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# Virtual Power Plants – general review: structure, application and optimization☆

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**Abstract**

The article presents information about Virtual Power Plants (VPP). Numerous papers have drawn attention to the new concept of generation and management of energy. The VPP concept underpins the growing number of installed Renewable Energy Sources (RES). The concept of smart controlled Distributed Energy Resources (DER) merits consideration. This article is a review of some VPP ideas and gives insight into and a general overview of VPP. Some VPP structure and control methods are described, test fields of VPP are presented and it ends with a short conclusion about VPP.

*Keywords:* Virtual Power Plant, VPP

## 1. Introduction

The Virtual Power Plant is quite a new concept. The VPP idea was born a few years ago and has a couple of advantages working in its favor. The main concept is based on a centralized control structure which connects, controls and visualizes a work of distributed generators. Combined heat and power generators (CHP), fuel cells (FC), photo voltaics (PV), heat pumps (HP), solar collectors and any other sources of power and heat might be aggregated and cooperate together in the local area. This is a good solution for harnessing Renewable Energy Sources (RES). At present RES have problems hooking up to power networks. This happens because of a lack of transmission capacity in the power network for RES. Further complicating matters is the irregular schedule that some RES work to: wind turbines for instance are obviously wind-dependent. This causes serious problems to the Transmission System Operator (TSO). RES might be suitable for installation on household sites. Capacity of thousands or millions of watts in such RES might eventually rival the capacity which is now installed in wind power plants etc.

VPP provides an opportunity to lower the load in the power network. More power is generated locally and is shared by participants without needing to transmit it over long distances at high tension. Therefore one energy loss factor is either minimized or eliminated. VPP causes a sea-change in energy relations. The participant is no longer merely a passive user. Being a part of VPP means everyone involved can influence the power system in an active way, although naturally only to a certain extent: it does not mean that participants are responsible for switching

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devices on and off.

Heading the VPP is a computer system controlled by the Distribution System Operator (DSO). This could be organized on the basis of an artificial neural network. In fact, a VPP could be supported by any household which has as little as 1 kW capacity in a generator such a PV, FC, CHP etc. In VPP irrespective of how much generation capacity is installed in a single building, the most important feature is connecting all the sources together and running them so as to obtain a state of self-balance in the most effective way. VPP places more attention on local generation, meaning that central generation can operate in more stable conditions. All peaks of heat and power demands can be more easily optimized by DSOs. Storage of heat or electricity should be used as well. This will help to achieve appropriate conditions of VPP work.

## 2. Main concept

The term Distributed Energy Resource (DER) comprises Distributed Generation (DG), Energy Storage and even Electric Vehicles.

If DER can cope with electricity peaks, it is possible to use power capacity to generate additional energy off-peak. This energy can then be sold on the energy market. DERs can be grouped and managed by a central unit, thereby becoming visible on the energy market. And it is open to any type of generation technology.

The main focus points within VPP research have been:

- feasibility of DER market participation;
- VPP control and coordination optimization;
- design of VPP and power system.

### *2.1. Structures of VPP*

Three different approaches to VPP can be used:

- CCVPP (Centralized Controlled Virtual Power Plant)—Fig. 1—in this design all control logic lies with the VPP and all knowledge about the market and the planning of production is separated from the DER. The advantage of this design is that the VPP is given a simple way of utilizing the DERs to meet market demand.

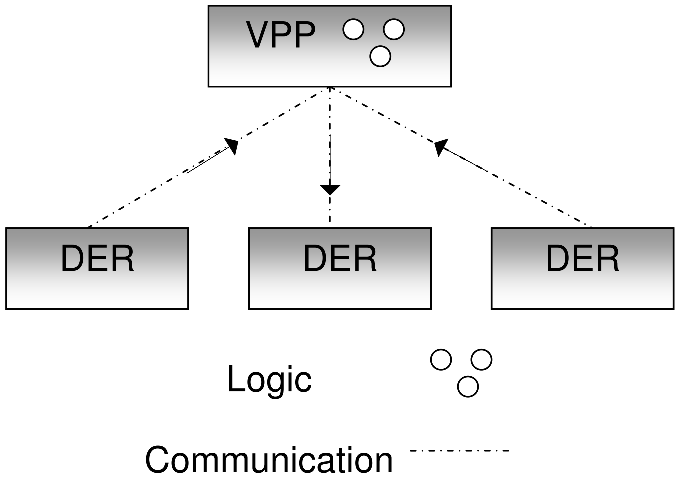


Figure 1: The CCVPP Design, after [1]

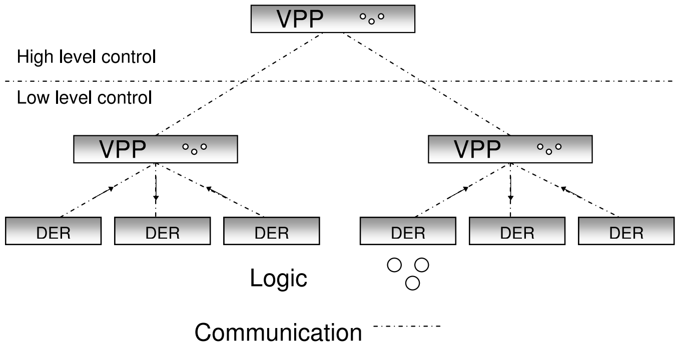


Figure 2: The DCVPP Design, after [1]

- DCVPP (Distributed Controlled Virtual Power Plant)—Fig. 2—DCVPP introduces a hierarchical model by defining VPPs on different levels. A local VPP supervises and coordinates a limited number of DERs while delegating certain decisions upwards to a higher level VPP. This design can help simplify the responsibilities and communication of the individual VPPs.
- FDCVPP (Fully Distributed Controlled Virtual Power Plant)—each DER acts as an independent and intelligent agent which participates in and reacts to the state of the power system and market. This design holds much promise as regards supplying a dynamic and optimized power system.

