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Trading wind power with barrier option

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HIGHLIGHTS

- Devised a barrier option for wind power to hedge against risks from both market price and power generation.
- Devised a bilateral contract with floating power exchanges for wind power and proposed the negotiation process.
- Put forward purchasing strategies of the barrier option both in pool market and with bilateral contract.

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ABSTRACT

The emerging renewable power system entails competition-driven instead of non-competitive regulations for wind power. An increasing amount of wind power is therefore traded in pool market. Due to wind power's fluctuation and randomness, wind power producers (WPPs) suffer from risks of both power generation and market price. Based on the proposed WP-traded (wind power-traded) price and equivalent WPP-traded quantity, this work devises a barrier option for wind power, with which WPPs can trade their hedged proportion of power at prices no less than a predetermined strike price during the option life. The optimal purchasing framework and negotiation process are provided both in pool market and with bilateral contract. Case studies based on the Iberian market are conducted to verify the applicability of the proposed barrier option. The results show notable benefits of the barrier option in improving WPP's utility. The bilateral contract takes advantage of customer's elastic demand to countervail WPP's power deviations and charges customer a lower price. Furthermore, Efficiencies of barrier option and bilateral contract are mutually promoted as barrier option results in lower price and larger boundary range of bilateral contract, while bilateral contract leads to less possibility on over-hedging and better utilization of barrier option.

1. Introduction

The world has witnessed a great expansion of wind power in recent years, with the installed capacity approaching 432.9 GW [1]. Anticipation of wind power's sustained growth is enhanced by its potential profitability in dealing with many urgent problems including environmental deterioration, climate change and the depletion of fossil fuels [2,3]. The mushrooming of wind power entails clearer market signals to shed light on the investment and WPP's profit strategy [4]. As a result, a growing amount of wind power is traded in pool market, instead of through non-competitive treatments, including the long-term power purchasing agreement (PPA), feed-in tariffs, premiums and green certificates [5–11]. In pool market, the WPPs face risks from both market price and power generation. In order to attract more WPPs to participate in pool market, efficient risk management tools are needed. This paper aims at devising a barrier option and studies the purchasing strategies for WPPs both in pool market and with bilateral contract.

To date, plenty of research has been conducted regarding hedging against risks and elevating profits for the WPP in trading in electricity market, categorized into the following five fields.

(1) Improving forecast accuracy and seeking optimal trading strategies.

A more accurate wind power forecast undoubtedly improves the profit of WPPs by reducing imbalance penalties [12]. Discrete Markov process [13], autoregressive integrated moving average (ARIMA) model [14] and kernel density estimation [15] have been used to model wind behavior for generating optimal trading strategies under distinct market mechanisms. Dai and Qiao [16]

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Nomenclature

h	index of time periods running from 1 to H
n	index of WPPs running from 1 to N_n
ω	index of scenarios running from 1 to N_ω
λ_{B}	barrier price of barrier option (€/MW h)
λ_{con}	price of bilateral contract (€/MW h)
$\lambda_{\mathrm{DA}}^{h,\omega}$, $\lambda_{\mathrm{RT}}^{h,\omega}$	DA, or balancing price in time period h and scenario ω (€/MW h)
$\lambda_{\mathrm{DN}}^{h,\omega}$, $\lambda_{\mathrm{UP}}^{h,\omega}$	downward, or upward price in balancing market in time period h and scenario ω (€/MW h)
λ_{K}	strike price of barrier option (€/MW h)
$\lambda_{\mathrm{RTP}}^{h,\omega}$	RTP for consumer in time period h and scenario ω (€/MW h)
$\lambda_{\mathrm{RTP,con}}^{h,\omega}$	equivalent RTP for consumer with bilateral contract in time period h and scenario ω (€/MW h)
$\lambda_{\mathrm{RTPbase}}^{h,\omega}$	mean RTP for consumer in time period h and scenario ω (€/MW h)
$\lambda_{\mathrm{TD}}^{h,\omega}$	transmission and distribution price for consumer in time period h and scenario ω (€/MW h)
$\lambda_{\mathrm{wp}}^{h,\omega}$	WP-traded price in time period h and scenario ω (€/MW h)
$\lambda_{\mathrm{wp,hed}}^{h,\omega}$	tariff of barrier option in time period h and scenario ω (€/MW h)
$\rho_{\mathrm{O}}^{\omega}(r)$	risk premium of barrier option in scenario ω under r (€)
$P_{\mathrm{con}}^{n,h,\omega}$	quantity traded via bilateral contract of WPP n in time period h and scenario ω (MW)
$P_{\mathrm{DA}}^{n,h,\omega}$, $P_{\mathrm{RT}}^{n,h,\omega}$	DA offered, or RT generated quantity of WPP n in time period h and scenario ω (MW)
$P_{\mathrm{DAbuy}}^{n,h,\omega}$, $P_{\mathrm{DAsell}}^{n,h,\omega}$, $P_{\mathrm{RTsell}}^{n,h,\omega}$	quantity purchased, offered in DA market, or sold in balancing market with bilateral contract of WPP n in time period h and scenario ω (MW)
P_{error}^{n}	averaged forecast error for WPPn(MW)
$P_{\mathrm{f}}^{n,h,\omega}$	DA predicted quantity of WPP n in time period h and scenario ω (MW)

