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Optimal Operation of a Virtual Power Plant in a Day-Ahead Market Considering Uncertainties of Renewable Generation and Risk Evaluation

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Abstract: The air pollution and global warming because of the increasing usage of fossil fuels with the rapid growth of technology are some of the major problems for many countries. To cope with these problems, distributed energy resources (DERs) including renewable sources are adding into the modern power systems as an alternative to traditional generation. However, the uncertain nature of some sources such as wind power and photovoltaic power leads to variable output and instability of the power system. Virtual Power Plant (VPP) is a convenient solution to overcome these challenges in the power system. It aggregates various DERs including renewable-based and fueled-based generation, storage systems and dispatchable loads. In this study, the optimum operating strategy of a VPP consisting of a Wind Power Plant (WPP), a Photovoltaic Power Plant (PVPP), a Conventional Power Plant (CPP) and a Pumped Hydro Storage Plant (PHSP) is determined to maximize the profit in a Day-Ahead Market (DAM). The uncertainty analysis for the intermittent renewable power generation is made by modeling the uncertain parameters (wind speed and solar radiation) with scenarios based upon historical data. Moreover, the risk of low-profit scenarios is evaluated by using Conditional Value at Risk (CVaR) as a risk measure.

Keywords : virtual power plant, day ahead market, profit, uncertainty, risk

Gün Öncesi Piyasasında Sanal Güç Santralinin Yenilenebilir Üretim Belirsizliklerini ve Risk Değerlendirmesini Göz Önünde Bulundurarak Optimum İşletilmesi

Öz: Teknolojinin hızla büyümesi ile artan fosil yakıt tüketimine bağlı olarak oluşan hava kirliliği ve küresel ısınma, birçok ülke için büyük sorun oluşturan problemlerdendir. Bu sorunlarla başa çıkmak için, yenilenebilir kaynakları içeren dağıtık enerji kaynakları (DEK), modern güç sistemlerine geleneksel üretime alternatif olarak eklenmektedirler. Bununla birlikte, rüzgâr enerjisi ve fotovoltaik enerji gibi bazı kaynakların belirsiz doğası, güç sisteminin değişken çıkışına ve kararsızlığına yol açmaktadır. Sanal Güç Santrali (SGS), güç sistemindeki bu zorlukların üstesinden gelmek için uygun bir çözümdür. SGS, yenilenebilir ve yakıt bazlı üretim sistemleri, depolama sistemleri ve yönetilebilir yüklerden oluşan dağıtık enerji kaynaklarını bir araya toplamaktadır. Bu çalışmada, bir Rüzgâr Enerjisi Santrali (RES), bir Fotovoltaik Enerji Santrali (FVES), bir Konvansiyonel Enerji Santrali (KES) ve bir Pompaj Depolamalı Hidroelektrik Santral (PDHS) içeren bir SGS'nin optimum işletme stratejisi, Gün Öncesi Piyasasında (GÖP) maksimum kâr elde edecek şekilde belirlenmiştir. Kesintili yenilenebilir enerji üretimi için belirsizlik analizi, belirsiz parametrelerin (rüzgâr hızı ve güneş radyasyonu) geçmiş verilere dayanan senaryolarla modellenmesi ile yapılmıştır. Ayrıca, düşük kâr senaryoları riski, bir risk ölçütü olan Koşullu Riske Maruz Değer (CVaR) kullanılarak değerlendirilmiştir.

Anahtar kelimeler: sanal güç santrali, gün öncesi piyasası, kâr, belirsizlik, risk

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1. Introduction

Today, it has become increasingly necessary to integrate new distributed generation systems into distribution networks [1]. The integration of renewable energy sources (RES) that are the form of distributed energy resources (DERs) into the power systems has grown significantly due to being more applicable and providing clean energy. However, they bring some challenges to power system operators and owners because of uncoordinated operation, their intermittent energy output and being difficult to control. The Virtual Power Plant (VPP) technology is introduced in order to terminate these concerns. The VPP can efficiently integrate the distributed generations that are in discrete regions with the technology of information and control them by energy management systems [2,3]. The VPP can attain coordinated operation of the distributed generations, reduce the uncertainties and increase the total profits.