### *2.2. Examples of VPP usage*

The most significant European projects that in some way use the concept of VPP and integrated DER:

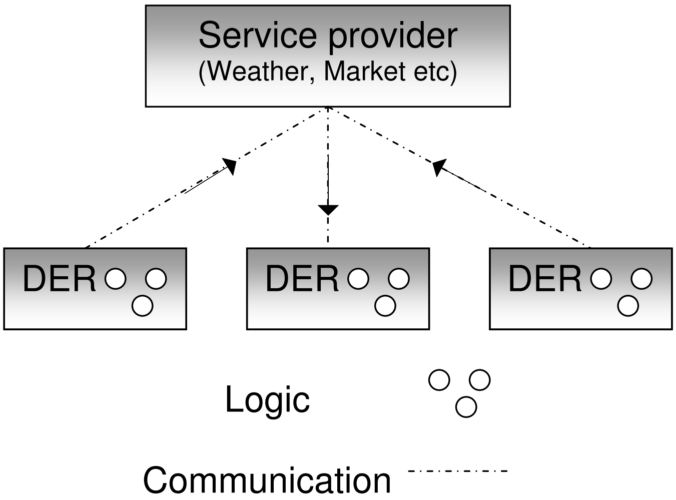


Figure 3: The FDCVPP Design, after [1]

- SmartGrid;
- FenixProject—the goal of the project is to move away from traditional management of small units in a power system. Thus, the 'fit and forget' principle must be rejected. Through the FenixProject all sources will be integrated in an active way with the system. The new approach should be used for every kind of DER unit. The FenixProject tests two types of VPP: commercial and technical.
- Ecogrid Project—introduces the concept of the Distributed Energy Market (DEM). The main purpose of DEM is to put the end-user at the center of the power market and provide the system operator with the most cost effective solutions for system management. An example of this is functioning on the island of Bornholm.

### *2.3. Challenges for VPP implementation*

Many different approaches have been taken to implementation and VPP control. Each has had to cope with some challenges:

- loose coupling—the production unit owner should be able to freely choose the VPP with which he would like to be grouped. The VPP group of members is not static.
- generic adoption—communication between the DER units and VPP operator must be standardized. Only one standard can be allowed and an information package must be determined.
- interchangeable strategies—the behavior exhibited by a production unit should change depending on the choice made by the unit's owner or VPP operator.
- security and robustness—the system must be protected from external dangers and must have a procedure for operating in the event of lost communication.

Proposal solutions:

- loose coupling solution—the 'match maker' module will be introduced. All information about the DER unit will be entered in the database of that module. It will be responsible for searching for connections with possible VPP operators. In the next step, after choosing a VPP, the match maker sets up a connection between a VPP and the unit.
- generic adoption solution—all exchange of data should be made according to one standard. XML is a proposal for this task.
- interchangeable strategies solution—the system has to react in a quick and efficient way so as to dynamically change behavior to fit the situation. It must be possible for the VPP operator, for instance, to change the strategy or logic of a production unit.
- security solution—the security standards and specifications for web services must be defined. In the case of a lost connection between the DER unit and VPP operator, the DER unit connects with 'Match Maker' to gain information about new, achievable connection with the operator of another VPP. Then the connection is established in a dynamic way.

## 3. VPP review

### *3.1. European Union 5th Framework Programme*

In [2] a project is presented that was realized under the EU's 5th Framework Programme. The aim was to develop the VPP concept, to implement and test it and show the results. Under consideration was whether fuel cells as DER for VPP could be installed at household locations. 31 stand-alone residential fuel cell systems were installed. Each unit had 4.6 $kW_{el}$ and 9 $kW_{th}$. An Energy Manager was set up to control the whole system. This module was responsible for benefits for end-users and grid pursuer. A Central Control System (CCS) was created to manage all the fuel cell systems. CCS communicated with the on-site Energy Manager and allowed the utilities to control the micro CHPs in terms of peak demand and defined load profiles. Wireless transmission standards, GSM and radio ripple control receivers were used for communication purposes. The project was successful. The whole system was stable. There were no emergency cases involving units being turned off. Fuel efficiencies of up to 90% were achieved was (with 30% electrical efficiencies).

The low temperature PEM fuel cell system worked for 138 000 hours. In that time ca. 400 MWh of electricity were generated. More than 50 million measurements of data were taken and analyzed. The system was tested to check how VPP delivers electricity supplies. The results demonstrated that there was no latency time in delivery. There are some problems which have to be solved before developing this type of system for the mass market:

- costs must be reduced significantly to increase the technology's economic viability;
- the system must be simplified to improve reliability;
- the temperature of the heat output must be increased to become compatible with existing heating systems, and to give opportunities for tri-generation.

The total cost of the project was EUR 8.3 million.

The fuel cell system comprised a fuel cell battery, peak heat boiler, hot water tank and control module. An Energy Manager controlled the whole system. The primary aim of the Energy Manager was to supply heat energy to meet heat demand in buildings. To do this, it communicated with the CHP system in household sites and controlled the fuel cell, boiler and hydraulic system. The MicroCHP was fed by natural gas. Heat was consumed on site and the electricity first went to the inverter where DC current was transformed into AC current and then the electricity was supplied to the building's main network.

### *3.2. EDISON Project*

The EDISON Project [3] aims to integrate an electric vehicle fleet with the power system. The integration is realized by VPP. RES cause problems with balancing in the power system. To this end a comprehensive solution must be developed. Electric vehicles can be treated as energy storage units. The first issue is to draw up a schedule for charging electric vehicles. This must factor in all boundary constraints of the system and aim to minimize costs. To solve this problem a special platform must be developed. It will be coordinated with the power system and energy market to gain all necessary information. RES will be taken into consideration as well. The comprehensive system must supply energy to all electric vehicles immediately. All boundary constraints of the electric distribution network must be taken into consideration. The platform described above will be located on the island of Bornholm. Every electric vehicle in every location on the island can be linked with the power system via VPP. A simulation was performed to gauge the influence of a fleet of electric vehicles on the local electric distribution network. One aspect which differentiates the EDISON Project VPP from other VPP is the common usage of electric vehicles as active energy storage units. Most VPPs concentrate only on intelligent management of generation units. Two possible ways of implementation are considered. In the first one, VPP will be integrated as part of the power system. In the second one, VPP will be a new system that cooperates with the existing power system. In the second approach VPP will be a new subject on market. If VPP is introduced with the power system as is being considered, then it will stay part of the power company. VPP will provide balancing tasks as Balancing Responsible Party (BPR). VPP might be a perfect tool to smooth the boundary between demand and supply. Standalone VPP architecture is an alternative to the above. There VPP is BRP too. But it is independent and works as every other member of the market.

