Virtual Power Plant Optimization within Liberalized Market Environment

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ABSTRACT

This paper considers market behaviour of a virtual power plant composed of wind power plant, photovoltaic power plant, hydro pump storage system and gas turbine conventional power plant. The problem is formulated as a mixed-integer linear programming model which incorporates long-term bilateral contracts with participating in the market. The aim of the optimization is the virtual power plant profit maximization. The efficiency of the proposed model is rendered through a realistic case study and detailed analysis of the results is provided.

INTRODUCTION

Because of increasing concerns over environmental impact of the conventional fossil-fueled power plants, during the last couple of decades renewable energy sources (RES) have been experiencing an extreme growth. Since RES still cannot provide levels of return on investment like fossil fuels do [1], various incentive schemes for RES are introduced. These include feed-in tariff scheme [2], feed-in premium scheme [3] and the quota scheme [4]. Due to immense incentives wind power and photovoltaic have imposed as the most propulsive RES technologies. In 2009 the worldwide wind power capacity reached 159 GW with annual growth rate of 32% [5], while the installed photovoltaic (PV) capacity in the same year reached 20 GW, with annual growth rate of 44% [6].

Nevertheless, the feed-in incentives have a time limit after which RESs will become non-favorized agents on the market. Exposing RES to the rigorous market environment presents a serious challenge for the RES owners. The prime reason for this is the uncertainty of forecasted power output of the most important RES. For instance, wind power plants (WPP) are inherently intermittent due to the stochastic nature of wind, and PV power plants' output depends on the solar irradiation and clouds [7]. Thus, the risk of not meeting the mid-term and long-term electricity delivery contracts is significant. In order to diversify this risk different types of renewable and non-renewable generators and storage devices are combined into a single virtual power plant (VPP). VPP enables the associated RES to pose in the electricity market as a single power plant with defined hourly output [8]. A virtual power plant, sometimes referred to as virtual utility [9], contains a mixture of different generators. A well-chosen mix of generating technologies can offset the inherent unreliability of some RES generators in order to set up a VPP which can be treated as a conventional one [10]. From the point of view of any other market agent a VPP is a unique entity, although in reality it represents a mix of multiple distributed energy resources (DER) and conventional power plants [11]. Incorporating distributed power plants into a single legal subject with substantially higher installed capacity obligates the VPP owner to connect its power plant to the transmission instead of the distribution grid. From the point of view of the Transmission System Operator (TSO), the VPP is a single power plant. Therefore, the VPP internal dispatch is strictly the problem of its owner and is crucial in order to achieve optimal results in the electricity market.

In case of the voluntary pool, generating companies have both open market and bilateral contracts at their disposal [12]. Bilateral contracts are concluded in the long-term. Major reasons for bilateral contracting are price volatility and possible TSO constraints. Each generating company decides how much of its capacity will be contracted bilaterally in advance, and how much will be offered in the market. On the other hand, market trading may have various time effects, ranging from the day-ahead to the balancing real-time market [13]. In this paper the day-ahead market based on hourly bids is considered.

MODEL DESRIPTION

Model assumptions

The VPP model consists of WPP, PV power plant, conventional gas turbine power plant, and hydro pumped storage (HPS). The WPP and PV output is considered stochastic and therefore provided by various scenarios. In order to preserve the linearity of the model, the quadratic CPP fuel cost function is given by its piecewise linear approximation. Having HPS system at its disposal, the VPP owner has the possibility of moving energy from some hours to the others, trying to optimize the operational profit defined as the difference between market incomes and variable costs [14].

Virtual power plant has bilateral contract which has to be fulfilled. The considered time horizon is one week, divided into 168 hours. The bilateral contract allows the discrepancy of 10% between the contracted and delivered electricity in each hour, but at the end of the week the amount of delivered electricity has to be equal to the contracted one. VPP also participates in the electricity market, where it can buy and sell electricity, strictly as a price taker. This assumption is valid due to the relatively small installed capacity of the VPP [15].

Uncertainty modelling

The described problem has three sources of uncertainty. First one is the WPP output due to its direct dependency on the stochastic nature of the wind speed. The second one is the PV output due to its dependency on the weather, especially cloudiness. Finally, the third source of uncertainty are prices in the electricity market which are known only after all producers and consumers submit their selling offers and purchase bids, respectively. Therefore, the market prices are anticipated based on the historical data and additional information which include river inflows (provides information on power capacity of hydro power plants in the system), power plant outages etc. In order to appropriately address all these uncertainties an adequate stochastic programming framework is used.

A stochastic process is said to be continuous or discrete if its variables are continuous or discrete, respectively [16]. Solving stochastic models with continuous stochastic processes is very difficult and often impossible. Therefore, the discrete representation of random variables is used to solve large scale models. The discrete stochastic processes are easy to embed into mathematical programming models which are solvable with the currently available branch-and-cut solvers in the reasonable amount of time [17]. For uncertainty modelling purposes in this paper, all three uncertain parameters are modelled by a set of finite outcomes, i.e. scenarios.

Formulation

The model is formulated as follows:

Maximize

$$\sum_{t=1}^{T}\left(\sum_{w=1}^{n_w}\pi(w)\cdot\sum_{s=1}^{n_s}\pi(s)\cdot\sum_{p=1}^{n_p}\pi(p)\cdot\left(\lambda^{p}(t)\cdot G^{wsp}(t)-C_{\mathrm{conv}}^{wsp}(t)-y_{\mathrm{conv}}^{wsp}(t)\cdot S_{\mathrm{conv}}\right)\right) \tag{1}$$

subject to:

$$x_{\mathrm{conv}}^{wsp}(t)\in\{0,1\},\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{2}$$

$$y_{\mathrm{conv}}^{wsp}(t)\in\{0,1\},\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{3}$$

$$g_{\mathrm{conv}}^{wsp}(t)=\sum_{j=1}^{m}g_{\mathrm{conv},j}^{wsp}(t),\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{4}$$

$$C_{\mathrm{conv}}^{wsp}(t)=a\cdot x_{\mathrm{conv}}^{wsp}(t)+\sum_{j=1}^{m}k_j\cdot g_{\mathrm{conv},j}^{wsp}(t),\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{5}$$

$$g_{\mathrm{conv}}^{wsp}(t)\le g_{\mathrm{conv},j}^{\max}\cdot x_{\mathrm{conv}}^{wsp}(t),\ \forall j\le m,\forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{6}$$