$P_{\mathrm{T}}^{n,h,\omega}$	equivalent traded quantity in pool market of WPP n in time period h and scenario ω (MW)
P_{conll}, P_{conul}	lower, or upper boundary of power exchange via bilateral contract (MW)
$P_{\mathrm{Tsell}}^{n,h,\omega}$	equivalent traded quantity in pool market with bilateral contract of WPP n in time period h and scenario ω (MW)
$P_{\mathrm{wpp,max}}^{n}$	maximum output of WPP n (MW)
$R_{\mathrm{con}}^{n,h,\omega}$, $R_{\mathrm{con,O}}^{n,h,\omega}$	profit of WPP n with bilateral contract, and without or with barrier option in time period h and scenario ω (€)
$R_{\mathrm{pool}}^{n,h,\omega}$, $R_{\mathrm{pool,O}}^{n,h,\omega}$	profit of WPP n in pool market without or with barrier option in time period h and scenario ω (€)
$U_{\mathrm{c}}(x)$	utility function for electricity consumption of consumer (€)
$U_{\mathrm{csm,pool}}$, $U_{\mathrm{csm,con}}$	utility of consumer in trading in pool market or with bilateral contract (€)
$U_{\mathrm{wpp,con}}^{n}$, $U_{\mathrm{wpp,con,O}}^{n}$	utility of WPP n in trading with bilateral contract and without or with barrier option (€)
$U_{\mathrm{wpp,pool}}^{n}$, $U_{\mathrm{wpp,pool,O}}^{n}$	utility of WPP n in trading in pool market without or with barrier option (€)
$V_{\mathrm{O}}(r)$	price of barrier option in scenario ω under r (%)
$x^{h,\omega}$	original demand of consumer in time period h and scenario ω (MW)
$x_{\mathrm{pool}}^{h,\omega}$, $x_{\mathrm{con}}^{h,\omega}$	changed demand of consumer in pool market, or with bilateral contract in time period h and scenario ω (MW)
β_{wpp}^{n}, β_{csm}	risk-aversion factor of WPP n or consumer
e	consumed energy (MW h)
r	hedge rate of barrier option
α	confidence level
$\varepsilon_{h,i}$	demand elasticity factor of consumer
θ_{c}, γ_{c}	parameters in utility function of consumer
π^{ω}	probability of occurrence of scenario ω
ξ, η^{ω}	auxiliary variables to compute CVaR (€)

proposed a game-theoretical method to acquire the optimal bidding strategy in both energy and bilateral reserve markets. Xiao et al. [17] established closed-form models for WPP's bidding behavior in two-settlement electricity market adopting the Stackelberg game model. Li and Shi [18] utilized a learning algorithm to analyze the bidding optimization issue with consideration of the marginal production price of wind power. Zhang et al. [19] put forward a one-leader multi-follower bi-level game model to address the trading strategies of a proactive distribution company with stochastic distributed energy.

(2) Adjustment of the market mechanism.

Makarov et al. [20] emphasized the importance of intra-day market, which was also stressed in [21–23]. Multiple ancillary services procured in ancillary market serve to alleviate the variability of wind power and compensate for forecast inaccuracies [24]. Zhao et al. [25] constructed a risky power market where WPPs trade uncertain future power, seeking a desirable mixture of random energy to achieve higher profit. Xiao et al. [26] introduced a two-compound bidding mode for WPPs to reduce the dependence on the extra-market subsidy while improving social benefits.