It buys and sells energy based on the collected data and state of each generation unit. The most important task is to create balancing schedules. VPP of EDISON Project contains 3 main modules:

- control module for each DER;
- data collecting module;
- connection, cooperation and communication module.

Each of the above modules contains other modules. For standalone VPP architecture the whole system is more complicated than if VPP is integrated in the existing power system structure as part of a power company. Bornholm was chosen as test field for VPP. 52 DER units are located around the island and 35 of them are wind turbines. It is good place to test such a system operating in island mode. 27 000 consumers of electricity are on the island. Total capacity is 135 MW and maximum load is 55 MW. The EDISON Project checks how electric vehicles can cope with wind farm generation. The potential exists to have active management of electric cars without any disruption to car owners. A simulation was performed based on a model of the power network of the island. This might be done using commercial software of Matlab/Simulin/Powersin or DigSilent's PowerFactory, which simulate and analyze transmission or distribution networks, power sources and consumers. The model can be used for data management, prediction and optimization of the operation of the whole system. With the present model it is possible to simulate energy flow in a power network dependent on electric car movement. All calculations are made with 15-minute intervals. The calculations are used to make an energy flow map. This can be used to determine where the network and transformers are overloaded. Generated energy and consumption are balanced by regulating wind turbines and power plants. Further work will be dedicated to two problems:

- prediction—electricity demands must be predicted in order to create a schedule of power source generation. Charging electric cars is another issue. Wind conditions must be predicted using weather forecasts and historic data. All these tasks require solutions and better models for improved results.
- optimization—various objective functions can be optimized, i.e. costs, power balancing in the case of intermittent operation of RES units and power supply for electric vehicles. Optimization must be developed to achieve a better global optimum based on local optimums.

### *3.3. Konwers 2010*

Basic requirements and experience with regards to VPP are set out in paper [4]. Increasing reliance on RES causes more problems in terms of balancing. RES depend strong on weather conditions. CHP operations too are driven based on heat demands which are determined largely by weather conditions. Liquidating the reserve power of central power sources is justified from an economic point of view. This reserve is used to compensate for a lack of power in the power network resulting from unpredictable RES generation. It is more sensible to transfer a balancing task to a different level of structure. This structure should contain different types of DERs, energy storage units and demand control facilities. It can all be clustered into VPP structure which can perform as system power plant. The operations of each unit can be scheduled in advance. A distributed energy management system (DEMS) supervises the whole system, taking into consideration all boundary conditions.

All these tasks can be performed because of innovative data transfer methods, communication and remote control which together can monitor a large number of distributed energy sources. VPP controls all energy flows in the system and factors in the weather forecast.

Modern power systems are based on the centralized generation of electricity and/or heat energy. However, global trends are heading toward increasing numbers of distributed generators. This means the management process has to adapt to the presence of distributed generators and their unique method of operation. The power system has to cope with unpredictable conditions of operating DG. Therefore, an innovative approach to management of the power system is demanded. The rise in and penetration of

RES is a challenge. The new approach to management must be cost effective, economic and provide a stable operating system. The balancing process in some areas can be taken over by VPP. VPP will operate based on schedules made in offline mode. VPP will supervise the schedule realization of each DER in online mode. VPP can be integrated vertically or horizontally. One VPP system can be a part of another, bigger VPP system. It is possible to connect many VPPs to the existing power system. As can be seen, VPP architecture is a very flexible structure. This is one of VPP's biggest advantages. The basic functionality of a VPP is provided by DEMS. The DEMS system performs generation, storage and load management. The main goal of the DEMS system is to achieve a win-win situation in the power system, meaning that it will benefit both the power system and the customers.

#### *3.3.1. VPP—operating description*

Renewable generation and electrical and thermal demand within the supply area is forecasted for each 15-minute billing period by offline modules of DEMS. Based on this, the operating schedule for each DER unit is made for each 15-minute period. All schedules are made 1–3 days in advance. Only units with a certain share on the maximum power of the VPP are considered. Small units and non-controllable units are only forecasted. It should be borne in mind that VPP can be optimized in several ways. The control of scheduled operation is made in online mode. Unplanned power fluctuations and deviations from the schedule require rapid adjustment of the real power flow within the individual period by dispatching controllable generation, storage units and demand in a one-minute time interval.

Additional reserve strategies must be provided to cope with unavoidable prediction errors. It will cover the reserve power locally with all technical constraints. The system must stay very simple, compatible and complete. An emergency situation should not eliminate the operation of the whole VPP. In paper [4] is described Konwers 2010 project. VPP includes CHP fired with biomass, wind turbines, solar plant and conventional power plants. All have to supply households, industry, hotels and offices. The main part of the electricity and heat demand is covered by DERs of VPP. If electricity production is insufficient, then extra electricity will be delivered to the VPP from external sources. Connection to the external power network is necessary. The Kalman filter was used to supply predictions of electricity and heat demand. The algorithm uses historical data—solar exposure, temperature and calendar data as well. Mean absolute deviation varies between 6–14% depending on the type of load. It must be noted that this filter is very sensitive to changes in system structure. New units cause increasing error. Prediction of RES generation is performed on the basis of weather forecasts, but its accuracy is very low with a mean absolute deviation of 40%.

