed or a SaaS solution is chosen.
Communication Box	50 – 1,000	N	N*50 – N*1,000	This position depends on the possibility of the usage of the existing communication infrastructure and interfaces. N is defined as the number of DERs that have no remote communication unit at site yet.
Additional hardware at plant level	~ 500	N	~ N*500	Depends on the necessity of further hardware that needs to be installed at the plant site in order to monitor and control. N is defined as the number of DERs that need additional hardware.
Network connection	~ 200 / a	N	~ N*200 / a	Existing internet connection via 3G, LTE, GPRS or DSL can be used depending on the use case, compare section 5.1. N is defined as the number of DERs that need to be integrated but have no internet access yet.

Software

Table 15 tries to give an idea of expected software costs.

Table 15: Software cost estimations for setting up a VPP

Entity	Unit Cost ($)	Amount	Sum ($)	Remarks
Monitoring Software	Free	0 – 1	Free	Useless if already in place or a SaaS solution is chosen. CheckMK would be a free option.
Database	Free	0 – 1	Free	Expected: Open Source Community Version. Example: NoSQL database MongoDB (Non-Enterprise version) is free for usage, see www.mongodb.com. Other databases that ship with the VPP vendor are usually included in the VPP license price.
Optimizer License	0 – 20,000 / a	0 – 1	0 – 20,000 / a	Useless if no optimizer core (for example for MILP) is needed or a SaaS solution is chosen. Price depends on type (for example Gurobi or CPLEX). Also possible to use Open Source Solver, but there are typically performance issues.
VPP License[2]	20,000 – 200,000 / a	1	20,000 – 200,000 /a	Price is use case and VPP provider dependent. The license price can rise significantly if a SaaS solution is selected.

The exact prices for hardware are also dependent on the market and need to be reviewed at the time the investment is seriously taken into account. Costs for software from third parties can vary and depend on the specific third party software provider.

Wind, solar and load forecasting

The following costs (Table 16) are highly dependent on the forecast provider. Further, depending on the forecast provider, the programming expenses might be raised. Moreover, the costs also depend on the quality and type (short-term, day-ahead) of the forecast.

Table 16: Cost estimations for implementing forecasting module in a VPP

Entity	Expected Costs per installed MW ($)	Remarks
Wind Forecast	50 - 1000 / a	**Optional**, if there are existing forecasts.
PV Forecast	50 - 1000 / a	**Optional**, if there are existing forecasts.
Load Forecast	25 - 500 / a	**Optional**, if there are existing forecasts.

Usually the costs are based on installed capacity. However, there are also forecast provider were the price is dependent on the amount of plants. Furthermore, there exist price models with an initial payment besides the cyclic payment.

Cost of development of software: algorithms, programs and control features

Table 17 lists implementation costs that could be necessary for the integration of the VPP.

Table 17: Estimated Cost for VPP integration

Entity	Tentative Unit Cost ($)	Amount	Sum ($)	Remarks
Interface Driver	0 – 10,000	N	0 – N*10,000	This depends on the amount of needed interface drivers, which are not yet supported by the base VPP software. N is defined as the number of such new interface drivers. It should be noted that there are VPP license models where this effort is directly included in the license costs itself.
Integration forecast provider	0 – 20,000	0 – 1	0 – 20,000	This depends on the type of forecast provider. If the integration of the specific forecast provider into the VPP software solution is already implemented, it therefore implicates no additional costs. It should be noted that there are VPP license models where this effort is directly included in the license costs itself.
Programming at PLC control level	0 – 500	N	0 – N*500	In order to be able to retrieve all necessary data, further programming expenses might be required. N is defined as the number of DERs where such expenses are need.

Total costs for a VPP implementation

As described in the previous paragraphs the costs for an operational VPP depends on a high number of influencing factors. These factors are mainly requirements from the concrete use case, amount of integrated DERs, existing hardware, software and other devices. However, the costs for a VPP implementation can be split up in an amount of total initial costs and an amount of regular, usually yearly costs.

The initial costs mainly consist of hardware and infrastructure acquisitions or custom software developments needed for the use case. The yearly costs primarily consist of license, support, operational and other regular costs to keep the VPP running.

The initial costs can be omitted but can also go as high as multiple 100.000 $. The possible cost range holds also true for the yearly costs. For a medium sized VPP with medium support with aggregated control functionality, costs in the range of 20.000 $ – 300.000 $ can be expected.

