

# MULTI CRITERIA OPTIMIZATION OF AN AUTONOMOUS VIRTUAL POWER PLANT WITH A HIGH DEGREE OF RENEWABLE ENERGY SOURCES

Pio Lombardi  
Otto - von – Guericke Universität  
Magdeburg, Germany  
[pio.lombardi@ovgu.de](mailto:pio.lombardi@ovgu.de)

**Abstract - Virtual power plants (VPP) are clusters of decentralized power plants, energy storage systems (ESS) and active loads that are mainly connected to the low and medium voltage level. VPP are optimally coordinated by an intelligent energy management system (EMS). The dispersion of such clusters increases the penetration of RES in the electric grid.**

**This paper analyzes an autonomous VPP with a high degree of penetration of RES and optimally models its energy storage system (ESS). Three ESS technologies were analyzed: a diabatic compressed air storage system (CAES), electric vehicles to grid (V2G) and a battery switch station (BSS). A multi-criteria analysis (MCA) approach was adopted to identify the optimal ESS technology and its optimal storage capacity. Three main criteria were selected, namely the costs of the system, the amount of pollution emitted and the reliability of the services. The results of a study case will be shown**

**Keywords:** Energy storage systems, multi-criteria analysis, renewable energy sources, virtual power plant.

optimal storage capacity is found through a multi-criteria optimization method, which takes into consideration economics, environmental aspects and the reliability of the delivered services. Three technologies were analyzed as energy storage systems: diabatic Compressed Air Storage System (CAES), Electric Vehicles (EV) connected to the grid (so called V2G) and Battery Switch Station (BSS). The VPP is composed of a Combined Heat and Power plant (CHP), which uses a Gas Turbine (GT) as prime mover and burns natural gas, a wind farm, a photovoltaic plant, an electric energy storage device and active customers. Although two different customer' categories were considered- residential and industrial customers- only the industrial customers use Load Management programs (LM). In addition to the evaluation of the optimal storage capacity, this study aims to discern whether VPP are economically competitive with traditional power systems.

## (1) INTRODUCTION

The awareness of environmental problems caused by the emission of greenhouse pollutants as well as the continuously increasing price of fossil sources, are pushing governments to invest in renewable energy sources. Renewable energies are becoming, in many countries, one of the most important topics on the politic agenda. However, due to the intermittent nature of renewable sources, the integration of such "clean" energy into the power system is not an easy task. For this reason new solutions have to be adopted. There are three candidate solutions to do this: build new power transfer lines, use load management programs and install energy storage systems. However the social acceptance of building new power transfer lines is generally quite low, which makes the first solution hard to implement.

Virtual Power Plants are systems that make use of load management programs and energy storage systems. They are clusters composed of distributed generators, mainly based on renewable energy sources, energy storage systems and "active" consumers that make use of load management programs. The cluster may be remote controlled by an Energy Management System (EMS) that optimally manages the system depending on the power demand, weather situation and the storage capacity.

In this study an autonomous VPP is analyzed and its

## (2) VIRTUAL POWER PLANT

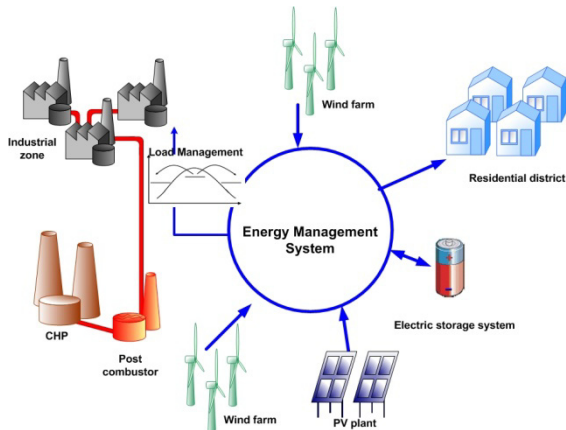
An autonomous VPP was analyzed in this study (see Figure 1). The generation side of the VPP is mainly composed of a CHP plant, a wind farm and a photovoltaic plant. The demand side is composed of two different consumers. The first is an industrial zone in which the VPP operator may control the load; the second is a residential district which does not use any LM program. Since the VPP is not connected to the main grid, an Energy Storage System (ESS) was needed to be installed in the VPP structure to guarantee a high level of reliability of the supplied services.