### *3.4. FENIX Project European project FENIX—Northern and Southern Scenarios*

In Europe VPP is considered as a new approach to meeting power demand. Two concepts of VPP—Technical VPP (TVPP) and Commercial VPP (CVPP) are developed in the project. TVPP is a concept of aggregated generators which are located in the same geographic area. DSO is given the real-time local demands of capacity. Those demands can be covered by DER. Moreover, the cost and operating characteristics of each generator are given too. In other words, TVPP is a local power management system which gives detailed information about all aspects of the local system. CVPP has functions which contain information about the costs and characteristics of distributed power sources. CVPP does not deal with the technical delivery of loads. It is a system which enables trading in the energy market and the balancing of trading. TVPP and CVPP do not have to be the same system. TVPP can contain more than one CVPP in FENIX. VPP were implemented in two networks. The first of them was the real power network of Iberdrola in Spain (Southern Scenario) and the second was the EDF Energy network in the UK (Northern Scenario).

#### *3.4.1. Northern Scenario*

The Northern Scenario concentrates on the usage of CVPP. It is dedicated to small scale generation: in households and municipal facilities (i.e. civic centers, conference centers etc.). The main parts of the devices are CHP and PV, connected to a low voltage network. But medium scale devices take part in the test too. The aim of the VPP tests was to prove that it is possible to use the VPP concept in the present-day network. The idea was to check if loads can be controlled for short periods of time. The VPP system contains a couple of different structures to fulfill different tasks. The first are generators. Without them it is impossible to deliver the VPP concept. Next are control boxes. They provide the data-gathering. All generators in the structure tree are visible in the control box system. The system gathers information about the actual generation level, demands and control flexibility. The data are sent to DEMS hosted by DSO and then to CVPP. The solution is prepared in response to incoming information and is then sent to generators as returned data. The answer contains information about the best generation level from the aggregated devices in the context of the actual situation on the energy market. Consideration has been given to involving the DSO as an active participant of the network in the future development of VPP. The DSO will have more rights to control and to act in all VPP processes. The main advantage of the system at hand is the near real-time visibility of generation and demand in the area where VPP is installed. It should not be forgotten that another important value is the visibility of flexibility as regards all elements which are aggregated in the main layer of VPP—from generators to the distributed network.

#### *3.4.2. Southern Scenario*

In contrast to the Northern Scenario, the Southern Scenario focuses on generators which are connected to a medium voltage network. They might serve as an ancillary service to DSOs and TSOs. In the network at hand DER 12 capacity of about 170 MVA is installed, which determines about 35% of all capacity linked to this medium voltage network. The VPP works as a parallel control system and is operated by DSO. There is no interference in real network movement. All information about the network is downloaded in real-time from a SCADA system. In this system no difference exists between DEMS and CVPP. DEMS is the same as CVPP. Data are exchanged between CVPP module and control boxes by the GPRS network. VPP was used to show its usefulness in: Voltage Control—support for maintaining a determined voltage level by providing reactive power to the network; Network Contingencies—generators available to work just in case; Tertiary Reserve—power reserves that can be put into the network within 15 minutes and help to cope with imbalances; Participation in the Day Ahead Energy Market. As previously, distributed generators can be used as part of the energy market. Each unit reports their state of availability and current level of work and creates a bid. All information is collected and sent to CVPP. CVPP processes the received data, makes one common bid and submits it to the energy market. After the trading session the returned information is delivered to CVPP, which divides it into single bids and informs the DSOs. The DSOs receive information about the assigned capacity output and a work schedule for each generator. Then every DSO has to make a decision about accepting or rejecting each bid in terms of technical feasibility. The results of this validation from all DSOs are sent back to CVPP system which hands it over to TSO. The TSO has full information about the work schedule of each generator. As a result, aside from the traditional balancing procedure, a new participant of the transmission network has been created. This manner of cooperation between DSOs, TSO and other participants of energy markets is well known in energy systems in many countries. The difference is the possibility to earn money from the hundreds and thousand of units which operate in the VPP structure. It benefits from the rule that the bigger you are, the more you can do. The Southern Scenario delivers experience in this field. It shows that the energy market is a place where VPP can be used in a commercial way.

### *3.5. 'Smart' Heat Pumps*

The increasing capacity of wind farms causes problems with balancing generation and demand. There is self-evidently little ability to affect generation. On the other hand, demand can be used as a factor to cope with problems of surplus capacity in the network. Demand might be shaped in an appropriate way to meet available generation. This is the main idea behind using heat pumps in the energy system. 'Smart' heat pumps can help to balance generation and demand and to manage network congestion. The role of heat pumps in the distribution network might be enhanced through active participation in the energy market. The smart heat pumps idea is being considered in a few countries, i.e. Germany, Switzerland and Denmark. A description of the smart program is set out below.

*Germany.* Vattenfall Europe launched VPP in Berlin. VPP controls the operation of CHPs and heat pumps which are aggregated in VPP. In Germany the whole concept is based on energy prices in the energy market. Currently, the whole system contains only 30 heat pumps and CHP in total—20 HP (with heat capacity of <25 $kW_{th}$ each) and 10 CHP. The capacity is 30 MW and the goal is to reach 500 MW by the end of 2011. The system is a response to increasing unpredictability due to more and more wind generation capacity. This causes sudden energy price fluctuations on the energy market. This can be reduced by using heat pumps. When the energy price is low, the heat pumps are turned on. When the price is high then CHPs are turned on and generate surplus power. The whole process is controlled by a Vattenfall control center. The VPP structure in Germany is simple. There are units which generate power or heat. Their operating schedule is mainly dependent on the profile of heat and power demands of customers. These units have a communication module which sends information about demand. All units are aggregated by VPP. VPP gathers all information flows from units and processes them. Everything is passed to the control center to ensure quality service and control. After correlation with energy prices taken from the day-ahead market, the control center generates a dispatch schedule for each HP and CHP for the following day. The report is then sent to the units. There is two-way communication between the units and control center. The aim is to achieve an optimized system which meets all demand and is able to generate extra income while saving energy.