5.4. Active VPP Solution Providers

Considering the changing power scenario and requirement of a RE-supporting technology, many firms are now venturing into VPP and are providing VPP solutions to various customers. Solution providers are now providing custom made VPP solution depending on the form of renewable energy to be aggregated, type of consumer, and the desired end-use/application of VPP.

Table 18 shows few of the VPP Solution Providers, who are providing VPP solution as a whole, and are operating in different parts of the world and performing tasks like – connecting and monitoring assets, data visualization, data processing, optimization of asset operation, operating central control system, etc.

Table 18: Few companies providing end-to-end VPP Solution

1. Next Kraftwerke	NEMOCS™
2. AutoGrid	AutoGrid VPP™
3. ABB	ABB Ability™
4. GreenSync	GreenSync VPP™
5. Limejump	Various Products: The Balancing Mechanism (BM) ™, Frequency Response – FR ™, The Capacity Market – CM ™
6. cyberGRID	cyberNOC™
7. Enbala	Concerto™
8. Schneider Electric	EcoStruxure™
9. Siemens	Decentralized Energy Management System™
10. EnergyHub	Mercury Distributed Energy Resources Management System™
11. REstore	FlexPond™
12. Opus One Solutions	GridOS™
13. GE	Advanced Distribution Management Solutions™
14. Lockheed Martin	Smart Energy Enterprise Suite (SEEsuite)™
15. Spirae	Spirae Wave™
16. Smarter Grid Solutions	Active Network Management™
17. Itron	
18. OATI	OATI webSmartEnergy™ Distributed Energy Resource Management System
19. Indra (ACS)	Centrix DERMS™
20. Doosan GridTech	Intelligent Controller (IC)™ and DER Optimizer (DERO)™
21. Energy & Meteo systems	The Virtual Power Plant Software

06

6. Way forward

6.1. Summary

Focus of this report is to show the relevance of virtual power plants in India. India is currently witnessing changes in its energy system. Decentralized energy resources are increasing, and growth of fossil fuel based centralized resources is decreasing. Renewable sources are penetrating deep into the Indian power system. A transition is also being seen from static system to dynamic (intelligent) system, which can respond to the real-time conditions of the grid. Section 1 of the report brings out facts and figures regarding similar transitions and the challenges which are currently being faced by the Indian power system due to these energy transitions.

Addressing these changes require a technology (or rather a solution) which can control the variability of RE and DER. Section 2 of report introduces one of the plausible solutions – VPP. To give a clear understanding of the subject, the concept of VPP is introduced and discussion on the technology is done in detail. The section also takes the reader through global scenario of VPP, various types of VPP implemented across globe and their use cases.

Section 3 of the report is entirely focused on German experience of VPP. The section gives an introduction of various business models and use cases implemented in Germany which have benefited different grid participants.

Section 4 brings out learning from case studies which are discussed in the previous two sections. These learnings have been used for exploring opportunity for VPP in Indian market. The section explores various developments happening in the Indian power market, making VPP more and more relevant for India. The section also analyses various regulations existing in India, which have already established a precedent for VPP implementation. Based on the global experience, various VPP configurations (both at grid and off-grid level) have been identified for India along with their suitable use-cases. To identify business cases for VPP and to trigger a discussion in the market, illustrative example has been taken to explore deviation settlement penalty as an opportunity for VPP in India. This analysis will give stakeholders a brief idea of the factors affecting VPP and its feasibility. A list of various actors and a brief on concept of operation has also been provided to help readers understand the concept extensively.

Section 5 of the report brings out the procedure for implementing and setting up a VPP, which is based on the experience of already existing VPPs in Germany. A rough estimate of cost required for installing VPP and ICT infrastructure has also been provided in the report.

The following section provides few recommendations to the players who are interested in implementing VPP in India. Through implementation of these measures, it is expected that the VPP sector in India will gain momentum and uptake of this technology will increase.

6.2. Recommendations

As discussed in Section 1, energy system architecture of India is changing and there is an urgent need to implement solution like VPP to cater to the changes. Figure 45 proposes few recommendations for Indian market, which will help in increasing penetration of VPP in India.