In recent years, relevant studies are carrying out optimal operation and bidding of a VPP in the energy markets. Sharma and Mishra have studied on a state power utility to establish the potential of VPP and its effectiveness [4]. Sadeghian et al. have formed a VPP including distributed generations in the power grid and presented a risk-based programming for maintenance control [5]. Sun et al. have performed a stochastic adaptive robust dispatch model for a VPP by considering the risks due to uncertainties in the electricity market prices and photovoltaic (PV) energy outputs [6]. Shafiekhani et al. have presented a method for the optimal strategic bidding of a VPP in the day-ahead and regulation markets to maximize the profit of the VPP and minimize its emission [7]. Liu et al. have provided an interval and deterministic combined optimization method to solve the dispatch problem for the virtual power plants [2]. Alahyari et al. have integrated electric vehicle storage capacity and wind generation to take part in the day-ahead and reserve market [8]. Zhao et al. have presented day-ahead scheduling strategies for a VPP consisting of concentrating solar power plant and some residential and industrial loads by considering risk constraints. They have considered the uncertainties of electricity price, thermal generation of the solar field and participation factor of residential demand response [9]. Baringo et al. have suggested a stochastic adaptive robust optimization (ARO) method for the self-scheduling of a VPP in energy and reserve electricity markets [10]. Kasaei has employed an imperialist competitive algorithm to minimize the total operating cost of the VPP consisting of different distributed generation and energy storage systems [11]. Kardakos and Simoglou have addressed the optimal bidding strategy problem of a commercial virtual power plant that is purposed to maximize the profit on the Greek power system [12]. Zhao et al. have proposed a novel control and bidding strategy for VPPs to minimize the cost in day-ahead and balancing markets by using local search algorithms to solve the problem [13]. Yang et al. have used GAMS software to find the optimal solution of the bidding strategy of the VPP in an auxiliary service market by considering the carbon-electricity integration trading [14]. Nosratabadi et al. have tried to determine the optimal VPP that has minimum long-term cost by using the binary particle swarm optimization algorithm. They have applied the presented model to the IEEE 33-bus distribution test network [15].

In this study, the optimal operating and bidding strategy of the VPP including a Wind Power Plant (WPP), a Photovoltaic Power Plant (PVPP), a Conventional Power Plant (CPP) and a Pumped Hydro Storage Plant (PHSP) and participating in the Day-Ahead Market (DAM) is determined. The problem aims to maximize the expected daily profit of the VPP. The uncertain parameters of wind speed and solar radiation are analyzed by using scenarios obtained from the historical data. Moreover, Conditional Value at Risk (CVaR) is used to control the risk of experiencing low-profit scenarios. The Mixed Integer Nonlinear Programming (MINLP) model is implemented in General Algebraic Modeling Systems (GAMS) software. The results show the effectiveness of the presented model and it can be used efficaciously by the VPP operators participating in the electricity market to get higher proceeds.

2. Model Formulation

The VPP model includes a WPP, a PVPP, a CPP, and a PHSP. The formulation of the VPP elements, the objective function, the risk modeling, and the energy balance are described below.

2.1. Wind Power Plant (WPP)

The output power of WPP depends on the wind speed of the region and the characteristics of the wind turbines. It is calculated by using Equation 1 [16].

$$\mathrm{P}_{s,t}^{wpp}(v_{s,t}) = N^{wind} \times \begin{cases} 0, & v_{s,t} < v_{in} \\ P_{rtd}^{wt} \times \left(\frac{v_{s,t}-v_{in}}{v_{rtd}-v_{in}}\right)^3, & v_{in} \le v_{s,t} \le v_{rtd} \\ P_{rtd}^{wt}, & v_{rtd} \le v_{s,t} < v_{out} \\ 0, & v_{out} \le v_{s,t} \end{cases} \tag{1}$$

where $\mathrm{P}_{s,t}^{wpp}$ is the output power of WPP at hour t and scenario s (MW), N^{wind} is the number of wind turbines in WPP, $v_{s,t}$ is the wind speed at hour t and scenario s (m/s), v_{in} , v_{rtd} , v_{out} are the cut-in, rated and cut-out wind speeds, respectively (m/s), P_{rtd}^{wt} is the nominal power of the wind turbine (MW).

2.2. Photovoltaic Power Plant (PVPP)

The output power of PVPP depends on the solar radiation and ambient temperature of the region and the characteristics of the PV panels. It is calculated by using Equations (2)-(6). [16].

$$T_{s,t}^{cell} = T_t^{amb} + SR_{s,t} \times \left(\frac{NOT_{cell}-20}{0.8}\right) \tag{2}$$

$$I_{s,t} = SR_{s,t} \times [I_{scc} + K_{ctc} \times (T_{s,t}^{cell} - 25)] \tag{3}$$

$$V_{s,t} = V_{ocv} - K_{vtc} \times T_{s,t}^{cell} \tag{4}$$

$$FL = \frac{V_{Max} \times I_{Max}}{V_{ocv} \times I_{scc}} \tag{5}$$

$$P_{s,t}^{pvpp}(SR_{s,t}) = N^{pv} \times FL \times V_{s,t} \times I_{s,t} \tag{6}$$