*The Netherlands.* The usage of household microCHPs was described in [5]. Those microCHPs can be used as sources of electricity and heat for local demand. 10 units were clustered in VPP and the performance test was conducted. ECN and Gasunie coordinated this test field. It was found that the opportunity exists to reduce substation peak load by 30–50%. Stirling engines were used as microCHP units, each unit having 1 kW electric. During tests not all of the units were connected to the same low-voltage network, but they all had a common substation. ECN developed the PowerMatcher module, which is responsible for coordinating supply and demand in the electricity network. A special software and communication module was installed in each microCHP unit. The software controlled a work of unit on the basis of a number of important economic factors. In such a case there was no need to implement a central optimization algorithm. Bids took the form of information exchanged between units and the PowerMatcher operator—bids as a signal for the electronic market. The bids consisted of information about the price which is acceptable for the unit's owner in the sense of buying or selling electricity (and capacity). In reply from the market, price signals were delivered. An autonomous decision about operating or not operating and waiting for the next round of bidding was taken on the basis of those signals. A PowerMatcher module can be connected to DER or other PowerMatcher modules. This is possible due to standardization of the transmitted information package. Various units can be clustered onto different levels and there is no problem with connecting units to PowerMatcher modules. In other words, one PowerMatcher can coordinate several units and can be connected to another PowerMatcher module—on a higher level—which in turn coordinates the operation of other units etc. The unit's owner could determine the main goal of operating the unit. Bids are then sent to the PowerMatcher module. The bids contain the aim preferred by the owner.

Field tests were made in 3 cases:

1. the load was assumed to be the standard profile of energy usage in households in the Netherlands—no micro CHP;
2. the same energy consumption as in 1, microCHP units were installed and operated only in a heat-demand driven manner;
3. as in 2, but VPP was launched and microCHP functioned in a new environment of collaboration between VPP and the market.

The field tests were conducted in May 2007. There was only heat demand for hot water. All households had a 120 liter tank for hot water. The paper

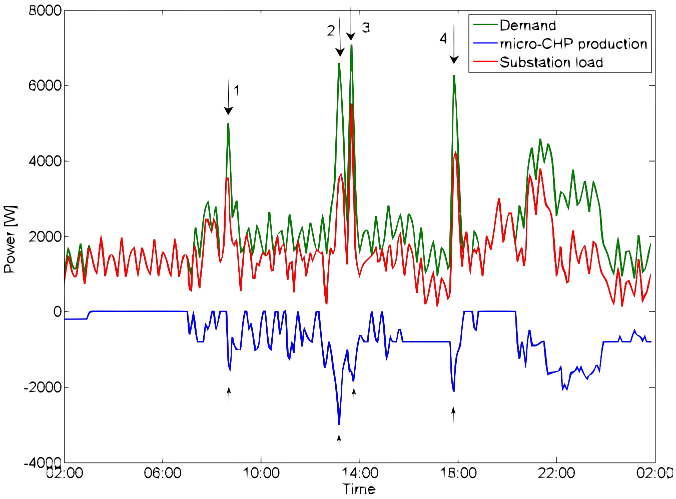


Figure 4: Field test result of clustered control of 10 microCHPs after [5]

showed results for one day during which only 5 microCHP units were participating without any problems and disruption. Figure 4 shows total electricity demand during one day. As can be seen, there were 4 peaks. PowerMatcher reacted to those peaks, shifting additional power production. The field test showed that 5 microCHPs mitigated the maximum value of peaks. But the boundary factor that resulted in a poorer quality outcome was the lack of sufficient heat storage space: units could not produce more electricity without producing additional waste heat. The hot water tanks were designed to cope with the waste heat problem, but they had limited capacity. And in a situation where peak loads appeared in very short intervals there was insufficient free capacity to take over additional heat production. Hot water tanks were filled during the first peak. The period of time between the first and second peak was very short, so there was no time to use the heat stored in tanks. As a consequence, the engines could not operate. All tests collected information about VPP potential. They clearly demonstrate that the DER intelligent management system produces benefits. The current way of power system management—fit and forget—delivers more system load. The suitable operating of DER units can result in lowering and mitigating the demand curve in the system.

The authors claim there is no problem with grouping together different types of power sources. The case presented above featured Stirling engines only, but implementation with other, different units does not pose a problem and should not cause any errors in the VPP system.

## 4. Methods of VPP control

### *4.1. Ohmic resistance control method*

The Virtual Power Plant can be considered as a cluster of distributed electricity generators (DEG). They are attached to the telecommunication network. In the paper [6] the possibility of VPP operating without additional costs of transmission are described. MicroCHPs which generate electricity and heat are considered. They have a high total efficiency. The typical heating system for a household comprises a CHP integrated in the central heating system and an additional burner which is used during winter peak time, plus a hot water tank. The electricity generated can be used on site or transferred by a low voltage network to the power system. When there is insufficient generation of electricity and unbalancing occurs, then external electricity is supported by a low voltage network. Two modes of operating are defined - heat driven and power driven. Hot water storage gives extra capacity for storing heat, which can be used to improve the operations of the whole system, and for switching between operating modes in light of the heat storage status. Each kind of system has specific parameters. The ohmic resistance of a low voltage network is higher than that present in a mid or high voltage network. This fact can be used to define areas where the power load is the greatest. Such areas are characterized by high voltage drops. Thus, the signal can determine the load of each CHP unit in the VPP system. This relates to units which operate in power driven mode. The idea is to increase the generation of CHP units in cases where the voltage in the feed-in nodes drops below certain levels and vice versa.

### *4.2. Marginal costs*

Supplying power demand to balance the power system in real time is one of the key advantages of VPP. The reserve power is at TSO's and DSO's disposal. VPP manages all units in the most cost effective way and minimizes total balancing costs. To operate correctly some input factor must be delivered to VPP. The impulse can take the form of the marginal electricity cost of the individual DER units. Marginal electricity costs are highly dependent on the local context and change over time. For example, CHP generates electricity depending on heat demands. The more heat is needed, the more electricity is generated and vice versa. VPP is a structure which contains a number of different types of DER. For the typical situation the power of each unit is not very high and so the DER units are small. The production of energy is a dynamic process, so the marginal energy costs are dynamic too. In article [6], a method is presented to determine DER marginal costs and benefits achieved through using bid strategies. DER units have to send information about marginal costs to VPP. This information is sent in the form of bidding formulas or demand curves which determine the needs of VPP for electricity at established prices. Negative values in the curve diagram means the DER unit is able to produce extra power at set price level. Bid offers are made by an agent using special software which is able to create a complex bid schedule for a particular moment. These offers are made based on:

- current operating state of the DER unit;
- economic parameters such as marginal operating costs;
- market environment with all market mechanisms;

The author of [7] sets out 3 different strategies which might be used in the bidding process:

- fully marginal-cost based strategy—this can be used in a situation where the VPP system contains only distributed electricity generators. It considers fuel prices, unit efficiency, running-history dependent maintenance costs and startup costs.
- fully price history based strategy—this can be used when storage devices are used, e.g. accumulators. It considers minimum and maximum prices from previous time periods and the level of available storage space. Storage devices are controlled by price signals—if the energy price is low then the storage device runs and vice versa.
- mixed strategy—this can be used for CHP units with additional heat sources and heat storage units. It is hybrid of the above two methods. In paper [6] a bidding strategy is presented for different types of DER.