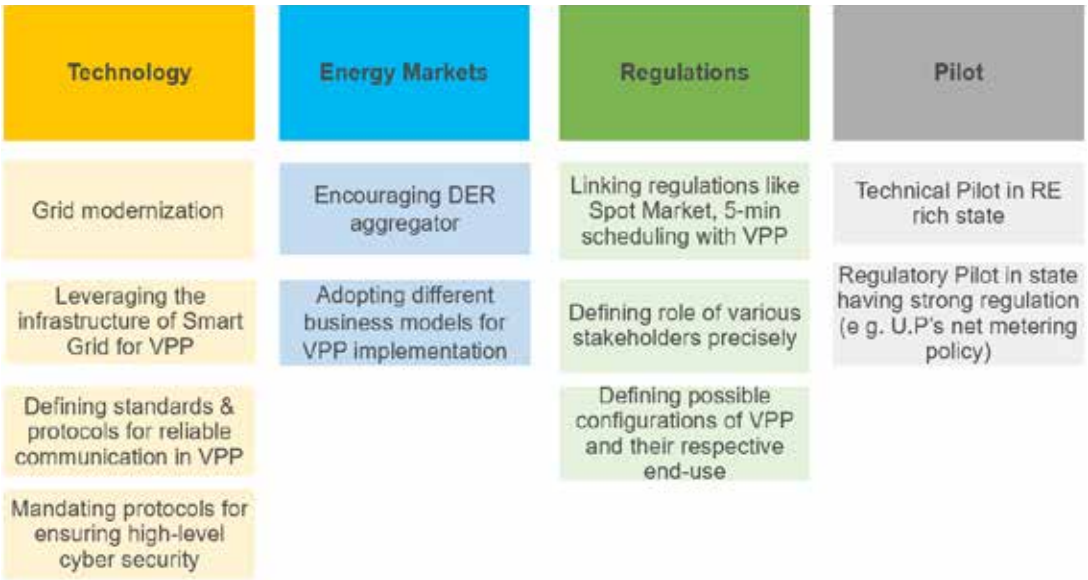


Figure 45: Recommendations to increase uptake of VPP in India

To understand all the aspects of this technology, India should begin with implementation of pilots at various scale and at various locations. The proof of concept needs to be designed and implemented to weigh the feasibility and understand the system functionalities – both at technical level and regulatory level.

Technical Pilots can be introduced in the RE rich states like Andhra Pradesh, Gujarat, Tamil Nadu, etc. to analyse the various technical concepts and benefits, which VPP may provide to grid. The pilot can be used to study the impact of VPP in grid congestion, frequency and voltage management, etc. Similarly, **Regulatory Pilots** can be introduced in states which already have provisions that lay the groundwork for implementing VPPs. For instance, Uttar Pradesh's net metering policy already talks about peer-to-peer transaction with proper accounting and billing mechanism. This will help in implementation of VPP at a larger and faster pace in the state. Various configurations of VPP can be tested in such pilots, and feasibility of each configuration can then be identified. In few states like Tamil Nadu, Andhra Pradesh and Gujarat, a precedent for VPPs have already been established with the requirement of a Qualified Coordinating Agency (QCA) in the state-level forecasting & scheduling regulations. QCAs can be involved in these pilots as VPP operator.

With active participation of DER installers in regular network operation, the demand for defined end-use in the grid code will increase. Alongside, role of each stakeholder will have to be defined precisely before deciding on a VPP configuration. In terms of technology, currently there is no standard interface for communication between generators, pooling stations, substations, load dispatch centers, and loads in India. This pose several challenges in streamlining connection between these elements and facilitating free flow of information along the value chain. Hence, standards and protocols are required to facilitate reliable communication in a VPP, and also for ensuring cyber security.

Remodeling of the energy market is also required to boost VPP implementation. DER aggregators need to increase and need to be responsible for coordinating between RE generator and Discoms/ LDCs/ Transcos. This is where role of QCAs will come into effect. In addition, business models supporting various VPP configurations will have to be proposed for successful implementation of VPP.

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Annexure-1

German power grid

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 [46]. In the year 2015 around 628.8 TWh of net energy was transported [46]. Responsible for the transport on the transmission level are the following four transmission system operators (TSOs), wo are responsible for their own control area (Figure 46):

- TenneT (green)
- 50Hertz Transmission (orange)
- Amprion (red)
- Transnet BW (blue)

Figure 46: Map of the German network operators at high voltage in February 2017 [55]

On the distribution level the market concentration is less developed. Here 875 distribution system operators (DSOs), the most diverse market in the European Union, are responsible to supply their end users [46]. However, most of them, 798, have less than 100,000 connected consumers and are owned by municipalities [46]. The remaining greater ones are mostly owned by the big four energy players in Germany: RWE, E.ON, Vattenfall and EnBW. Their market share was 76.2 % without taking into account subsidized generated renewable energy [46]. These four companies are also called CR 4, the concentration ratio of the German energy economy.