Regarding the generation side, the CHP plant supplies not only electricity, but also thermal power to the industrial zone.

The behaviour of the VPP was evaluated using hourly profiles which describe both the power generated and demanded, for each component of the VPP.

The power load profile of the residential district as well as the power generation profile of the wind farm was obtained by a limited amount of measurement data from two German network operators. The power profile of the PV plant was obtained from limited measurements of the power plants situated on the roof of Building 9 at the University "Otto von Guericke" in Magdeburg, Germany. These data were normalized with regards to the maximal installed power of the plant.

Different from the above mentioned profiles, the power profiles (electric and thermal) of the industrial zone were obtained from literature [1]. Considering the CHP plant, it was assumed that it is heat driven and the heat to power ratio was equal to one. With these assumptions the power profiles (electric and thermal) of the CHP correspond to the thermal power demanded by the industrial zone.



**Figure 1** Autonomous virtual power plant

Table 1 shows the installed power capacity of the three power plants and the power demanded. In this study it was assumed that the renewable based plants (wind farm and photovoltaic) had to supply at least 20% of the power demanded.

	Electric power	Thermal power
CHP	25	25
Wind farm	24.8	-
Photovoltaic plan	6.2	-
Residential district	20	-
Industrial zone	15	25

**Table 1** Electric and thermal power generated and demanded

### (3) OPTIMIZATION TOOL: THE WEIGHTED METHOD

Different optimization tools are used in power sector. Cost-benefit analyses (CBA), costs effectiveness analyses (CEA) and Multi-Criteria Analysis (MCA) are some of the most used tools in power sector optimization problems. Both CBA and CEA are analytical comparison techniques where different forms of input and outputs are all considered in monetary value. Although CBA and CEA are widely applied in the power sector, some typical problems of power system industries can not be solved by a mere economical criterion, but instead require Multi Criteria Analysis (MCA) [2]. A MCA was used in this study. A MCA may be performed through an optimal weighted method. It consists into allotting a weight to each criterion and analyzing the effect it has on the optimal solution. One of the characteristics of this method is to develop a performance matrix, where each row describes an option and each column describes the

performance of the options against each criterion. In a performance matrix a value score ( $S_{j,i}$ ) is evaluated for each option. Value scores are generally allotted to a scale between 0 and 100 (generally to the worst case is allotted 0, while to the best case is allotted 100). Once the end points are established, the scoring of the halfway options can be done by a linear interpolation function. The weighting process consists of assigning a numerical weight to each criterion. The highest weights are assigned to the most relevant criteria. A characteristic of the weighting process is that the sum of the weighted values ( $w_i$ ) relating to an option has to equal one. The combination of weights and scores for each option is done by evaluating the Weighted Average Values (WAV) on all criteria, which also represents the Objective Function (OF) of the optimization problem. To evaluate the WAV for the option  $j$  the formula expressed in Eq.(1) was used:

$$S_j = w_1 \cdot S_{j,1} + w_2 \cdot S_{j,2} + \dots + w_n \cdot S_{j,n} = \sum_{i=1}^n w_i \cdot S_{j,i} \quad (1)$$

where

- $S_j$  is the Weighted Average Value for the option  $j$ ;
- $w_i$  is the weight given to each criterion;
- $s_{j,i}$  is the scored value assigned to each option;
- $n$  is the number of options.

Generally, the weighting process of criteria is the hardest process. The optimal solution strongly depends on the weights given to each criterion. To get a wider view on the effect that the weights have on the WAV, sensitivity analysis may be also elaborated. It consists in changing the weights assigned to each criterion and then analyzing which effect they have on the Pareto optimal solutions. Sensitivity analysis may be a test to prove if the found optimal solution is robust. A solution is defined as robust if, by varying the weights of the criteria, it always results in the optimal choice.