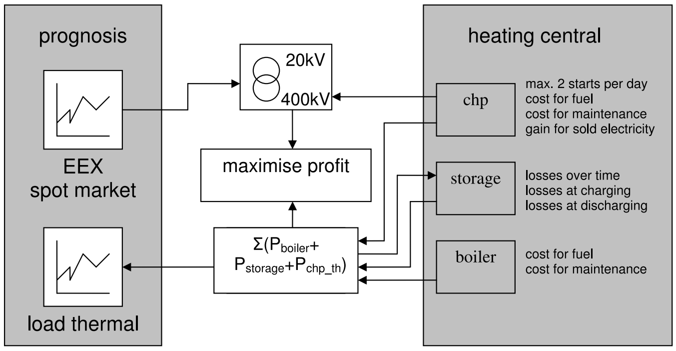


Figure 5: Structure of the prognosis based optimization algorithm for cogeneration system, after [8]

### *4.3. Optimization of CHP*

The algorithm for CHP optimization is described in [8]. The aim of the algorithm is to set all devices in such a way as to maximize the benefits from system operation. Everything is based on the variation of electricity prices over time. The operation schedule of units must be known one day before physical supplies. This schedule has to be delivered to EEX. Underpinning the algorithm are the predicted electricity prices on the spot market and the heat demand forecast. Heat can be produced by boilers, CHP or a heat storage tank. The heat storage tank gives an opportunity to separate the production of electricity from heat. A CHP can operate even if there is no demand for heat from the user. The main need is to maintain heat supply to a customer at an adequate level. The CHP can operate in such a way as to generate surplus electricity which can be sold on the market. The algorithm maximizes benefits from sales of surplus electricity and handles heat supplies. At the same time there are boundary conditions on the algorithm objective function. The boundary conditions come from the technical restriction of operating CHP units. To achieve the best fitted result of optimization, prediction data must be delivered. The authors suggest using statistical methods with empirical functions to fit loads (prognosis with multiple linear regression). Physical model based functions can be used. In the opinion of the authors, neural networks are not well-suited to make forecasts. In the method employed the forecast is done using a database with a time horizon of at least 1 year. The data used are: weather conditions, calendar data and the commercial weather forecast. As a result the heat demand curve is obtained for a specific building. The results correlate reasonably well with real data and values. The idea of optimization is to find the maximum or minimum value of some objective function in some calculation area. The authors used the MILP method to optimize the objective function (Mixed Integer Linear Programming). This method can find the optimum in a model which is described by linear function as well as integer variables. Optimization calculations for a local heat system are formulated in the solver-independent language AMPL and are solved by CPLEX optimization software. A couple of formulas which are the mathematical models of different elements of the energy system are presented in the paper. There are formulas for the heat system, CHP, boiler and heat storage. The objective function is determined as maximum benefit from total heat and electricity sales considering the costs of energy production in each CHP and boiler unit. The maximization of benefits can be contrary to other goals, e.g. to minimization of primary fuel energy. The model based on MILP was used to optimize the operation of an existing heat system which is supplied by [3] the same CHP units. The forecast was done using data from the EXX spot market of 2004. The simulation was performed and compared with real values. 2 power diagrams were obtained—one with the simulation and other with real operation. The total analysis for the whole year showed that there was a cost savings potential of 10%. Moreover, the appropriate usage of heat storage reduced the energy losses to a small extent. As is shown, great potential for optimal management still exists.

### *4.4. Reduction of generation costs*

The emergence of new sorts of power sources such as RES causes new problems. Due to their connection to the low or mid voltage network, those problems are located exactly on the low or mid voltage network level. They manifest themselves in: change in energy flow direction, overload of network, problems with frequency and balancing. The control system of VPP and optimal structure of VPP are described in paper [9]. The authors highlight need for a central Energy Management System (EMS) module. Each VPP has to be connected directly or indirectly with EMS so as to enable the exchange of important data. The EMS controls the entire exchange procedure in real time. The data contain information about the current situation and state of each market participant. The appropriate communication must be provided to transfer data. The VPP system should be local in nature, react quickly with minimal latency time and have the ability to connect new units. The network hierarchy structure should adjust according to the number of users. Too many points connecting with the EMS at any one time may result in the whole system slowing down and thus overloading. The authors point out problems with energy flow. In the considered VPP more attention must be put on control of the energy flow in the network. Thus, the measurement of energy flow has to change. There is at present only measurement on the power sources side. The new concept assumes measurement will take place in real time on the demand side too. Measurement devices will have to be installed and a special protocol for data transmission implemented too. The authors suggest using a measurement system coupled with GPS technology. Transmission will be possible by satellites. The operator demands full possible knowledge about the network to determine what happens in individual lines of the network. Several service tasks must be performed to avoid network faults; usually the TSO will be responsible for this. Through this activity the system can operate without disturbance. The role of the DSO is very limited. This situation will change due to VPP presence. The DSO will cooperate with VPP and more service tasks will be transferred to the lower level—that of the DSO. The power system operation schedule will be done by DSOs. They will deliver information about the reserve power of the DER for the following day.