To transport the energy in Germany four different levels of voltage are used by TSOs and DSOs:

- In the transmission grid: Connection of large conventional power plants, cross border connections and offshore wind farms
- Only 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

German ancillary services

To operate a power system in a safe manner so-called ancillary service are required. They "include maintaining frequency and voltage stability, the restoration of supply and system operations such as grid congestion management" [31]. Beginning with the most important one regarding costs and complexity - the frequency stability. Besides several regulations and directives, like the grid codes, that mandate generators to support the power system under specific conditions like over-frequency when the active power feed-in of distributed energy resources (DERs) is reduced constantly at a system frequency of 50.2 Hz. In Germany, three types of control reserve exist, as described in Table 19.

The other criterion of power system stability is voltage stability. Resulting from its local influence, TSOs and DSOs are responsible to keep the voltage within nominal range at all times. Typically, conventional synchronous generators and network equipment, as reactive power compensators or tap-changing transformers, allow a secure supply of power. Nevertheless, DERs are mandated by grid codes to support the voltage by feeding-in reactive power in dependence of the current voltage level or to be capable of a fault-ride-through during a voltage droop.

With regard to black start capabilities, TSOs are currently responsible to restart the grid from the transmission level down to the distributional level within their control area. Their main instruments are bilateral agreements with large conventional power plants, equipped with backup power supply, and pumped-hydro storages, as well as established communication channels with DSOs to reconnect their distribution networks in a reasonable order.

Table 19: "Comparison of the three types of control reserve" (based on table 11 in Knorr, et al., 2014)

	PCR	SCR	TCR
Minimum offer	+/- 1 MW	5 MW	5 MW
Pooling	Yes, within control area	Yes, within control area	Yes, within control area
Tendering period	1 week	1 week	Daily, except weekends and public holidays
Product length	1 week	High tariff of 12 hours (08:00 - 20:00 weekdays, otherwise low tariff)	6 daily blocks of 4 hours beginning at 00:00
Remuneration principles	capacity price	capacity and energy price	capacity and energy price
Auction criteria	lowest capacity price	lowest capacity price	lowest capacity price
Activation speed	30 seconds	5 minutes	7.5 to 15 minutes
Dispatch	De-centrally via frequency measurement	Signal from central network controller	Demand from TSO

The last ancillary service in Germany is congestion management. TSOs are allowed to redispatch power plants at specific grid nodes to overcome grid restrictions that would occur if the plants would follow their pre-defined schedule according to their market activities. These adaptations of the plants' schedules will be financially compensated and charged to the grid users. In the case of distribution grids, a pro-active approach is currently not implemented due to insufficient data, e.g. of detailed DERs' schedules

or forecasts, available to a DSO. As a result, a DSO can only ramp down remotely controllable DERs if a congestion situation is appearing and recognized by the DSO.

German electricity market

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

For procuring the process of energy trading energy exchanges, like the European Power Exchange (EPEX) or Nord Pool, provide trading platforms for different channels of trading. Primarily there is the transparent wholesale electricity market that is centrally organized at the different power exchanges. It provides multiple standardized products, which can be traded anonymously [47]:

- The "future market", it allows long-term products to be concluded years before the agreed period of delivery. Its most popular product is the "baseload future", an hourly delivery for a specific full year.
- The next one, ending one day previously to delivery, similar to the future market, called the "day-ahead market", is characterized by the highest liquidity, meaning highest trading volume and the greatest number of participants. Energy is traded here for each hour of the corresponding day of delivery. Thereby are day-ahead forecasts of demand and generation the main source of information for traders.
- For the period just before market closure, the end of trading before delivery, trading parties can participate in the "intra-day market". It is a continuous market of 15 minutes products to e.g. adjust their 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 [47]. At this market, bilateral agreements of power delivery are negotiated. It typically takes action at power exchanges as well, where brokers procure the trading process between the parties. The price level of OTC trading is usually orientated to the transparent power exchange prices.

In the context of renewable energies and their market integration, the German instrument of direct marketing should be recognized. Since the German Renewable Energy Source Act of 2014 (RES Act, "Erneuerbare-Energien-Gesetz – EEG") all DERs must directly sell their produced energy in the power market instead of only receiving a fixed feed-in-tariff like before (RES Act 2014). 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") the band-width 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 DER operator to assign a market aggregator for trading the generated power on its behalf.

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