$$g_{\mathrm{conv}}^{\min}\cdot x_{\mathrm{conv}}^{wsp}(t)\le g_{\mathrm{conv}}^{wsp}(t)\le g_{\mathrm{conv}}^{\max}\cdot x_{\mathrm{conv}}^{wsp}(t),\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{7}$$

$$-ramp\le g_{\mathrm{conv}}^{wsp}(t)-g_{\mathrm{conv}}^{wsp}(t-1)\le ramp,\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{8}$$

$$x_{\mathrm{conv}}^{wsp}(t)-x_{\mathrm{conv}}^{wsp}(t-1)\le y_{\mathrm{conv}}^{wsp}(t),\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{9}$$

$$g_{\mathrm{t}}^{wsp}(t)\le g_{\mathrm{t}}^{\max},\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{10}$$

$$g_{\mathrm{p}}^{wsp}(t)\le g_{\mathrm{p}}^{\max},\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{11}$$

$$\begin{gathered}storage^{wsp}(t)=storage^{wsp}(t-1)+g_{\mathrm{p}}^{wsp}(t)-g_{\mathrm{t}}^{wsp}(t),\\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p\end{gathered} \tag{12}$$

$$0\le storage^{wsp}(t)\le storage^{\max},\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{13}$$

$$0.9\cdot bc(t)\le d^{wsp}(t)\le 1.1\cdot bc(t),\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{14}$$

$$\sum_{t=1}^{T}d^{wsp}(t)=\sum_{t=1}^{T}bc(t),\ \forall t\le T,\forall w\le n_w,\forall s\le n_s,\forall p\le n_p \tag{15}$$

$$g^{w}(t)+g^{s}(t)+g_{\mathrm{conv}}^{wsp}(t)+g_{\mathrm{t}}^{wsp}(t)=d^{wsp}(t)+G^{wsp}(t)+\frac{g_{\mathrm{p}}^{wsp}(t)}{\mu}+r^{wsp}(t) \qquad (16)$$
$$\forall t\le T,\forall w\le n_{w},\forall s\le n_{s},\forall p\le n_{p}$$

$$g_{\mathrm{conv}}^{w_1s_1p_1}=g_{\mathrm{conv}}^{w_1s_1p_2}=g_{\mathrm{conv}}^{w_1s_1p_3}=...=g_{\mathrm{conv}}^{w_1s_2p_1}=...=g_{\mathrm{conv}}^{n_wn_sn_p},\ \forall t\le T \qquad (17)$$

$$g_{\mathrm{t}}^{w_1s_1p_1}=g_{\mathrm{t}}^{w_1s_1p_2}=g_{\mathrm{t}}^{w_1s_1p_3}=...=g_{\mathrm{t}}^{w_1s_2p_1}=...=g_{\mathrm{t}}^{n_wn_sn_p},\ \forall t\le T \qquad (18)$$

$$g_{\mathrm{p}}^{w_1s_1p_1}=g_{\mathrm{p}}^{w_1s_1p_2}=g_{\mathrm{p}}^{w_1s_1p_3}=...=g_{\mathrm{p}}^{w_1s_2p_1}=...=g_{\mathrm{p}}^{n_wn_sn_p},\ \forall t\le T \qquad (19)$$

$$G^{w_1s_1p_1}=G^{w_1s_1p_2}=G^{w_1s_1p_3}=...=G^{w_1s_2p_1}=...=G^{n_wn_sn_p},\ \forall t\le T \qquad (20)$$

The notation used in the model is provided in the Nomenclature section at the end of the paper.

The objective function (1) is a profit maximization function which considers the electricity sold/purchased in the market, CPP production and CPP start-up cost. It is important to note that the objective function (1) does not contain revenue from bilateral contracts, since they were negotiated in the past at a fixed price. In order to calculate the real profit during the week the value of bilateral contract should be added to the objective function.

Constraints (2) and (3) are binary variables declarations. Constraints (4) state that the CPP output is equal to the summation of all production levels *j* in each time period for each WPP production, PV production and market price scenario, while constraints (5) define the CPP production costs also for each time period and each WPP production, PV production and market price scenario. Constraints (6) define the output of each CPP production level. Constraints (7) define the CPP output limits regarding its technical minimum and production capacity, and constraints (8) regarding its ramp limits. Constraints (9) are used to define the CPP start-up binary variable.

Constraints (10) and (11) are HPS turbine and pump capacities limits, respectively. Constraints (12) are used to define the available energy storage at the end of each time period, while constraints (13) are upper basin energy storage limits.

Constraints (14) ensure that the bilaterally delivered electricity in each hour is between 90% and 110% of the contracted amount, since hourly discrepancy between contracted and delivered electricity is set to 10% of bilaterally contracted electricity delivery. Constraints (15) state that bilaterally contracted and delivered electricity within the time horizon of one week have to be equal. Constraints (16) are energy balance constraints. They state that the summation of the overall produced electricity has to be equal to the electricity delivered according to bilateral contract, electricity sold in the market, and electricity used for pumping water in the hydro pump storage upper basin. Variable $r(t)$ denotes the electricity surplus depending on the scenario realization.

Constraints (17) are the CPP non-anticipativity constraints and reflect the fact that information on scenarios cannot be anticipated. This indicates that we cannot know which scenario will come true. Therefore, the CPP operation is optimized taking into consideration the probability of each scenario. In other words, constraints (17) are necessary to model the fact that only one bidding curve can be submitted to the day-ahead market for each hour, irrespective of the wind power, solar power and market price realizations [18]. Constraints (18) and (19) are the non-anticipativity constraints for HPS turbine and pump operation, respectively.

Since bids are submitted before knowing the market prices, WPP output or PV output, the VPP electricity offers/bids submitted in all scenarios have to be the same, which is reflected through constraints (20).

CASE STUDY

VPP description

The VPP presented in the case study consists of WPP, PV power plant, HPS and gas turbine CPP. The rated capacities of WPP and PV are 9.6 and 6 MW, respectively. HPS is modelled as an isolated system with energy value of accumulation set to 40 MWh. The turbine and pump regime capacities are 8 and 6 MW, respectively. The water volume storage is expressed as equivalent energy. Also, it is considered that HPS system has no additional inflows in the upper basin, i.e. it can use only the water pumped from the lower basin which always contains enough water for pumping to the upper basin.

The CPP is based on TAU5670 turbine [19] with 5.67 MW rated capacity. Its technical minimum is 2.5 MW, and ramp level is 3 MW/hour. The CPP cost curve is approximated using a 3-part piecewise linear approximation provided in Figure 1.