where $T_{s,t}^{cell}$ is the temperature of solar cell at hour t and scenario s (^{o}C), T_{t}^{amb} is the ambient temperature at hour t (^{o}C), $SR_{s,t}$ is the solar radiation at hour t and scenario s (kW/m^2), NOT_{cell} is the PV nominal operating cell temperature (^{o}C), I_{scc} is the short circuit current of PV panel (A), K_{ctc} is the current temperature coefficient of PV panel (A/^{o}C), V_{ocv} is the open-circuit voltage of PV panel (V), K_{vtc} is the voltage temperature coefficient of PV panel (V/^{o}C), FL is the fill factor of PV panel, V_{Max} is the voltage at maximum power point of PV panel (V), I_{Max} is the current at maximum power point of PV panel (A), N^{pv} is the number of PV panels in PVPP, $P_{s,t}^{pvpp}$ is the output power of PVPP at hour t and scenario s (MW).

2.3. Conventional Power Plant (CPP)

The total operation cost of the CPP is composed of the start-up cost of the unit and the generation cost of the unit as shown in Equation 7.

$$\mathrm{TOC}_{s,t}^{cpp} = SUC^{cpp} \times y_{s,t}^{cpp} + \left(a \times (P_{s,t}^{cpp})^2 + b \times P_{s,t}^{cpp} + c \times x_{s,t}^{cpp}\right) \tag{7}$$

where $\mathrm{TOC}_{s,t}^{cpp}$ is the total operation cost of the CPP at hour t and scenario s (\$/MWh), SUC^{cpp} is the start-up cost of the unit in CPP, $y_{s,t}^{cpp}$ is the binary variable equal to 1 if CPP is started up at hour t and scenario s (0 otherwise), a, b and c are cost coefficients of the unit in CPP, $x_{s,t}^{cpp}$ is the binary variable equal to 1 if CPP is generating electricity at hour t and scenario s (0 otherwise), $P_{s,t}^{cpp}$ is the power output of CPP unit at hour t and scenario s (MW). In Equation 7, the first term represents the start-up cost of the unit and the second term represents the generation cost of the unit. The lower and upper power limits of the CPP unit are shown in Equation 8.

$$P_{min}^{cpp} \times x_{s,t}^{cpp} \leq P_{s,t}^{cpp} \leq P_{max}^{cpp} \times x_{s,t}^{cpp} \tag{8}$$

where P_{min}^{cpp} is the lower power limit and P_{max}^{cpp} is the upper power limit for CPP unit (MW). The ramp limits of the CPP unit are shown in Equation 9.

$$P_{s,t}^{cpp} - P_{s,t-1}^{cpp} \leq P_{RU}^{cpp}, \quad P_{s,t-1}^{cpp} - P_{s,t}^{cpp} \leq P_{RD}^{cpp} \tag{9}$$

where P_{RU}^{cpp} is the ramp-up power limit and P_{RD}^{cpp} is the ramp-down power limit for CPP unit (MW). The start-up and shut-down binary variables of the CPP unit are set to prevent decision interference as shown in Equations (10)-(13).

$$x_{s,t}^{cpp} - x_{s,t-1}^{cpp} \leq y_{s,t}^{cpp} \tag{10}$$

$$x_{s,t-1}^{cpp} - x_{s,t}^{cpp} \leq z_{s,t}^{cpp} \tag{11}$$

$$y_{s,t}^{cpp} + z_{s,t}^{cpp} \leq 1 \tag{12}$$

$$x_{s,t}^{cpp} - x_{s,t-1}^{cpp} = y_{s,t}^{cpp} - z_{s,t}^{cpp} \tag{13}$$

where $z_{s,t}^{cpp}$ is the binary variable equal to 1 if CPP is shut down at hour t and scenario s (0 otherwise).

2.4. Pumped Hydro Storage Plant (PHSP)

The turbine and pump capacity limits are shown in Equation 14 and Equation 15, respectively.

$$P_{s,t}^{turbine} \leq P_{max}^{turbine} \times w_{s,t}^{turbine} \quad (14)$$

$$P_{s,t}^{pump} \leq P_{max}^{pump} \times w_{s,t}^{pump} \quad (15)$$

where $P_{s,t}^{turbine}$ is the turbine output of the PHSP at hour t and scenario s (MW), $P_{max}^{turbine}$ is the maximum turbine capacity of the PHSP (MW), $P_{s,t}^{pump}$ is the pump output of the PHSP at hour t and scenario s (MW), P_{max}^{pump} is the maximum pump capacity of the PHSP (MW), $w_{s,t}^{turbine}$ is the binary variable equal to 1 if PHSP is operated in turbine mode at hour t and scenario s (0 otherwise), and $w_{s,t}^{pump}$ s the binary variable equal to 1 if PHSP is operated in pump mode at hour t and scenario s (0 otherwise).