(3) Coordinated trading.

Baeyens et al. [27] showed how the expected profit of WPPs has been improved through jointly offerings and fairly allocated based on the Shapley value. Hydro [28], thermal [29], pumped-hydro [30], energy storage system [31] could act as *springs* to mitigate the intermittence and variability of wind power, thus increasing the profit of WPPs. Wind power can also be coupled to district heating as a virtual power plant in order to achieve a profit increase [32].

(4) Aggregating demand response.

Flexible demand helps lower consumers' bills, shrink load peak-valley differences, and reduce the imbalance penalties caused by wind power forecast errors [33,34]. Amelin [22] pointed out how retailers were allowed to adjust loads along with varying power generation based on conditions in the Nordic market with sufficient flexible hydro generation. Mahmoudi et al. [35] proposed a two-stage plan for the WPPs to offer with various demand response agreements. Heydarian-Forushani et al. [36] presented a stochastic network constrained unit commitment associated with demand response to schedule the wind power and responsive loads. Madaeni and Sioshansi [37] used the ERCOT power system as an example to measure the benefits of demand response on reducing wind-uncertainty costs and figured out that an in-time response could countervail more than 75% of the cost. It is noted that a tension exists that shorter timeframes enables more accurate wind power forecast, while customers need longer timeframes for more flexible response [38].

(5) Financial tools.

Xiao et al. [39] proposed a block purchase framework of standard futures contracts to the WPPs. Hedman and Sheble [40] raised an option purchasing methodology by the Black-Scholes pricing equations and verified its efficiency by comparing to conventional hedging methods using pumped storage hydro units. Fernandes et al. [41] focused on WPPs' volume risk under the framework of forward contracts with fixed volume and price, and proposed collars-type wind insurance.

Among the aforementioned 5 fields, few literatures have made the in-depth analysis of financial tools in hedging against risks for WPPs, and most relevant researches focus on European options. However, purchasing European options could be a heavy work for the WPPs since the European options are exercised only on the expiration day, while the WPPs suffer from severe and frequent risks. Therefore, an exotic barrier option is adopted in this paper which represents the right for the option holders to exercise their option whenever price of the underlying asset crosses a certain barrier level during the option life [42]. As a path-dependent option, the barrier option can be utilized to hedge against frequent risk in trading wind power.

The objectives and contributions of the paper are threefold. (1) To devise a barrier option for wind power to hedge against risks from both market price and power generation, and propose the purchasing strategies of the barrier option. (2) To study the purchasing strategies of the barrier option with bilateral contract after putting forward a bilateral contract with floating power exchanges. (3) To conduct case studies to demonstrate factors affecting the price of barrier option, validate the WPP's utility can be improved by both barrier option and bilateral contract, and justify the efficiencies of the barrier option and bilateral contract are mutually promoted.

For the sake of clarity, the main assumptions are listed.

(1) The two-settlement market mechanism is adopted for the pool market, including the day-ahead (DA) market and the real-time (RT) balancing market.
(2) The WPPs are treated as price-takers.
(3) The two-price system is adopted as the system operator generates an up-regulation price and a down-regulation price for the balancing market [8,15]. The balancing price $\lambda_{\mathrm{RT}}^{h,\omega}$ is defined in Table 1. When the system imbalance is positive (excess of generation), the WPP sells its excess of energy ($P_{\mathrm{RT}}^{n,h,\omega} - P_{\mathrm{DA}}^{n,h,\omega}$) at a price no more than the DA price ($\min(\lambda_{\mathrm{DN}}^{h,\omega}, \lambda_{\mathrm{DA}}^{h,\omega})$), or purchases its deficit of energy ($P_{\mathrm{DA}}^{n,h,\omega} - P_{\mathrm{RT}}^{n,h,\omega}$) at the DA price ($\lambda_{\mathrm{DA}}^{h,\omega}$). When the system imbalance is negative (deficit of generation), the WPP sells its excess of energy ($P_{\mathrm{RT}}^{n,h,\omega} - P_{\mathrm{DA}}^{n,h,\omega}$) at the DA price ($\lambda_{\mathrm{DA}}^{h,\omega}$), or purchases its deficit of energy ($P_{\mathrm{DA}}^{n,h,\omega} - P_{\mathrm{RT}}^{n,h,\omega}$) at a price no less than the DA price $\left(\max\left(\lambda_{\mathrm{UP}}^{h,\omega}, \lambda_{\mathrm{DA}}^{h,\omega}\right)\right)$.