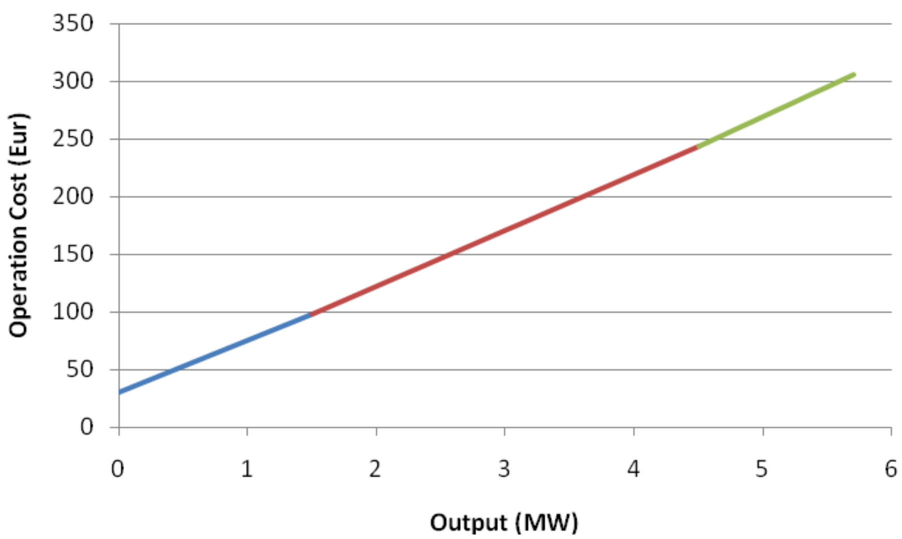

Figure 1. Linear piecewise approximation of the CPP production cost curve

Input parameters

The time horizon of one week is divided into 168 hourly time periods. Bilateral electricity delivery contracts which VPP must fulfil are provided in Figure 2. In order to diversify the risk of not meeting the bilaterally contracted electricity delivery and/or incurring significant economical losses, the minimum hourly amount of bilaterally contracted electricity delivery is set to 2.5 MW, i.e. the technical minimum of the CPP. The overall amount of electricity to be delivered due to bilateral contract is 726.8 MWh.

Besides having bilateral contracts, VPP also acts in the electricity market. Since the prices are not deterministic, they are modelled by five equally likely scenarios shown in Figure 3. The electricity prices used are actual prices on the EEX in time period May 31 – June 20, 2010 and June 01 – 14, 2009 [20].

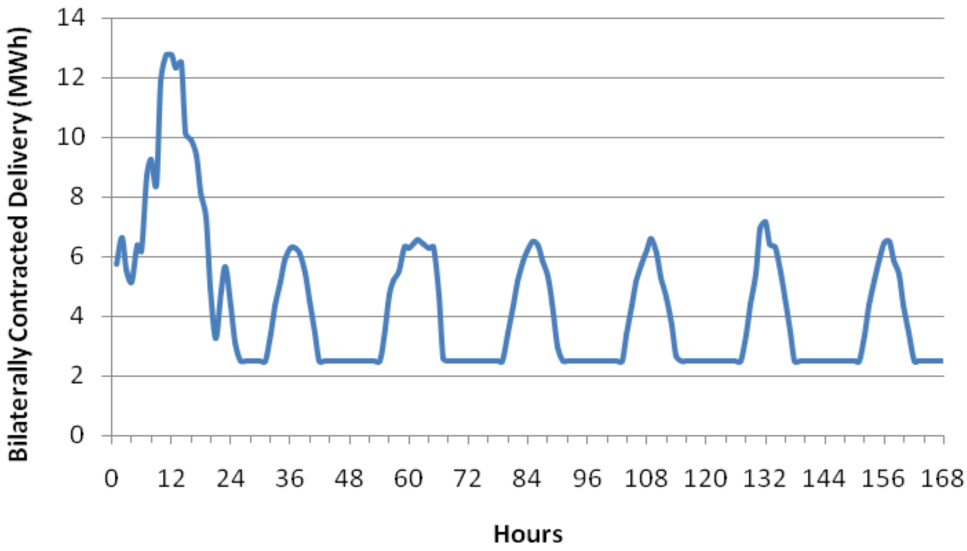

Figure 2. Bilaterally contracted electricity delivery

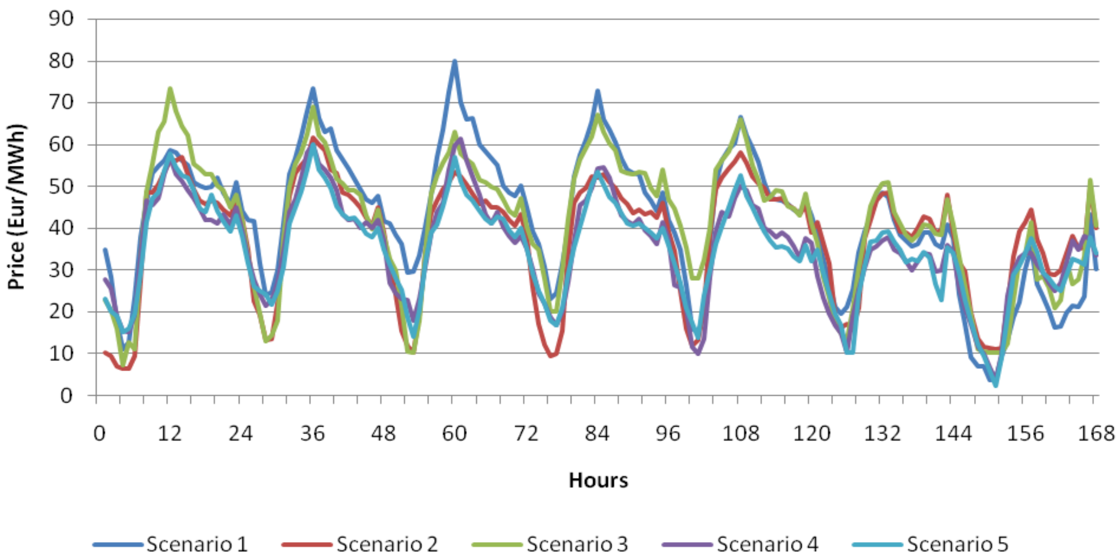

Figure 3. Estimated electricity prices in the market

The estimated power output of WPP provided in Figure 4 is based on the actual output of the WPP already operating in Šibenik County in Croatia in time period May 31 – June 20, 2010 and June 01 – 14, 2009. These 5 week measurements are divided into 5 scenarios, each with identical probability of 20%. Thus, the timeframe of electricity prices in the EEX used in the model is correlated with the electricity production of the actual WPP in the Šibenik County.