Equation 16 states that the turbine and pump modes of the PHSP cannot occur simultaneously.

$$w_{s,t}^{turbine} + w_{s,t}^{pump} \leq 1 \quad (16)$$

The energy stored in the upper basin of the PHSP is calculated as shown in Equation 18.

$$storage_{s,t}^{phsp} = (storage_{s,t-1}^{phsp} + P_{s,t}^{pump} - P_{s,t}^{turbine}) \times \Delta t \quad \Delta t = 1 \quad (17)$$

where $storage_{s,t}^{phsp}$ is the stored energy in the PHSP at hour t and scenario s (MWh).

The storage capacity limit is shown in Equation 18.

$$0 \leq storage_{s,t}^{phsp} \leq storage_{max}^{phsp} \quad (18)$$

where $storage_{max}^{phsp}$ is the maximum storage capacity of the PHSP (MWh).

2.5. Objective function

The problem aims to maximize the expected profit of the VPP in a DAM by considering the risk evaluation that is calculated by using Equation 19.

$$max \sum_{t=1}^{T} \sum_{s=1}^{S} \pi_s \times [EP_t \times GR_{s,t} - \mathrm{TOC}_{s,t}^{cpp}] + (\beta \times Risk) \quad (19)$$

where S is the number of scenarios, π_s is the probability of the sth scenario, EP_t is the electricity price in the DAM ($/MWh), $GR_{s,t}$ is the amount of electricity sold (if positive) and electricity purchased (if negative) at hour t and scenario s (MWh). The last term $(\beta \times Risk)$ is the formulation of risk measurement, where β represents the importance of risk minimization in the objective function.

2.6. Risk Modeling

Conditional Value at Risk (CVaR) is used to account for the risk of profit variability encountered by the generation companies. It represents approximately the profit of the (1-α)×100 scenarios that supplies the lowest profits [17]. To model the risk, Equations (20)-(22) are used.

$$\eta - \sum_{t=1}^{T}[EP_t \times GR_{s,t} - \mathrm{TOC}_{s,t}^{cpp}] \leq r_s \tag{20}$$

$$Risk = \eta - \frac{1}{1-\alpha} \times \sum_{s=1}^{S} \pi_s \times r_s \tag{21}$$

$$r_s \geq 0 \tag{22}$$

where η and r_s are the auxiliary variables to calculate the CVaR, α is the confidence level that is between (0,1).

2.7. Energy Balance

The energy balance constraint is shown in Equation 23. It declares that the sum of the electricity generated by the WPP, PVPP, CPP, and PHSP has to be equal to the sum of the electricity sold/purchased in DAM and electricity used for pumping water in the PHSP upper basin.

$$\mathrm{P}_{s,t}^{wpp} + P_{s,t}^{pvpp} + P_{s,t}^{cpp} + P_{s,t}^{turbine} = GR_{s,t} + \frac{P_{s,t}^{pump}}{\mu} \tag{23}$$

where μ is the efficiency factor of the PHSP.

The non-anticipativity constraint that is necessary for the fact that only one offering curve can be submitted to the DAM is also added to the model formulation as shown in Equation 24.

$$GR_{s1,t} = GR_{s2,t} = \dots = GR_{sS,t} \tag{24}$$

3. Case Studies and Results

3.1. Input Data

The proposed VPP in this study consists of WPP, PVPP, CPP, and PHSP. The problem aims to maximize the expected profit by considering risk evaluation for generation companies that participate in the DAM. The data of WPP, PVPP, CPP, and PHSP are given in Tables 1-4 respectively.

Table 1. Data of WPP [18]

Turbine type	N^{wind}	P_{rtd}^{wt}	v_{in}	v_{rtd}	v_{out}
Enercon E-66	3	1800 kW	2.5 m/s	12 m/s	28 m/s

Table 2. Data of PVPP [19]

N^{pv}	V_{ocv}	I_{scc}	K_{ctc}	NOT_{cell}	V_{Max}	I_{Max}
300	21.98 V	5.32 A	0.00122 V/C°	43 C°	17. 32 V	4.76 A

Table 3. Data of CPP [20]

a	b	c	SUC^{cpp}	P_{RU}^{cpp}	P_{RD}^{cpp}	P_{min}^{cpp}	P_{max}^{cpp}

0.0055 $/MW^2	44.5 $/MW	23.9 $	20 $	2 MW	2 MW	0 MW	5 MW

Table 4. Data of PHSP [21]

$P_{max}^{turbine}$	P_{max}^{pump}	$storage_{max}^{phsp}$	μ
10 MW	8 MW	40 MWh	0.70

The hourly data of wind speed of a region in Turkey, and hourly solar radiation and the ambient temperature of a region in Turkey are obtained from the Turkish State Meteorological Service. The uncertainty of wind speed and solar radiation is analyzed by using the data for hourly data of December 2018. The data of ambient temperature are taken as the hourly mean of this month. It is given in Table 5.