The remainder of this paper is organized as follows. In Section 2, we devise the barrier option for wind power based on concepts of WP-traded price and equivalent WPP-traded quantity, and propose the purchasing framework in pool market. Section 3 characterizes a bilateral contract for wind power and puts forward corresponding purchasing strategies of barrier option. Section 4 is a case study based on real-world data from the Iberia electricity market, and in Section 5 we draw conclusions.

Table 1
Balancing price $\lambda_{\mathrm{RT}}^{h,\omega}$ in two-price system.

	Excess of generation	Deficit of generation
$P_{\mathrm{RT}}^{n,h,\omega} > P_{\mathrm{DA}}^{n,h,\omega}$	$\min(\lambda_{\mathrm{DN}}^{h,\omega}, \lambda_{\mathrm{DA}}^{h,\omega})$	$\lambda_{\mathrm{DA}}^{h,\omega}$
$P_{\mathrm{RT}}^{n,h,\omega} < P_{\mathrm{DA}}^{n,h,\omega}$	$-\lambda_{\mathrm{DA}}^{h,\omega}$	$-\max(\lambda_{\mathrm{UP}}^{h,\omega}, \lambda_{\mathrm{DA}}^{h,\omega})$

2. Barrier option of wind power and purchasing strategy in pool market

2.1. Relevant concepts in pool market

Both price and quantity risks have influence on WPP's profit. The underlying asset of the barrier option should reflect this two-fold risk. Therefore, the WP-traded price and equivalent WPP-traded quantity are introduced.

2.2. WP-traded price

The WP-traded price represents the actual profit in trading per-unit wind power in pool market through a complete trading process, defined as,

$$\lambda_{\mathrm{wp}}^{h,\omega} = \frac{\sum_n R_{\mathrm{pool}}^{n,h,\omega}}{\sum_n P_{\mathrm{RT}}^{n,h,\omega}} \tag{1}$$

$$\text{s.t.} \quad R_{\mathrm{pool}}^{n,h,\omega} = \lambda_{\mathrm{DA}}^{h,\omega} \cdot P_{\mathrm{DA}}^{n,h,\omega} + \lambda_{\mathrm{RT}}^{h,\omega} \cdot \left(P_{\mathrm{RT}}^{n,h,\omega} - P_{\mathrm{DA}}^{n,h,\omega}\right) \tag{2}$$

In (1), the numerator represents overall profits of WPPs, and the denominator represents the overall generated wind power. The two terms of the right-hand side of (2) represent profit in trading wind power in DA and balancing market, respectively. Therefore, the WP-traded price can be viewed as the average price of per-unit wind power in pool market. Risks of both market price and power generation are reflected in the WP-traded price.

2.3. Equivalent WPP-traded quantity

The equivalent WPP-traded quantity represents the equivalent traded quantity of each WPP assuming all wind power is traded at the WP-traded price, defined as,

$$P_{\mathrm{T}}^{n,h,\omega} = \frac{R_{\mathrm{pool}}^{n,h,\omega}}{\lambda_{\mathrm{wp}}^{h,\omega}} \tag{3}$$

2.4. WPP's utility in pool market

To calculate WPP's utility, besides profit in (2), risk should also be taken into account. Utilizing the Conditional Value at Risk (CVaR) [43,44] to describe the risk, WPP's utility is represented as,

$$U_{\mathrm{wpp,pool}}^{n} = \sum_{\omega}^{N_\omega} \sum_{h}^{H} \pi^{\omega} \cdot R_{\mathrm{pool}}^{n,h,\omega} + \beta_{\mathrm{wpp}}^{n} \cdot CVaR_{\mathrm{wpp,pool}}^{n} \tag{4}$$

The two terms of the right-hand side of (4) represent profit and risk, respectively. The CVaR multiplied by a weighting factor β_{wpp}^{n} demonstrates the risk-aversion degree of the WPP. Note that the calculation method of CVaR will be referred to in Section 4.1.