### (4) ANALYZED CRITERIA

In this study three main criteria were considered: economic, environmental and reliability. The energy generation and storage costs were evaluated as economics criteria. These costs were estimated by adopting the Levelized Unit Energy Costs method (LUEC), which takes into consideration the investment costs, the maintenance and operation costs, and the life time. All these parameters refer to the plant. Moreover, it considers a discount factor and, for fossil based power plants, the price of the fuel and its efficiency of conversion. The CO<sub>2</sub> equivalent emitted by the CHP plant is the parameter which evaluates the environmental criterion. The combustion of natural gas

was considered in this study. The CO<sub>2</sub> equivalent takes in consideration the emitted amount of the Green House Gases (GHG) such as CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>. For estimating the emitted amount of these GHG, the emission factors tabled by the IPCC were used [3]. The amount of the CO<sub>2eq</sub> was evaluated as the sum of the amount of GHG times their Global Warming Potential (GWP), as shown in Eq. (2), where  $A$  is the amount of the green house gas, which is indicated as  $i$ . The amount of the GHG directly depends on the burned natural gas, which in turn depends on the demanded power and on the overall efficiency of the CHP plant.

$$CO_{2eq} = \sum_i A_i \cdot GWP_i \quad (2)$$

It was assumed that the VPP offers not only electric and thermal power to the customers, but also other kinds of network services such as the management of fully loaded batteries for electric vehicles owners. There are different methods to estimate the reliability of a system. Related to the power services it can be easily estimated as the sum of energy not delivered to the customers. In the same way, for a VPP that also manages a Battery Switch Station (BSS) the reliability can be estimated as the number of customers to whom fully charged batteries were not delivered. Generally, the reliability of the power supplied from a system is economically estimated through the Value of Lost Load (VOLL). The VOLL is usually defined as the value, expressed as €/MWh, which represents the customers willingness to lose supply and as the value that customers would place on a unit of not delivered energy [4]. It is more difficult to estimate the reliability to supply fully charged batteries to the EV owners, since up to now there is no information in the literature about this business. However, in this study a method is proposed. The VPP operator may offer the EV owners some kind of monetary refund if it is not able to supply the required power for charging the EV. For example, these monetary refunds can be evaluated as the price paid to a taxi driver, who has to drive the EV owner to his destination.

## (5) OPTIMIZATION PROBLEM AND VPP CONTROL

The EMS can be defined as the heart of the Virtual Power Plant. Thanks to Information and Communication Technologies (ICT) and to remote control devices, the EMS is able to receive information on the status of each component of the VPP and, if necessary, to control them. The strategy control of the EMS depends on the targets (Objective Function) that the EMS has set. Typically the OF for a VPP is economic oriented, that is that the EMS controls the VPP in order to minimize the costs (i.e. generation costs) and/or to maximize the revenue. Nonetheless, a strategy control of a VPP may not only be driven by a

mere economic criterion but by multi criteria considerations. In this last case the EMS controls the VPP in order to maximize or minimize the Weighted Average Value (WAV) which was defined by Eq.(1) Since the best option to compose the performance matrix was scored by allotting it the maximal score (100), the OF of the EMS aims to maximize the WAV; in this case the OF can be expressed as in Eq.(3)

$$OF = \max \sum_{i=1}^n w_i \cdot s_{j,i} \quad (3)$$

Nonetheless, the optimal strategy control of the EMS has to be subjected to the following constraints: active power balance constraint Eq.(4), thermal powers balance constraint Eq.(5), conventional plant capacity limits Eq.(6), renewable plants capacity limits Eq.(7) and Eq.(8), and to the Energy Storage capacity limits Eq.(9),

$$\sum_{i=1}^n P_i - \sum_{j=1}^m P_j = 0 \quad (4)$$

$$\sum_{i=1}^n Q_i - \sum_{j=1}^m Q_j = 0 \quad (5)$$

$$5 \text{ MW} \leq P_{CHP} \leq 25 \text{ MW} \quad (6)$$

$$0 \text{ MW} \leq P_{wind} \leq 24.8 \text{ MW} \quad (7)$$

$$0 \text{ MW} \leq P_{PV} \leq 6.2 \text{ MW} \quad (8)$$

$$P_{\min\_storage} \leq P_{storage} \leq P_{\max\_storage} \quad (9)$$

where

$P_i$  is the active generated electric power and  $P_j$  is the active demanded electric power;

$n$  is the number of the electric/thermal power generators and  $m$  is the number of the electric/thermal power demanders;

$Q_i$  is the thermal power generated and  $Q_j$  is the thermal power demanded;

$P_{CHP}$  is the active electric power generated by the CHP plant;

$P_{wind}$  is the active electric power generated by the Wind farm;

$P_{PV}$  is the active electric power generated by the PV plant;

$P_{\min\_storage}$  and  $P_{\max\_storage}$  are respectively the minimal and maximal electric power storage capacity;

$P_{storage}$  is the active electric power of the storage system.