Table 5. Data of ambient temperature of the region

Hour	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10	t=11	t=12
T_t^{amb}(C^o)	4.35	4.18	4.05	3.79	3.66	3.71	3.95	5.08	6.25	7.68	8.95	9.77
Hour	t=13	t=14	t=15	t=16	t=17	t=18	t=19	t=20	t=21	t=22	t=23	t=24
T_t^{amb}(C^o)	9.96	9.42	8.85	7.84	7.07	6.48	6.02	5.51	5.15	4.85	4.71	4.52

The data electricity market prices are taken as the hourly mean of this month. It is given in Table 6.

Table 6. Data of electricity market prices [22]

Hour	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8
EP_t($/MWh)	51.937	45.379	33.412	33.531	26.962	32.340	41.999	47.151
Hour	t=9	t=10	t=11	t=12	t=13	t=14	t=15	t=16
EP_t($/MWh)	50.632	54.155	53.781	54.781	54.316	53.901	54.740	55.555
Hour	t=17	t=18	t=19	t=20	t=21	t=22	t=23	t=24
EP_t($/MWh)	55.422	55.605	55.675	53.965	54.633	54.365	49.277	45.476

3.2. Uncertainty Analysis

The uncertainty analysis is performed using the data of wind speed and solar radiation of December 2018 by using the scenario reduction and scenario tree construction algorithms [23]. A set of scenarios of wind speed and solar radiation profiles are given in Figure 1. They are reduced to a scenario tree that each node has an associate probability. The sum of the probabilities in all the branches of the tree is equal to 1. Three scenarios are obtained in this study. The obtained values of wind speed and solar radiation for three scenarios are given in Figure 2.