Figure 5 shows the expected PV power plant electricity production in five equally probable scenarios based on the solar irradiation data for the Šibenik County given in [21].

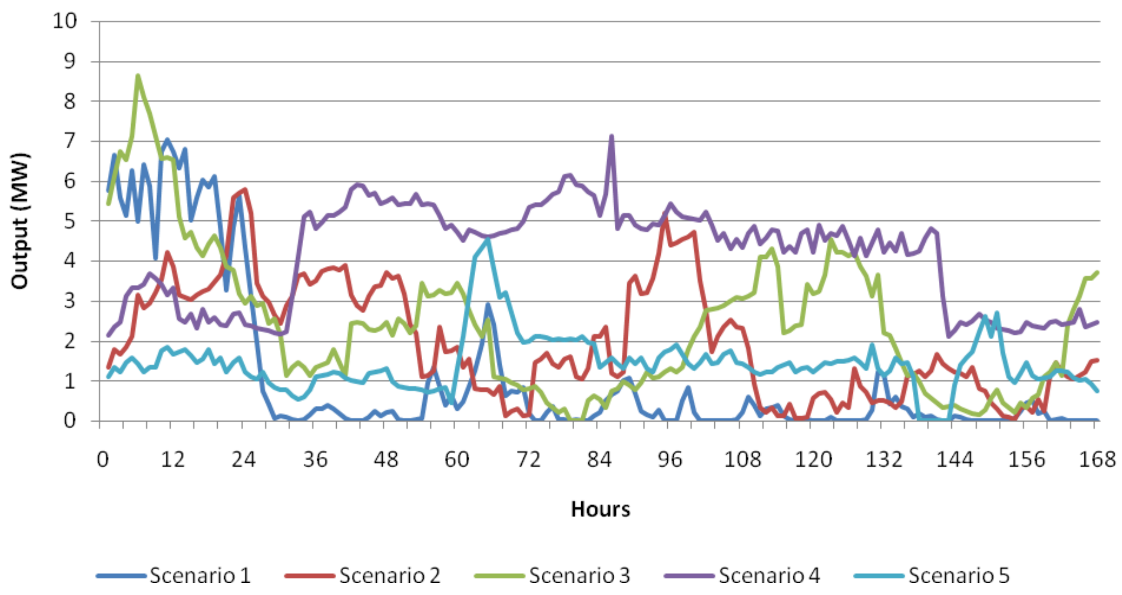

Figure 4. Estimated power output of the WPP

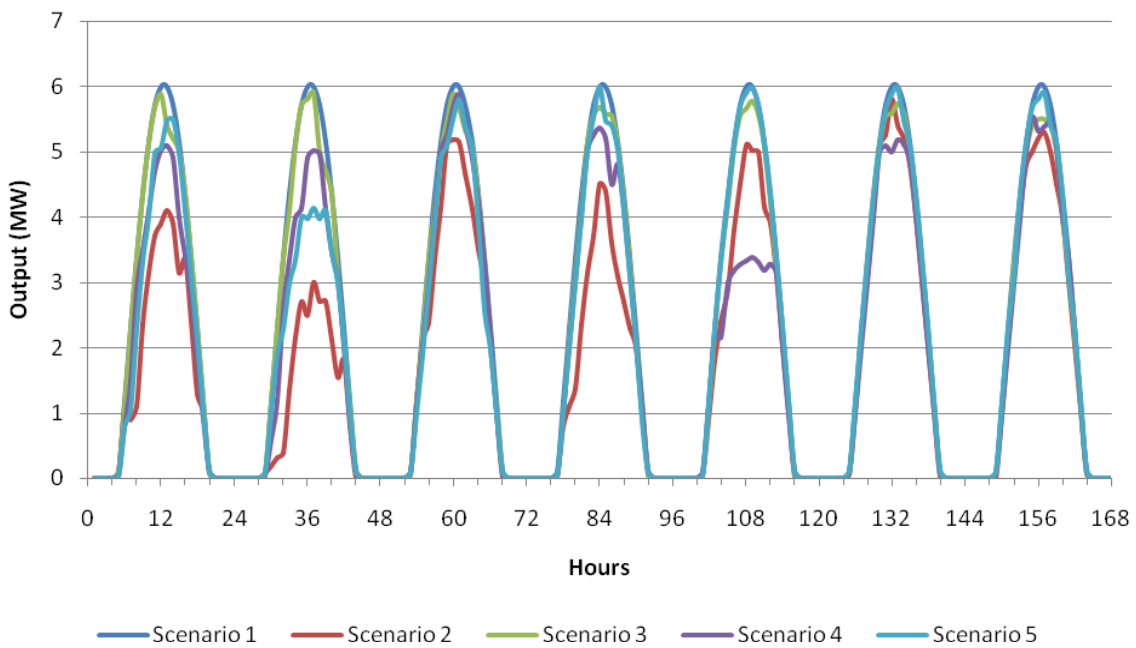

Figure 5. Estimated power output of PV power plant

The upper basin of HPS was empty at the beginning of the regarded week, and there are no constraints regarding the water level of the upper basin at the end of the week. The efficiency of the HPS system is set to 70%.

Results

The expected overall weekly profit is -6 215 Eur. The value is negative since it does not include the value of bilateral contract. If value of electricity contract is assumed to be 30 Eur/MWh, the overall weekly profit is 15 588 Eur. Cumulative profit in electricity market at the end of each hour is shown in Figure 6. The negative profit in most hours reflects purchased electricity in order to satisfy the electricity delivery bilateral contract, but also to pump water to the upper basin of the HPS system in order to sell it in high-price time periods.