In order to stabilize the electric network of the VPP, the EMS has to continually balance the generated electric power according to the demanded electric power. The EMS gives priority to dispatching electric power produced from the generators based on renewable energy sources.

If there is electric surplus coming from the Wind farm and PV plant, and if is not possible to store it, the EMS first reduces the electric power of the CHP plant; it is able to decrease the electric power of the CHP

down to 20% of its nominal power capacity. Since the CHP is heat driven and its heat to power ratio is one (at nominal working point), reducing the electric power causes, the thermal power to reduce proportionally. In such a situation the EMS activates a post combustor which aims to re-heat the exhaust gases in order to supply the demanded thermal power thereby avoiding a shortage of the thermal power. The power combustor has the advantage of giving the CHP plant more flexibility concerning the thermal power production. In fact its use can increase the heat to power ratio up to five. If the electric surplus is not yet balanced after reducing the electric power generated by the CHP plant, then the EMS first controls the Wind farm and then the PV plant by reducing their power generation until the electric power is balanced.

If there is a deficit of electric power, and if the CHP plant is not working at its maximal power capacity, the EMS increases the electric power of the CHP plant. If the electric deficit is not totally covered, then the EMS, through LM programs, controls the load of the less gainful industrial processes of the industrial zone. Nevertheless, increasing the electric power of the CHP causes its thermal power generation to increase proportionally as well. This is because, as mentioned above, the heat to power ratio is one. In this case a by-pass valve needs to be installed in the CHP plant. The by-pass valve aims to directly channel a part of the exhaust gases to the chimney, thereby avoiding that it goes through the heat exchanger. However, using this control strategy for the CHP plant decreases the overall efficiency of the plant since a part of the thermal energy carried by the exhaust gases is not recovered. A consequence of such a control strategy is an increase of the specific emissions of GHG as well as of the energy generation costs.

## (6) CASES STUDY

### 6.1. VPP with diabatic CAES system as energy storage system

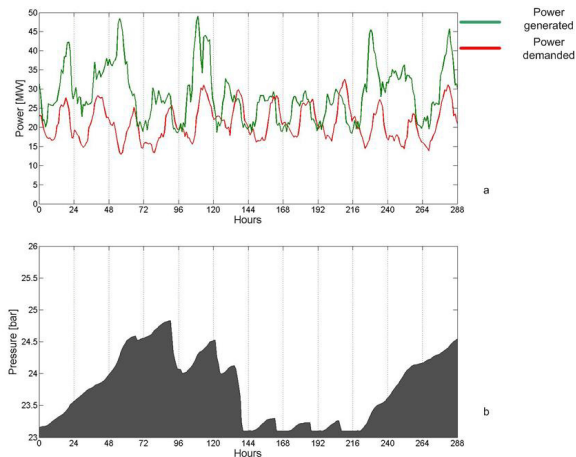
The first type of energy storage technology chosen for the VPP was a diabatic Compressed Air Storage System (CAES). An algorithm was developed to simulate the properties of the compressed air at every point of the CAES cycle. The properties of a real gas instead of an ideal gas were considered. It was assumed that the compressed air is stored in an underground cavern with a total volume of 100000 m<sup>3</sup>. The maximal pressure of the stored air was fixed to 34 bar, while the minimal pressure corresponds to the inlet pressure of the gas turbine: 23 bar. It was also assumed that the ambient temperature inside the cavern is constant at 293,15 K (20°C). Table 2 summarizes the main parameters used to model the behavior of the CAES system. Through the CAES system, the EMS is able to optimally manage the

VPP both in situations of electricity surplus and in those of deficit. In fact, if there is an overproduction of electricity coming from renewable based generators the EMS will store it in the form of compressed air. The storage of electricity is only allowed if the cavern is not fully charged with compressed air. In this case the compressed air pressure inside the cavern reaches its maximal value of 33 bar. Moreover, during electric surplus contingency, the EMS may also reduce the generation power of the CHP if is not able to store the entire electricity surplus in the cavern. If reducing the electric power of the CHP does not balance the system then the EMS reduces the generation coming from RES generators.