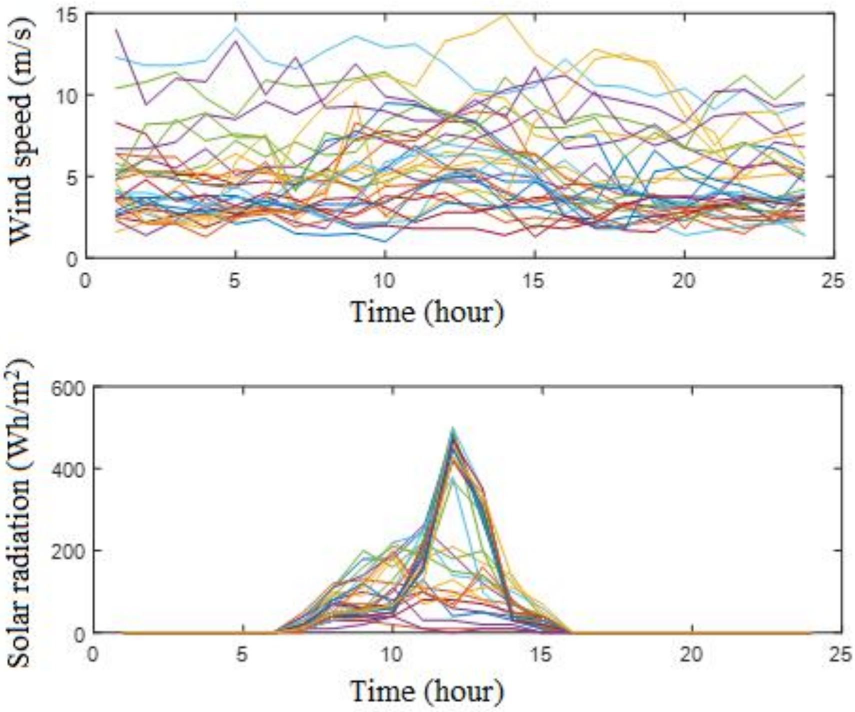

Figure 1. Wind speed and solar radiation profiles of December 2018

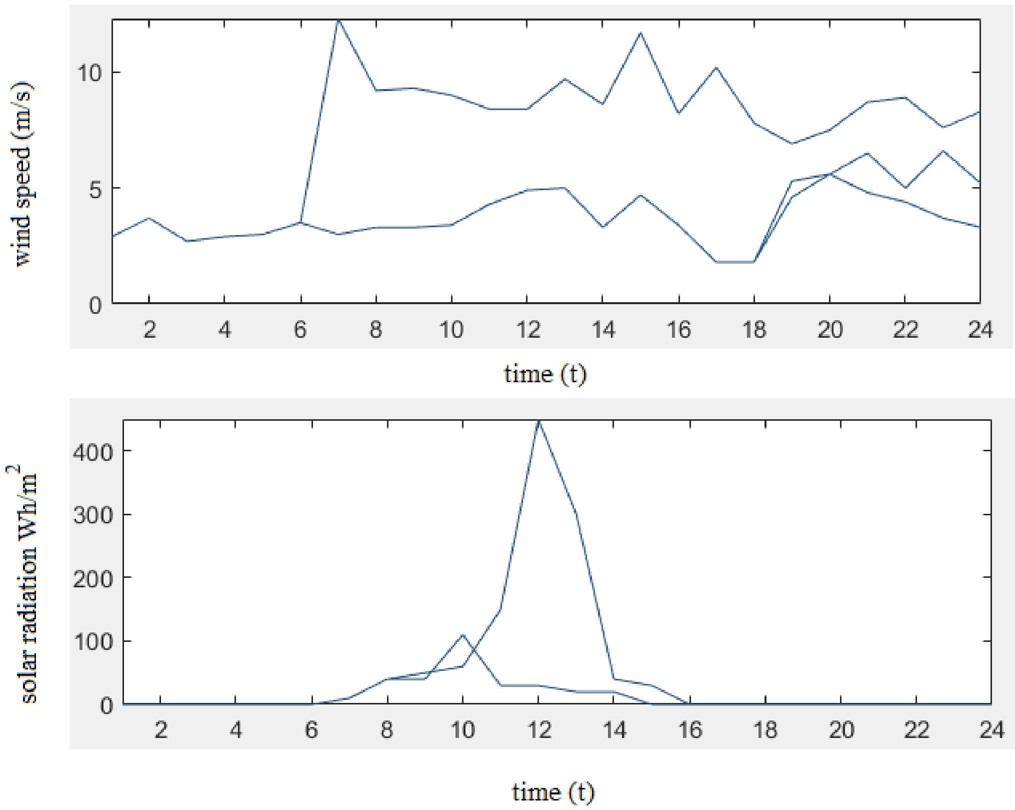

Figure 2. The obtained values of wind speed and solar radiation for three scenarios

3.3. Results

The presented MINLP model is solved by using GAMS 25.1.3 software [24]. To examine the optimum operational scheduling of VPP, two different cases are considered in this study:

Case 1: VPP scheduling model without considering risk evaluation
Case 2: VPP scheduling model with considering risk evaluation

In case 1, the expected daily profit is found as 2369.426 $. Table 7 presents the results of the optimum operational scheduling of CPP, turbine, and pump of PHSP for each scenario. The amount of electricity sold (positive values)/purchased (negative values) in the DAM for case 1 is shown in Figure 3. As shown in Figure 3, the electricity is purchased in the market due to low market prices in hours 3-6. In hour 5, the highest amount of electricity (11.428 MWh) is purchased because of the lowest market price (26.962 $) in this hour. The electricity is sold in the market due to high market prices in other hours. In general, the electricity is not sold in the market and the generated and purchased electricity is stored in the pump of the PHSP when the market prices are low. The electricity is sold when the market prices are high.

In case 2, the risk evaluation is considered to stay away from the risk of experiencing profit distributions with undesired characteristics such as a high probability of low profit. In this case, the expected daily profit is found as 2321.067 $ by assuming β=0.4 and α=0.95. Table 8 presents the results of the optimum operational scheduling of CPP, turbine, and pump of PHSP for each scenario. The amount of electricity sold (positive values)/purchased (negative values) in the DAM for case 1 is shown in Figure 4. The expected profit is decreased compared to a profit in case 1 because the expected profit term becomes less important concerning the risk term with increasing β values. As β increases, profit and risk are decreased.

Table 7. The results of the optimum operational scheduling of CPP, turbine, and pump of PHSP for case 1

	Scenario 1			Scenario 2			Scenario 3		
Hour	$P_{s,t}^{cpp}$	$P_{s,t}^{turbine}$	$P_{s,t}^{pump}$	$P_{s,t}^{cpp}$	$P_{s,t}^{turbine}$	$P_{s,t}^{pump}$	$P_{s,t}^{cpp}$	$P_{s,t}^{turbine}$	$P_{s,t}^{pump}$
1	2	0	1.4	2	0	1.4	0	0	0
2	4	0	2.8	4	0	2.8	0	0	0
3	4	0	8	4	0	8	0	0	5.2
4	2	0	8	2	0	8	0	0	6.6
5	0	0	8	0	0	8	0	0	8
6	2	0	8	2	0	8	0	0	6.6
7	2	0	1.4	0	0	3.779	0	0	0
8	0	1.861	0	0	0	0.021	0	1.861	0
9	1.871	0	0	0	0.139	0	0	1.871	0
10	0	2.948	0	0	0	0	0	2.948	0
11	2	0	0	2	1.676	0	0	2	0
12	4	0	0	4	9.017	0	0	4	0
13	5	0	0	2	7.576	0	0	5	0
14	5	0	0	0	4.062	0	2	3	0
15	5	0	0	0	0.898	0	4	1	0
16	5	0	0	0	3.839	0	4.989	0.011	0
17	5	0	0	2	0.125	0	4.989	0.011	0
18	4	0.938	0	4	0	0	4.938	0	0
19	2	7.17	0	2	6.691		5	4.09	0
20	0	5	0	0	4.401	0	5	0	0