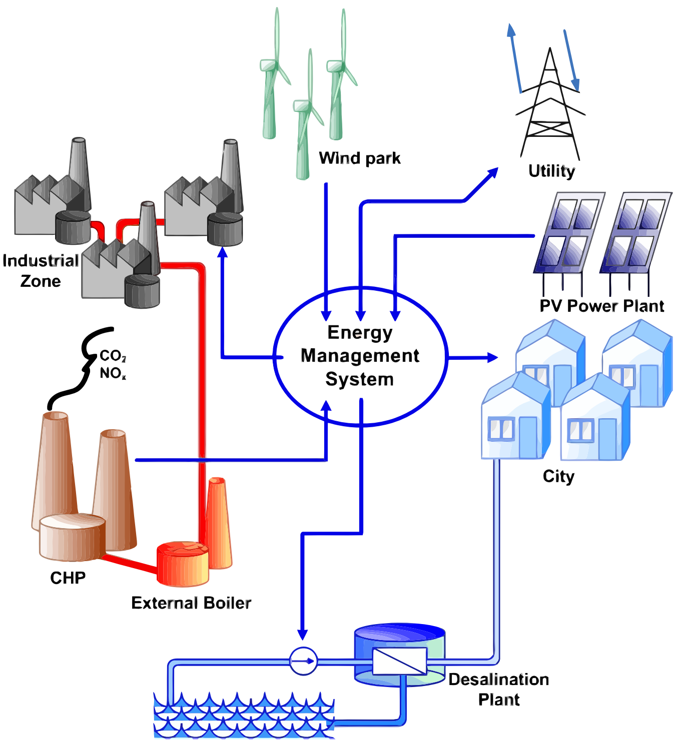


Figure 6: Structure of the VPP, after [9]

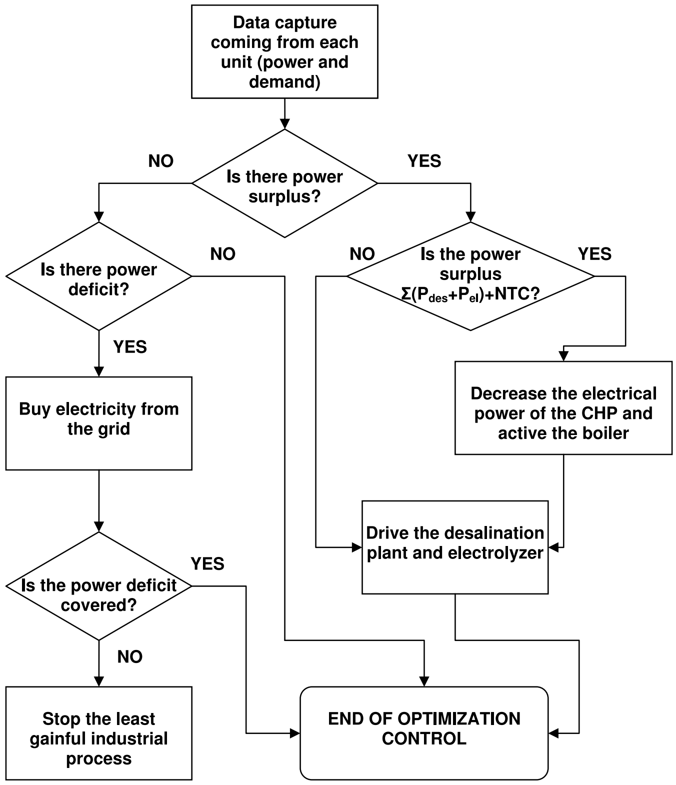


Figure 7: Flow chart of the optimization control, after [9]

### *4.4.1. Optimization approach*

The objective function of EMS is determined as minimum: energy generation costs, total costs and transmission losses. The boundary for the objective function is network overload. Measurement technology must be improved, as mentioned above. The considered case involved a VPP system with 3 energy suppliers and 4 different consumers. A desalination plant and electrolyzer for hydrogen production were implemented as consumers. It clearly demonstrates that VPP also has great potential for operating with different kind of units. Nowhere else in the literature was a solution of this type described. EMS lies at the head of the whole system and directs all energy flows to fulfill the needs of the consumers and to optimize use of the generated energy. The entire model was tested using data from the German energy system. A simulation of the VPP system was performed. It transpired that there is a specific capacity of wind farm for which total operation costs of VPP are minimal. For the data used, this capacity was 125 MW level. More information about structure and test results are described in [9].

## 5. Decision-support software for VPP management

The decision-support tool for Virtual Power Producers is presented in article [10]. A tool usage analysis is made. The authors highlight that long distance energy transmission is unjustified in terms of DER production. All consumption of the produced energy takes place at or near to the site of production. The DER units are connected with the distribution network. Due to the increasing number of RES there will be a marked increase in energy production from such decentralized sources in the near future. Thus, a solution needs to be designed that will be able to make effective use of that renewable energy. To achieve that aim, broad-based knowledge must be gathered on all kinds of DER units. The main idea is to develop a system which provides an opportunity to coordinate all units in one common system without sharing DER units. All units must be able to cooperate together to achieve the common aim. The required knowledge concerns the particular operating features of units such as: technology ripeness, profitability, availability, reliability, production and capture of greenhouse gases, relation with external factors and lifetime.

The schematic diagram of VPP is presented in the paper. It consists of 5 layers which are closely interconnected. They are: meteorology, power producer, VPP, Market and System operator. Fig. 8 shows the challenges facing VPP and the operations required to achieve results. The schematic gives a general overview on VPP foundations.

The name of the tool is ViProd. It is responsible for VPP simulation and its interaction with market. This tool uses the characteristics listed above and helps with the decision-making process. It has been split into 2 parts. The first part calculates the energy production for the one day ahead and the second one simulates generations. It is possible to simulate energy production from wind turbine, small hydroelectric and photovoltaic plant. Real external data is needed to make correct calculations, e.g. wind direction and speed, water flow rate, temperature or solar radiation coefficient.