	Unit
Cavern volume	100000 [m <sup>3</sup> ]
Minimal pressure inside the cavern	23 bar
Maximal pressure inside the cavern	33 bar
Cavern air temperature	20 °K
CAES compressor power	35 [MW]

**Table 2** Main parameters assumed to model the CAES system

Figure 2,a shows the behavior of the VPP. The green curve represents the power generated, while the red one the power demanded. According to the algorithm, the pressure inside the cavern increases when there is surplus, while during deficit situation it decreases, see Figure 2,b. In Table 3 the performance matrix is shown. Three criteria have been considered which are expressed with five sub-criteria: electricity production costs of the VPP [€/MWh], energy storage costs [€/MWh], electricity not supplied to the industrial customers [MWh/year], renewable energy not fed into the grid [MWh/year], and amount of emitted CO<sub>2</sub> equivalent [ton/year]. Related to each criterion, the best option was scored with the value 100, while the worst one with the value 0. The remaining options were scored by linear interpolation. The electricity production costs criterion represents the average value of the electricity production costs of the three generators. To evaluate the energy storage costs it was considered that the compressor of the CAES system costs 600€ pro kW, while the storage capacity costs 3 € pro kWh (costs due to the solution mining of the cavern) [5]. All of the criteria were equally weighted to find the optimal Pareto solutions. With these weighting factors the optimal storage capacity turns out to be at 27 bar. In order to establish a sense of robustness of the results obtained by these weights a series of sensitivity analysis is conducted. The results of this analysis can be easily understood in a graphic format such as in Figure 3.

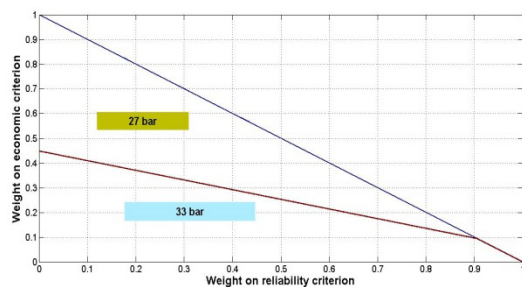


**Figure 2** Generated and demanded power (a), pressure variation inside the cavern (b)

Pressure [bar]	Economic criteria		Reliability criteria		Environmental criteria		Weighted Average Value
	I	II	III	IV	V		
24	0	0	0	0	0	0	0
25	58	11	69	51	56	49.03	
26	80	17	91	71	81	67.94	
27	88	100	98	79	90	90.87	
28	90	28	99	83	92	78.59	
28	93	33	100	87	95	81.63	
30	95	39	100	91	97	84.41	
31	97	39	100	94	98	85.50	
32	99	44	100	97	99	87.76	
33	100	50	100	100	100	90.06	
Weights	0.20	0.20	0.20	0.20	0.20	1.00	

I: Electricity production costs;  
 II: Energy storage costs;  
 III: Electricity not supplied to the industrial customers ;  
 IV: RES not fed into the grid;  
 V: Emitted CO<sub>2</sub> equivalent

**Table 3** Performance matrix



**Figure 3** Sensitivity analysis

This graphic expresses only two of the three criteria: the economical and reliability criteria. The values of the third criterion (environmental) are implicitly evaluated as  $1-(X+Y)$ , where the X represents the values of the reliability criterion while Y the value of the economical one. The weight allotted to each criterion is equally shared between the sub-criteria. The sensitivity analysis shows that among ten different storage pressures, there are only two optimal values, namely 27 and 33 bar. One of the most important pieces of information that can be obtained from the sensitivity analysis is the fact that storing air at 27 bar is the dominant solution.

Graphically the area of the solution related to the pressure at 27 bar is higher than that of the pressure at 33 bar.