21	0	4.674	0	2	1.576	0	5	0	0
22	0	5.553	0	4	0	0	5	0.608	0
23	0	4.577	0	4.176	0	0	5	0	0
24	0	4.879	0	3.774	0	0	5	0	0

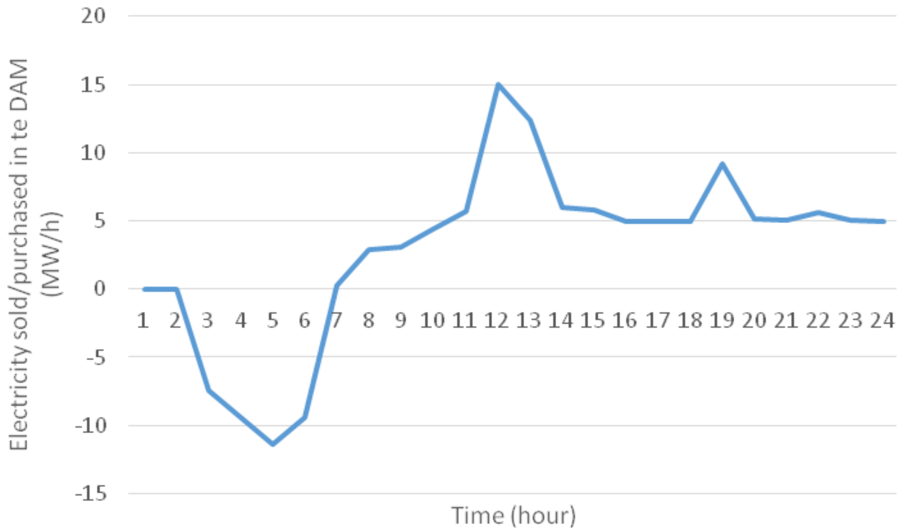

Figure 3. Electricity sold/purchased in the DAM for case 1

Table 8. The results of the optimum operational scheduling of CPP, turbine, and pump of PHSP for case 2

	Scenario 1			Scenario 2			Scenario 3		
Hour	$P^{cpp}_{s,t}$	$P^{turbine}_{s,t}$	$P^{pump}_{s,t}$	$P^{cpp}_{s,t}$	$P^{turbine}_{s,t}$	$P^{pump}_{s,t}$	$P^{cpp}_{s,t}$	$P^{turbine}_{s,t}$	$P^{pump}_{s,t}$
1	0	0	0	2	0	1.4	0	0	0
2	0	0	0	4	0	2.8	0	0	0
3	0	0	6.6	2	0	8	0	0	6.6
4	0	0	8	0	0	8	0	0	8
5	0	0	8	0	0	8	0	0	8
6	2	0	8	2	0	8	0	0	6.6
7	4	0	2.8	0	0	3.779	0	0	0
8	5	0	2.197	0	0	0.021	1.861	0	0
9	5	0	0	0	3.268	0	3.861	1.139	0
10	5	0	0	2	0.052	0	4.228	0.772	0
11	5	0	0	4	2.676	0	4.228	0.772	0
12	5	0	0	5	9.017	0	4.228	0.772	0
13	5	0	0	5	4.576	0	4.228	0.772	0
14	5	0	0	4.062	0	0	4.28	0.772	0
15	5	4.102	0	5	0	0	4.228	4.874	0
16	5	1.161	0	5	0	0	4.228	1.933	0
17	5	2.875	0	5	0	0	4.228	3.647	0
18	5	3.578	0	5	2.64	0	4.228	4.35	0
19	5	9.479	0	4	10	0	5	9.399	0
20	4	1	0	2	2.401	0	5	0	0

21	2	2.674	0	0	3.576	0	5	0	0
22	0	4.945	0	2	1.392	0	5	0	0
23	0	3.741	0	2.938	0.402	0	4.164	0	0
24	0	2.043	0	0.938	0	0	2.164	0	0