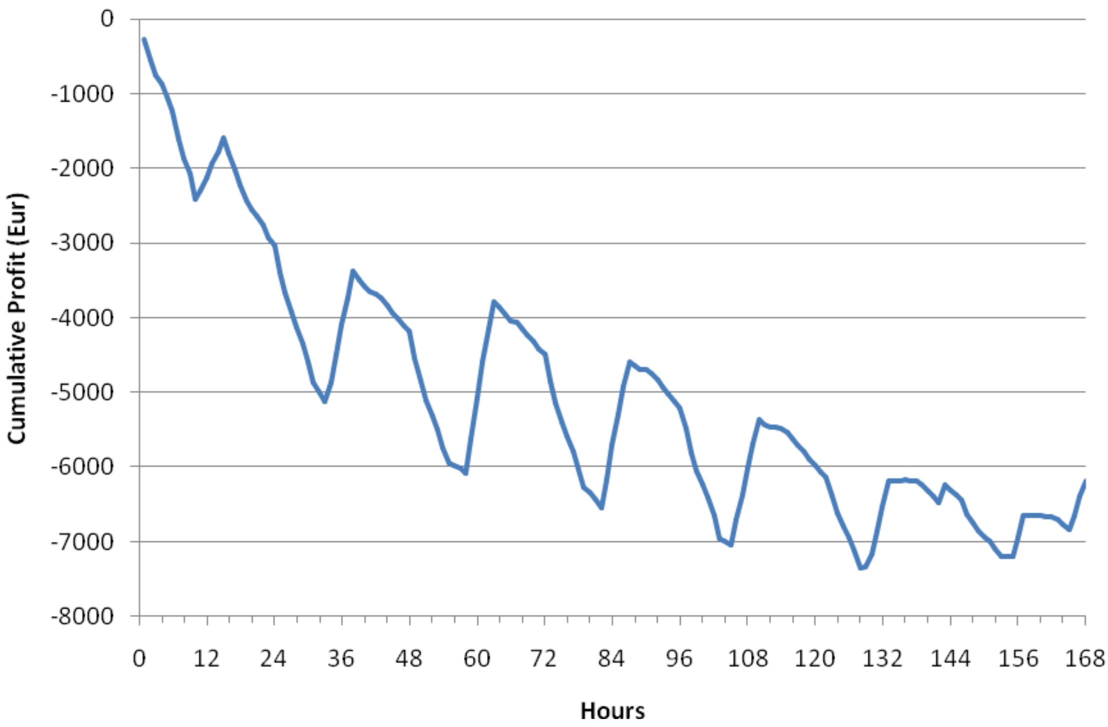

Figure 6. Cumulative profit in electricity market at the end of each hour

Bilaterally contracted and delivered electricity curves are provided in Figure 7. Since the allowed discrepancy between bilaterally contracted and delivered electricity is ±10%, in time periods in which the expected market price is high the maximum allowed amount of electricity is sold in the market, and vice versa, if the market price is low, additional electricity is purchased to replace the deficit in delivered electricity in time periods with high market price. For this reason the scenario delivered electricity curves are dispersed around bilaterally contracted electricity delivery curve (black dotted line).

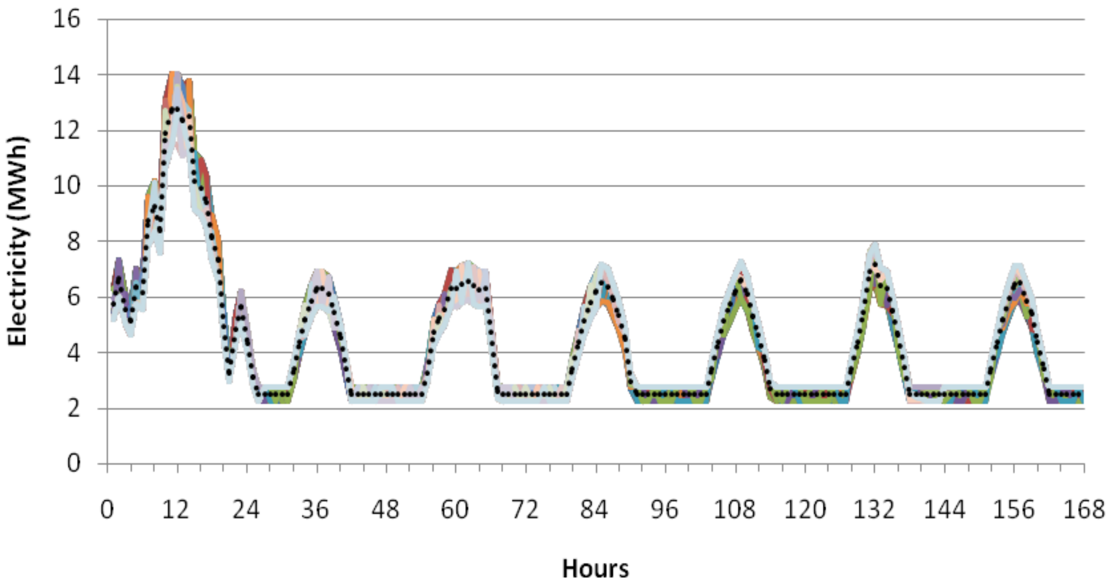

Figure 7. Graph of bilaterally contracted (black dotted line) and delivered electricity in all scenarios

As can be seen in Figure 8, the VPP activity in the market is in direct correlation with the expected market price. Namely, the VPP sells electricity when the price is high and purchases electricity during the night, when the price is lower. The purchased electricity is used both for settling the bilateral contract commitments and pumping the water into HPS upper reservoir.