### 6.2. VPP with Electric Vehicles as energy storage system

The second scenario investigates the impact of Electric Vehicles (EV), which are used also as storage systems, on the VPP. The basic concept of "vehicle-to-grid" technology (V2G) is that the EV exchange energy with the grid while parked [6]. Thus, fleets of EV can operate either as energy sources, when they are needed by the VPP operators, or as loads, during strategic hours of the day when EV batteries need to be charged [7]. In this scenario, it is assumed that the fleet of EV is composed of a number of N electric vehicles, each with a storage capacity of 9.2 kWh. Additional parameters are as follows:

- **Storage capacity:** A Li-ion battery pack is composed of 16 modules (each module consisting of 12 cells) that is installed in each EV for obtaining a total storage capacity of 9.2 kWh at a DC voltage average of 346 V;
- **Transfer Limit:** The electrical power capacity that a single EV can deliver to the grid is mostly determined by two factors: the maximal flow of the connection to the grid during the batteries' discharge, which is assumed to be 16 A (residential connection, 230 V AC), and the stored energy divided by the time used. It is also important to consider the converter efficiency, which in this work is assumed to be 95 %. The flow from the grid into the EV during the batteries' charging periods generally depends on the type of the batteries and is controlled by the Battery Management System (BMS);
- **Cycles of charge and discharge:** In order to extend the life time of the batteries and thus to have a long-term efficient usage of the EV's storage system, the range of discharge and charge are set between  $E_{low} = 30\%$ , and  $E_{up} = 90\%$ . Abiding by this work cycle, the life time of the battery-based storage system is set to 10 years;
- **Charge and Discharge times:** The charge time of the batteries,  $t_{charge}$ , is assumed as a linear function of the incremental energy stored. In fact, this parameter can be assessed by considering that a fully discharged EV needs a time ( $t_{full}$ ) = 5 hours to be completely charged (from 0 to 100 %,  $E_{max}$ ) with a reduced current flow controlled by the battery management system and a voltage of 230 V, see Eq.(10). Discharge time,  $t_{discharge}$ , depends either on the power injected to the grid ( $P_{inj}$ ) or on the power delivered to the electrical motor, as well as on the converter efficiency ( $\eta_{conv}$ ) and on the actual level of charge,  $E_o$ , see Eq.(11)

$$t_{charge} = \frac{(E_{up} - E_o)}{E_{max}} \cdot t_{full} \quad (10)$$

$$t_{discharge} = \frac{(E_0 - E_{low})}{P_{inj}} \cdot \eta_{conv} \quad (11)$$

Additional important information about the EV, which when plugged in is within the control of the VPP operator, is combined with the distance that the EV travels every day as well as the periods during the day that they are not parked. These parameters depend on the uncertain and diverse daily requirements of each EV owner. However, EV used with residential or private purposes could exhibit, as fleets, an overall predictable behaviour with extended periods plugged to the grid. In this scenario it is assumed that, during one day, three equivalent firm fleets operate. They exhibit the following behaviour: fleet a: 30 % of the N EVs do not stay parked from 7 am to 8 am and from 5 pm to 6 pm; fleet b: 40 % of the N EVs do not stay parked from 8 am to 9 am and from 6 pm to 7 pm; fleet c: 30 % of the N EVs do not stay parked from 9 am to 10 am and from 7 pm to 8 pm.

Each day EVs travel an average distance of 35 km, 40 km and 30 km, for the fleets a, b and c, respectively. A distance of 20 km entails an energy consumption of 2.3 kWh.

Finally, based on information found in the reviewed literature, the cost of one EV including connection and communication modules is set at € 30,000 [8] and [9]. Additionally, it was assumed that the EV are charged only with renewable energy sources.

In case of power surplus, the EMS is able to control the power flow by charging the batteries of the vehicles, if they are parked. If it is not possible to dispatch the entire power surplus in this way, then the EMS reduces first the electrical power of the CHP and if necessary, it reduces the power coming from renewable sources. On the other hand, when there is an electricity deficit, if the EV are parked and have enough stored energy, this can be injected to the grid. If the stored electricity can not cover the entire deficit, the EMS will increase the power capacity of CHP. If such an operating procedure is not enough to cover the electric loads, then the EMS sheds the electric load of the industrial customers according to the Load Management program. The performance matrix is shown in Table 4. The optimal storage capacity, expressed as the optimal number of EV, can be estimated by this matrix. A range from 200 to 2000 EV was taken into consideration in this study, and three criteria were analyzed, which are expressed by six sub-criteria. One additional sub-criterion was adopted. This last criterion evaluates how often the EV owners are not able to use their vehicles because the battery of the EV is empty. In this case it was supposed that the EV owners have to use an alternative means of transportation to reach their destination (office, home, etc.). This sub criterion was classified inside the reliability criterion since the VPP operator has to ensure that all the loads (EVs are also considered as load) have to be supplied. All the criteria are equally weighted as