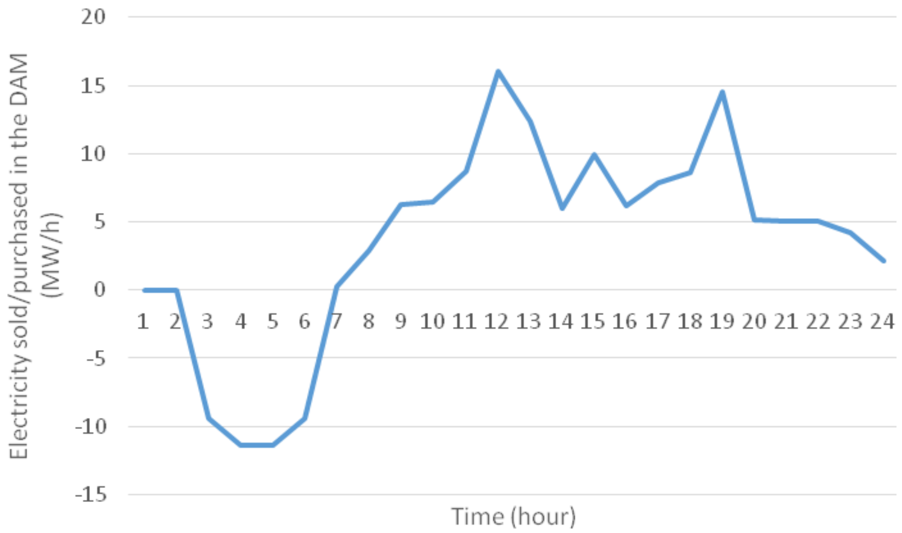

Figure 4. Electricity sold/purchased in the DAM for case 2

The amount of profit for three scenarios for Case 1 and Case 2 are presented in Figure 5.

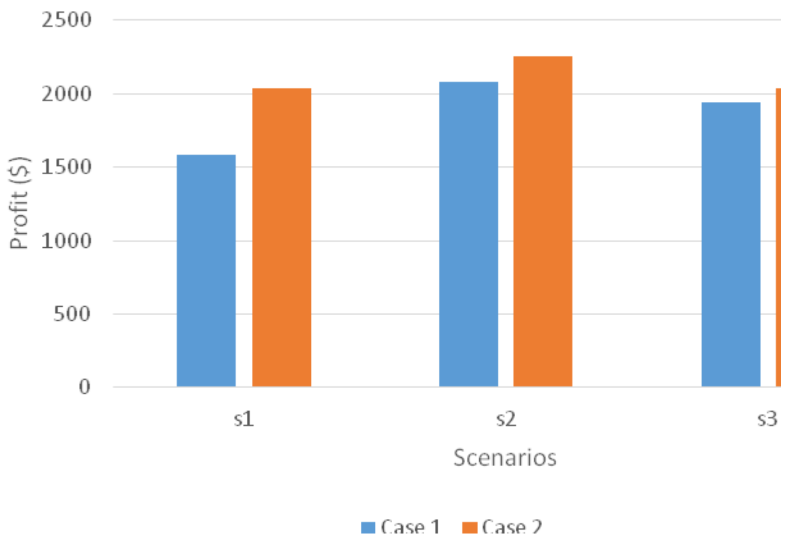

Figure 5. The amount of profit for three scenarios for Case 1 and Case 2

As seen in Figure 5, the amount of profits for three scenarios in Case 1 is lower than the amount of profits for three scenarios in Case 2. The risk of making a low profit is high in Case 1, where risk evaluation is not considered. An increase in the amount of profit for each scenario is observed in

Case 2, where risk evaluation is considered. In other words, the VPP operator would not experience low-profit scenarios in Case 2.

The amount of profit with different values of β for the same confidence level, α, are shown in Table 9. When β is equal to 0, the problem becomes the risk-neutral due to disregarding the risk term in the objective function. The term of expected profit becomes less important relating to the risk term as β increases.

Table 9. Profit with different values of β

β	**Profit ($)**
0.0	2369.426
0.4	2321.067
0.6	2272.888
0.8	2204.879
1.0	2163.461

4. Conclusion

In this study, the optimum operational and bidding strategy of a VPP comprising of WPP, PVPP, CPP, and PHSP is investigated. The problem aims to maximize the profit by considering the risk evaluation in the DAM. The presented MINLP model is solved by using GAMS 25.1.3 software. The intermittent outputs of WPP and PVPP leads to uncertainty in the power system. Therefore, the uncertain parameters of wind speed and solar radiation are analyzed by using scenarios obtained from the historical data. Moreover, risk measure is included in the objective function by using CVaR that is a suitable risk measure for optimization models. β demonstrates the trade-off between the risk aversion and expected profit by controlling the risk met by the VPP operator. When β is equal to 0, the VPP operator is risk-neutral and maximizes the expected profit only. The optimum solution becomes more profitable and has the highest risk. When β is equal to 1, optimum solution becomes the least profitable and has the lowest risk. The results show the effectiveness of the presented model and it can be used efficaciously by the VPP operators participating in the electricity market.

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