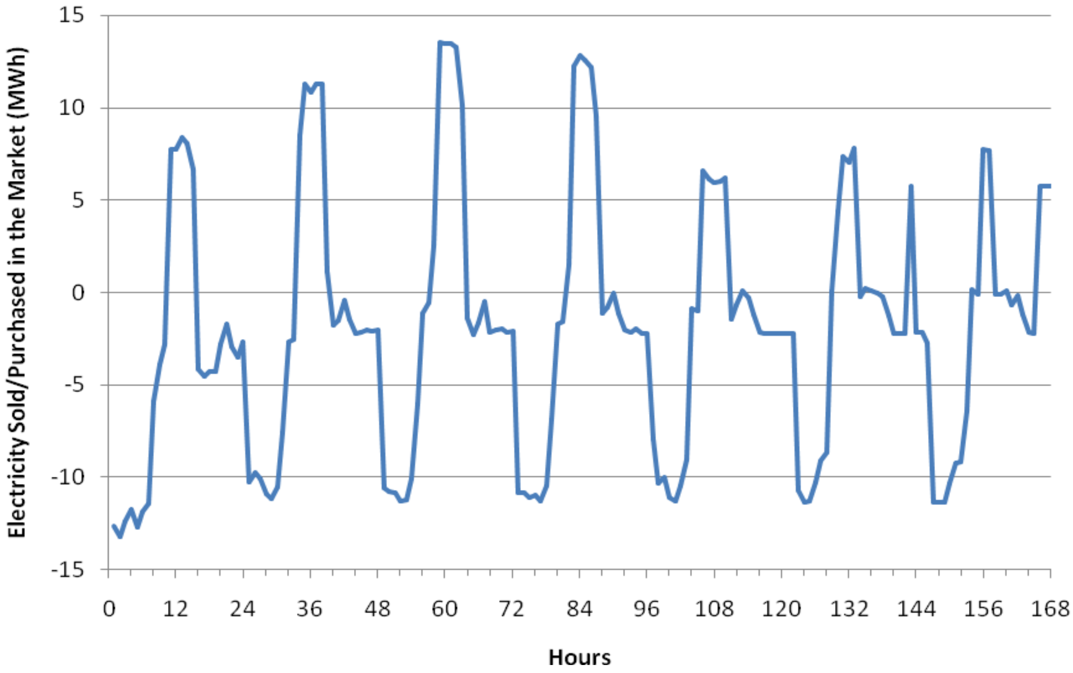

Figure 8. Electricity sold/purchased in the market

Since the presented model is stochastic, and the electricity market bids/offers, HPS operation and CPP operation are deterministic, each scenario has expected electricity surpluses shown in Figure 9. These surpluses vary between 67 and 650 MWh per week, depending on the scenario. Relatively large expected electricity surpluses are the consequence of compulsory bilateral contract fulfilment and significant variation between various scenario parameters, i.e. the solution in each hour has to satisfy all the electricity delivery constraints for the worst case scenario in the regarded hour. However, the electricity surplus may be sold in adjustment and balancing electricity market, which will bring extra profit to the VPP owner, not considered in this paper.

Figure 10 shows the amount of electricity produced by the CPP compared to the electricity market prices. The CPP, in order to make profit, produces electricity when the electricity price in the market is favourable. This is the case in time periods 10-15; 34-39; 58-63; 82-87, which correspond to first four days of the week. On Friday and during the weekend the anticipated market prices are low and the CPP stays shut-down. The reason for relatively small production of CPP are generally low electricity prices in the market compared to the CPP generation cost.

Since VPP is considered to be the price taker, when CPP produces electricity it produces at its maximum capacity and the possible surplus of electricity is sold in the market. During the regarded week the CPP produced 114.72 MWh of electricity which cost 6224 Eur.