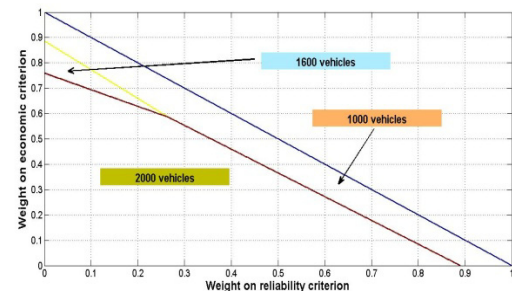
1/6. The optimal storage capacity is obtained when the number of EV is 2000, as shown in Table 4.

Number of EV	Economic criteria		Reliability criteria		Environmental criteria		Weighted Average Value
	I	II	III	IV	V	VI	
200	0	1000	0	100	0	0	32.60
400	22	89	5	81	10	8	34.87
600	36	78	27	63	22	19	39.87
800	47	67	52	50	34	33	45.57
1000	64	56	87	58	47	52	57.98
1200	69	44	86	43	58	62	56.23
1400	75	33	85	32	69	71	58.47
1600	90	22	89	17	79	83	61.09
1800	92	11	94	6	90	01	61.51
<b>2000</b>	<b>100</b>	<b>0</b>	<b>100</b>	<b>0</b>	<b>100</b>	<b>100</b>	<b>64.00</b>
Weights	0.16	0.16	0.16	0.16	0.16	0.16	1.00

I: Electricity production costs;  
 II: Energy storage costs;  
 III: Electricity not supplied to the industrial customers;  
 IV: Use of alternative vehicles to reach the destination;  
 V: RES not fed into the grid;  
 VI: Emitted CO<sub>2</sub> equivalent

**Table 4** Performance matrix

The sensitivity analysis shows that two more optimal solutions can be achieved with 1600 and 1000 electric vehicles. Among the three alternative solutions (1000, 1600 and 2000 EV), the storage capacity based on the use of 2000 EV has a higher robustness, since it is valid for a larger combination of weights, see Figure 4.



**Figure 4** Sensitivity analysis

### 6.3. VPP with Battery Switch station as energy storage system

The third scenario investigates a Battery Switch Station (BSS) which is used as a storage system. The BSS has to both supply fully charged batteries to the EV owners and to balance the power generated by RES.

At a BSS an automated process replaces the discharged batteries of an electric vehicle with charged batteries. This process can be realized in a few minutes as shown by the company Better Place [10]. When driving within the city, charging stations to load the battery are available to the vehicle owner. The battery is charged at the switching station under optimal conditions, i.e. an optimal charging current and charging procedure, optimal temperature conditions, and trickle charging are possible. The main requirement for this technology, which has already been implemented in several pilot plants successfully in Japan [10], is the unified configuration of the traction battery in the vehicle. This requires a degree of compatibility for

various vehicle concepts and types of batteries, so that the vehicle owner can use any BSS. In addition BSSs may also be used for energy management purposes, balancing the intermittent generation of RES.

From the point of view of battery life, BSS offers the opportunity to conduct an optimal charging process which positively influences the life time of the batteries.

In this scenario it was assumed that 1000 EV circulate within the area where the VPP operates. A random function describes when and how many EVs have to charge. The strategy control both during surplus and deficit contingencies is similar to those described in the first two scenarios above. An analysis between 20 MWh and 200 MWh of storage capacity was conducted to find the optimal storage capacity. In this scenario the criteria are also all weighed with the same value equal to 1/6, see Table 5. With these weights the optimal storage capacity turns out to be 200 MWh.

Storage Capacity [MWh]	Economic criteria		Reliability criteria		Environmental criteria		Weighted Average Value
	I	II	III	IV	V	VI	
20	0	0	0	0	0	0	0
40	50	44	44	9	8	40	43.13
60	60	80	65	9	21	56	50.26
80	70	93	73	18	36	65	56.75
100	100	100	80	73	75	100	75.05
120	100	95	85	74	78	100	74.62
140	100	91	90	75	80	100	76.62
160	100	86	94	84	88	100	78.85
180	100	85	97	91	05	100	80.35
<b>200</b>	<b>100</b>	<b>83</b>	<b>100</b>	<b>100</b>	<b>100</b>	<b>100</b>	<b>83</b>
Weights	0.16	0.16	0.16	0.16	0.16	0.16	1.00