The tool simulates the energy production possibilities for each type of DER unit, taking into consideration the characteristics of local demand, peaks and time variation of factors which can influence production. Prediction about factors gives approximate real conditions and reduces forecasting error. The article presents only the part of the tool which forecasts wind condition based on various input data and the part of the tool which simulates the operation of wind turbines. The simulator uses results which are derived by the first part of the tool, and information about possible energy generation over a defined period of time is delivered as a result. The application is responsible for running all clustered units in one specific VPP structure. Power is distributed properly among a number of DER units in function of sold energy, production cost and available power. A checking procedure is performed regarding the predicted amount of energy and power. Next a report is created about the reserve power of each unit which is at the operator's disposal. A software test was conducted. Ten units were implemented as the VPP system. The test was performed in order to determine whether the reserve power is sufficient to cope with unbalancing in the power network. Unbalancing might be caused by, for instance, turning the wind farm off. Two tests were conducted. The first one showed that VPP was able to cope with the problem of a sudden turning off of the wind farm. The second test simulated the situation where the balancing from the VPP side was not at an appropriate level, so some unbalancing occurred in the distribution network.

Matlab/Simuling was used to make ViProd.

The following conclusions were presented by the authors. The appropriate designed VPP structure can eliminate:

- uncertainty of energy production forecasts;
- fines for unbalancing;
- the lack of small energy producers on the market—there is space for small players;
- problems with the $CO_2$ market;
- high management costs.

The following step will be to connect ViProd to the energy market simulator—MASCEM.

## 6. Conclusions

The number of small DER units will increase over time. Currently, the world is powered by large power plants which supply power systems. But this situation will change due to RES among other things. The central power sources will be turned into decentralized sources. This trend is observable in Denmark, where the number of small CHP units has increased significantly in recent years. To adapt to change, a suitable management system will be needed. VPP is a concept which is able to cope with managing a large number of different types of DER units. The biggest advantage of VPP is its modular structure. It can be connected to power systems and comprise a number of DER units. Depending on requirements, extra modules can be added, in order to optimize the system, secure transmission and/or report results. VPP has the flexibility of building blocks.

As is reiterated in the paper, every VPP system differs in the detail. There are many approaches to the VPP concept. Every scientist and engineer involved has her/his own vision of VPP. But the core idea stays the same—gather together and manage as many DER units as possible to achieve better, more cost effective and environment friendly results.

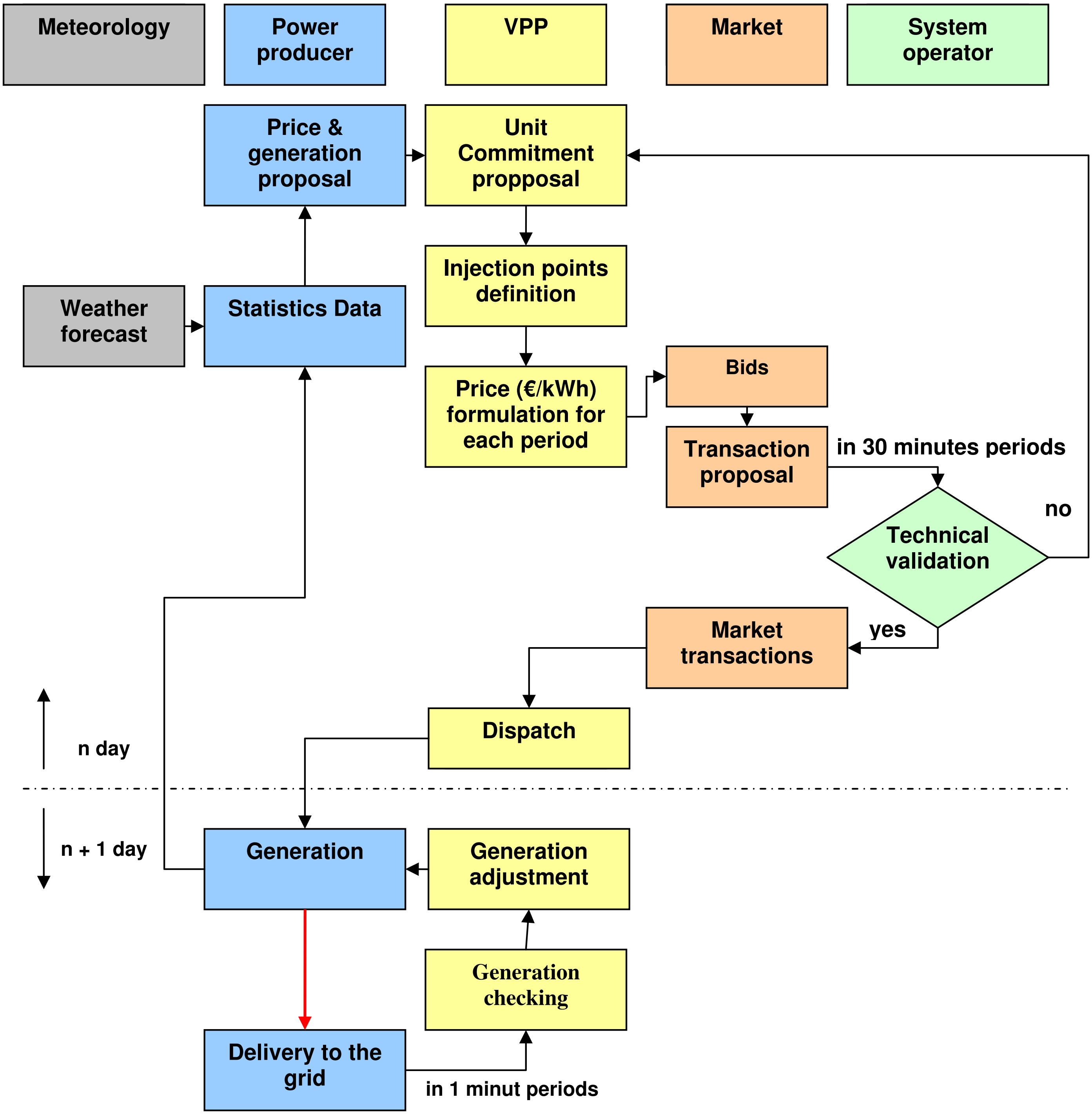


Figure 8: Schematic representation of the functioning of VPP, after [10]

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