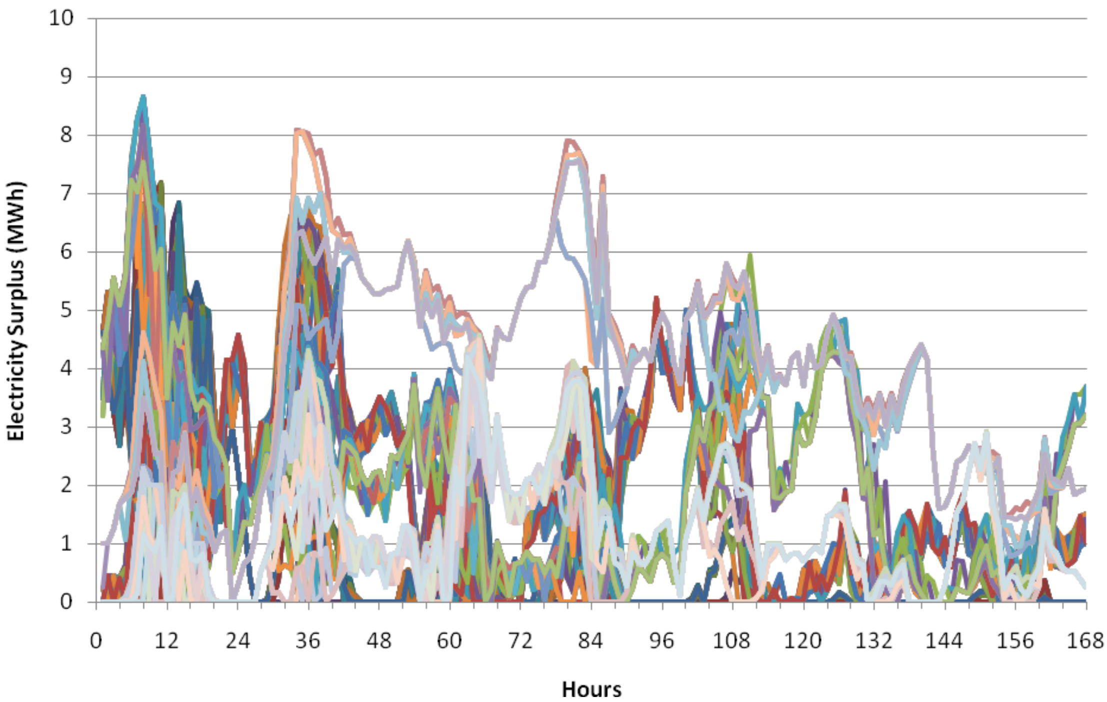

Figure 9. Electricity surplus for each scenario

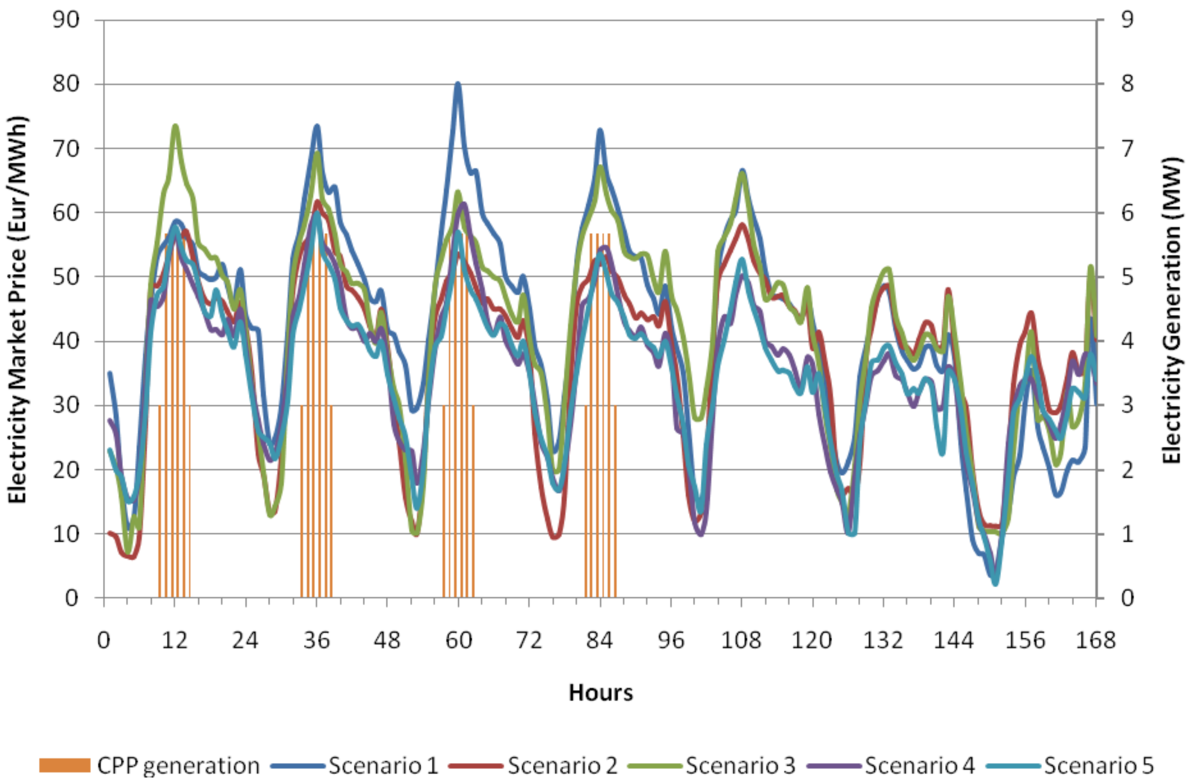

Figure 10. Electricity produced by the CPP compared to the electricity market prices

The HPS status compared to turbine and pump power is given in Figure 11. During weekdays a pump/turbine regime of HPS is periodically changing during the day. The HPS pumps water to the upper basin during the night and produces electricity approximately between 11 AM and 3 PM, when the expected daily prices are highest. On Saturday and Sunday, some water in the upper basin is preserved for the evening peak consumption.

The HPS works in pump regime during 48 and in turbine regime during 35 time periods, which is the result of greater turbine capacity (8 MW) compared to the pump capacity (6 MW).

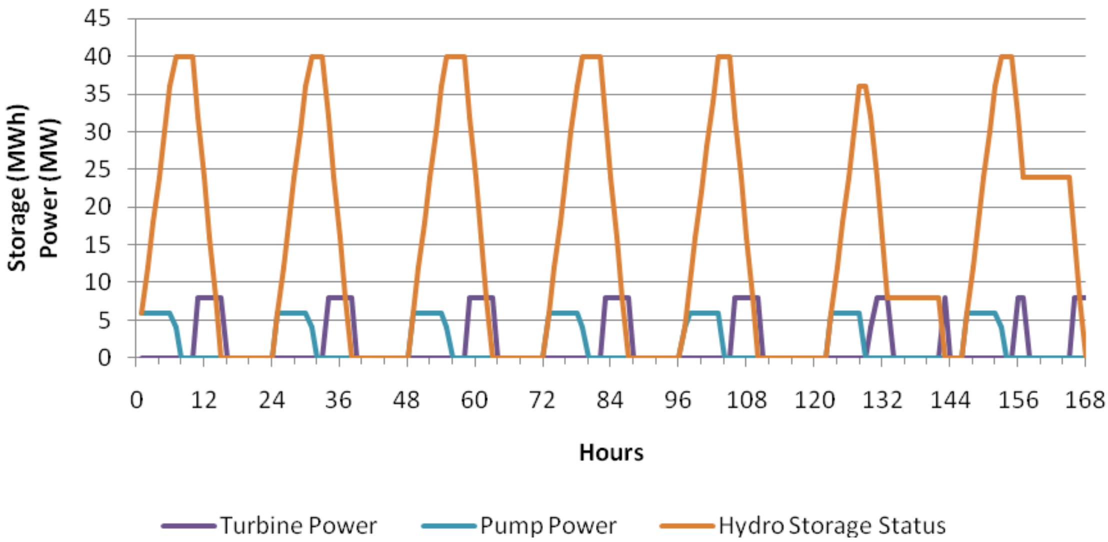

Figure 11. HPS status compared to turbine and pump power

The role of the HPS

In order to perceive the impact of the HPS upper basin volume on the VPP profit the optimization results for various upper basin volumes are provided in Table 1. Having even small volume accumulation HPS system significantly improves the profit of VPP owner. Nevertheless, after a certain volume, in our case 50 MWh, the objective function value stops increasing. This is because the pump and turbine installed capacity acts as the bottleneck for manipulating greater amount of water in the HPS system.

Table 1. Objective function values and overall weekly profit (including 30 Eur/MWh assumed bilateral contract value) for various HPS system upper basin volumes

Accumulation Volume (MWh)	Objective Function (Eur)	Overall Profit (Eur)
0	-12 159	9 644
10	-9 707	12 096
20	-7 920	13 883
30	-6 658	15 145
40	-6 215	15 588
50	-6 160	15 643
60	-6 160	15 643
70	-6 160	15 643
80	-6 160	15 643

CONCLUSION

The model proposed in this paper is intended to help the VPP owner maximize its profit in the weekly timeframe. The conclusions derived from the model are following:

1. It is important to have well-balanced generator capacities. Having significantly larger capacity in non-controllable generators, such as WPP, in regard to the controllable ones does not provide large enough security margin of not meeting the bilaterally contracted electricity delivery and/or incurring great economical losses.
2. Having as cheapest and flexible possible CPP is a great advantage since it provides extra revenue.
3. The capacity of the HPS system has to be well-balanced in order to provide sufficient span of electricity production from night-time to daytime.

The future research will be focused on mid-term and long-term VPP operation scheduling. This is considered to be relevant for determining the specific role of the HPS upper basin capacity. It is considered that in a long-term the role of a very large accumulation will be of high importance.