I: Electricity production costs;  
 II: Energy storage costs;  
 III: Electricity not supplied to the industrial customers;  
 IV: Use of alternative vehicles to reach the destination;  
 V: RES not fed into the grid;  
 VI: Emitted CO<sub>2</sub> equivalent

Table 5 Performance matrix

The sensitivity analysis, see Figure 5, shows that in addition to the solution listed in Table 5 there is one more optimal storage capacity at 100 MWh. However, the solution with 200 MWh has a higher robustness since it is valid for a wider range of weights.

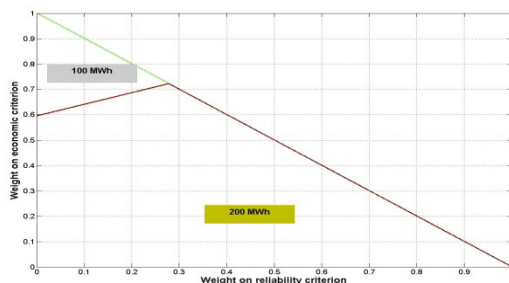


Figure 5 Sensitivity analysis

## (7) CONCLUSION AND COMMENTS

In the three scenarios above a multi criteria method was used for estimating the optimal storage capacity for

an autonomous VPP. This method turns out to be very useful, since the decision on the storage capacity can be taken very easily and quickly. Beyond that the obtained results are very interesting and need to be commented on. Through this study the electricity generation costs of the VPP were estimated. Considering all three generation technologies, their generation costs and the amount of electricity produced, the average of electricity generation costs results in around 60 € per MWh. These costs are slightly higher than the average electricity price in Germany in 2009 [11]. However, a VPP does not use high voltage transmission systems to transfer the electricity to the consumers. These costs were estimated at 60-130 € per MWh [12]. With these considerations, VPP might be economically competitive with the traditional power systems even if, to ensure a high degree of reliability, a VPP needs to use energy storage systems (as an alternative it should be connected to the electric grid and used as a storage medium). Summing the generation and the storage costs, the total costs are lower or at the least equal to those offered by the traditional system; see the storage costs in Table 6.

Energy storage technologies	Economic criterion		
	I	II	III
CAES 27 bar	49.7	83.5	361
1000 EV	49.7	92.2	361
BSS 200 MWh	43.2	62	361

I Electricity generation costs CHP [€/MWh];  
 II Electricity generation costs Wind [€/MWh];  
 III Electricity generation costs PV [€/MWh]

Table 6 Electricity generation costs

## REFERENCES

- [1] Energy & more energiebroker GMBH und Co. KG, online: <http://www.stromportfoliomanagement.info>
- [2] N. I. Voropai, E. Yu. Ivanova, "Multi criteria decision analysis techniques in electric power system expansion planning", Electrical Power and Energy System, November 2000.
- [3] Intergovernmental Panel on Climate Change (IPCC), Emission Factor Database. <http://www.ipcc-nggip.iges.or.jp/EFDB/main.php>.
- [4] J. Curtin, T. Doherty, "The value of lost load, the market price cap and the market price floor, A consultation Paper", July 2007.
- [5] C. Kruck, "Integration of offshore wind farms and compressed air energy storage plants", Third international renewable energy storage conference (IRES 2008), 24-25 November 2008, Berlin, Germany
- [6] P. Lombardi, P. Vasquez, Z. Styczynski, "Plug-in Electric vehicles as Storage devices within an Autonomous Power System: Optimization Issue", IEEE Power Tech, 28 June-2 July 2009, Bucharest, Romania.
- [7] J. Tomic, W. Kempton, "Using fleets of electric drive vehicles for grid support" Journal of Power Sources, March 2007.
- [8] "Photon das Solarstrom Magazin, Fahren mit Strom", pp.52-74, Sep. 2008, <http://www.photon.de>.
- [9] The Clean Green Car Company, <http://www.cleangreencar.co.nz/>.
- [10] Better Place, <http://www.betterplace.com>
- [11] European Energy Exchange (EEX), [www.eex.com](http://www.eex.com)
- [12] WADE, "Projected costs of generating electricity (2005 Update)", 2005.