NOMENCLATURE

Acronyms:

CPP	Conventional Power Plant
DER	Distributed Energy Resources
EEX	European Energy eXchange
PV	PhotoVoltaic
RES	Renewable Energy Sources
TSO	Transmission System Operator
VPP	Virtual Power Plant
WPP	Wind Power Plant

Parameters:

a	minimum cost production of CPP (Eur),
$bc(t)$	bilaterally contracted electricity delivery in time period t (MW),
$g_{\text{conv}}^{\max}$	CPP installed capacity (MW),
$g_{\text{conv},j}^{\max}$	capacity of the j-th CPP production level (MW),
$g_{\text{conv}}^{\min}$	CPP technical minimum (MW),
k_j	slope of the j-th segment of the CPP production cost curve (Eur/MW),
$g_{\text{p}}^{\max}$	pump capacity of the HPS (MW),
$g_{\text{t}}^{\max}$	turbine capacity of the HPS (MW),
$g^{s}(t)$	PV output in time period t for s-th solar scenario (MW),
$g^{w}(t)$	WPP output in time period t for w-th wind scenario (MW),
m	number of parts of linearized CPP production cost curve,
n_p	number of electricity market price scenarios,
n_s	number of PV output scenarios,
n_w	number of WPP output scenarios,
$\pi(p)$	probability of p-th electricity market price scenario,

$\pi(s)$	probability of s-th PV output scenario,
$\pi(w)$	probability of w-th WPP output scenario,
$ramp$	CPP maximum hourly increase/decrease of electricity production (MW/h),
$storage^{\max}$	energy capacity of the HPS upper basin (MWh),
S_{conv}	CPP start-up cost (Eur),
T	number of time periods,
$\lambda^{p}(t)$	electricity price in the market in price scenario p (Eur/MWh),
μ	HPS system efficiency factor.

Variables:

$C^{wsp}(t)$	cost of CPP electricity production in time period t, WPP output scenario w, PV output scenario s and price scenario p (Eur/MWh),
$d^{wsp}(t)$	electricity delivered due to bilateral contracts in time period t, WPP output scenario w, PV output scenario s and price scenario p (MWh),
$g_{\text{conv}}^{wsp}(t)$	CPP output in time period t, WPP output scenario w, PV output scenario s and price scenario p (MW),
$g_{\text{conv},j}^{wsp}(t)$	CPP production level j output in time period t, WPP output scenario w, PV output scenario s and price scenario p (MW),
$g_{\text{p}}^{wsp}(t)$	pump output of the HPS in time period t, WPP output scenario w, PV output scenario s and price scenario p (MW),
$g_{\text{t}}^{wsp}(t)$	turbine output of the HPS in time period t, WPP output scenario w, PV output scenario s and price scenario p (MW),
$G^{wsp}(t)$	if positive, electricity sold in the market, if negative, electricity purchased in the market in time period t, WPP output scenario w, PV output scenario s and price scenario p (MWh),
$r^{wsp}(t)$	electricity surplus in time period t, WPP output scenario w, PV output scenario s and price scenario p (MWh),
$storage^{wsp}(t)$	energy stored in the upper basin of HPS at the end of time period t, in WPP output scenario w, PV output scenario s and price scenario p (MWh),
$x_{\text{conv}}^{wsp}(t)$	binary variable equal to 1 if CPP is producing electricity in time period t, WPP output scenario w, PV output scenario s and price scenario p, and 0 otherwise,
$y_{\text{conv}}^{wsp}(t)$	binary variable equal to 1 if CPP is started-up in time period t, WPP output scenario w, PV output scenario s and price scenario p, and 0 otherwise.

REFERENCES

1. Cavallo, A., Controllable and affordable utility-scale electricity from intermittent wind resources and compressed air energy storage (CAES), *Energy*, Vol. 32, No. 2, pp 120–127, 2007.
2. Erneuerbare-Energien-Gesetz, *Bundesgesetzblatt*, Vol. 1, No. 40, pp 1918, 2004.
3. Real Decreto 661/2007, *Boletin Oficial del Estado*, Vol. 126, pp 22846, 2007.
4. Renewables Obligation, *Queen's Printer of Acts of Parliament*, 2002.

5. WWEA: World Wind Energy Report 2009, March 2010.
6. International Energy Agency, Trends in Photovoltaics Applications – Survey report of selected IEA countries between 1992 and 2009, *Photovoltaic Power Systems Programme*, 2010.
7. Wanjiku, J., Khan, M., Barendse, P., and Sebitosi A., Analytical Sizing of an Electrolyser for a Small Scale Wind Electrolysis Plant, *Proceedings of EnergyCon 2010*, December 18-22, 2010, pp 1–6.
8. Koeppel, G., Distributed Generation Literature Review and Outline of the Swiss Situation, *Report*, pp 12 – 13, November 2003.
9. Bayegan, M., A Vision of the Future Grid, *IEEE Power Engineering Review*, Vol. 21, No. 12, pp 10 – 12, December 2001.
10. Kuzle, I., Zdrilić, M., and Pandžić, H., Virtual Power Plant Dispatch Optimization Using Linear Programming, *Proceedings of 10th International Conference on Environment and Electrical Engineering*, Rome, May 8-11, 2011, pp 514-517.
11. Oyarzabal, J., Marti, J., Ilo, A., Sebastian, M., Alvira, D., and Johansen, K., Integration of DER into power system operation through Virtual Power Plant concept applied for voltage regulation, *CIGRE/IEEE PES Joint Symposium*, Calgary, July 29-31, 2009.
12. Tešnjak, S., Banovac, E., and Kuzle, I., *Electricity Energy Market* (in Croatian). Graphis, 2010.
13. Klessmann, C., Nabe, C., and Burges, K., Pros and cons of exposing renewables to electricity market risks–A comparison of the market integration approaches in Germany, Spain, and the UK, *Energy Policy*, Vol. 36, No. 10, pp 3646 – 3661, 2008.
14. Harcia-Gonzales, J., Moraga, R., Matres, L., Mateo, A., Stochastic joint optimization of wind generation and pumped-storage units in an electricity market, *IEEE Transactions on Power Systems*, Vol. 23, No. 2, pp 460-468, May 2008.
15. Zdrilić, M., Pandžić, H. and Kuzle, I., The Mixed-Integer Linear Optimization Model of Virtual Power Plant Operation, *Proceedings of 8th International Conference on the European Energy Market*, Zagreb, May 25-27, 2011, pp 467-471.
16. Birge, J.R. and Louveaux, F., *Introduction to Stochastic Programming*, Springer, 1997.
17. Conejo, A.J., Carrion, M. and Morales, J.M., *Decision Making Under Uncertainty in Electricity Markets*, Springer, 2010.
18. Morales, J.M., Conejo, A.J., and Perez-Ruiz, J., Short-Term Trading for a Wind Power Producer, *IEEE Transactions on Power Systems*, Vol. 25, No. 1, pp 554-564, February 2010.
19. European Energy Exchange: Hourly Contracts. [Online]. Available: http://www.eex.com
20. Solar Turbines: Home. [Online]. Available: http://mysolar.cat.com/cda/layout
21. Matić, Z., *Solar Irradiation in Croatia* (in Croatian). Energy Institute Hrvoje Požar, 2007.