2.5. Barrier option for wind power

2.5.1. Brief of electricity option

An electricity option is an agreement which gives the buyer the right, but not the obligation, to sell/buy a certain amount (determined by hedge rate r) of electricity (referred to as underlying asset) during a specified future time interval H at a fixed price (referred to as the strike price λ_{K}) [40,42,45]. To purchase an

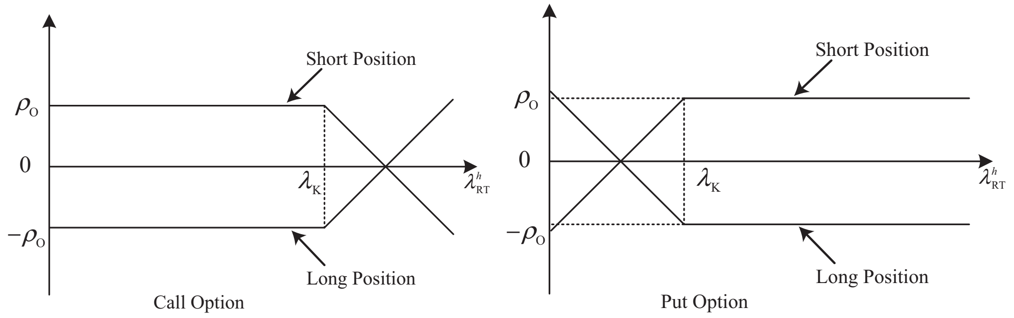

Fig. 1. Profit and loss of different positions of an electricity option.

option, one has to pay an additional cost (referred to as the risk premium ρ_O) even if the option is not exercised.

There are two main types of electricity options: calls and puts. The call/put option gives its holder the right to buy/sell a given amount of electricity at the strike price. For each option contract, there are two sides: long position and short position. The buyer of the option takes the long position, while the seller takes the short position. As an efficient risk management tool, the electricity option has been introduced in many electricity markets, such as the PJM and NordPoolSpot [46,47].

Fig. 1 further shows the profit and loss from different positions of a common electricity option whose underlying asset's price is the balancing market price in time period h (λ_{RT}^h). In a call option, the long position has the right to buy the electricity at a price no higher than the strike price λ_K. In a put option, the long position has the right to sell the electricity at a price no less than the strike price λ_K. It can be observed that the two long positions limit the possible losses to the risk premium of the electricity option and can be considered as risk-averse agents. On the contrary, the two short positions limit the possible financial profits and can be considered as risk-taker agents.

2.5.2. Characteristics of barrier option for wind power

The barrier options are options where the payoff depends on not only the underlying asset's price at the time when the option is exercised, but also whether the underlying asset's price reaches a certain level (barrier) during the option life [42]. Therefore, besides the aforementioned features of an option including hedge rate r, covered time interval H, strike price λ_K and risk premium λ_O, the barrier option has another feature indicating the barrier of the underlying asset's price (referred to as barrier price λ_B).

There are two main types of the barrier options: knock-in options and knock-out options. A knock-in option comes into existence only when the underlying asset's price reaches the barrier price, while a knock-out option ceases to exist when the underlying asset's price reaches the barrier option [42,48]. The barrier options have been employed in many aspects regarding electricity markets, such as hedge contracts of real-time pricing (RTP) for electricity consumers [44], hedging risks against use-of-system tariffs for network users [49], and incorporating interruptible electricity contracts for electricity utilities [50].

In this paper, a barrier option for wind power is devised. According to (1), DA price, balancing price, and wind power generation are all employed in calculating the WP-trade price. Therefore, adopting the WP-traded price as the underlying asset's price can reflect risks from both market price and power generation. The barrier option gives the WPP the right to sell its hedged proportion of power at prices no less than the strike price when the WP-traded price falls below the barrier price. When the WP-traded price is higher than the strike price, the hedged proportion of wind power is traded at the WP-traded price. However, when the WP-traded price is lower than the strike price, the hedged proportion of wind power is traded at the strike price. According to the aforementioned classification of the options, the barrier option for wind power is in fact a knock-in put option, where the WPP takes the long position and the power exchanges take the short position. Therefore, the tariff structure of the barrier option is

$$\lambda_{\text{wp,hed}}^{h,\omega} = \max\left(\lambda_{\text{wp}}^{h,\omega}, \lambda_K\right) \cdot \mathrm{I}\left(\lambda_{\text{wp}}^{h,\omega} \leqslant \lambda_B\right) \tag{5}$$

$$\text{s.t.} \quad \mathrm{I}\left(\lambda_{\text{wp}}^{h,\omega} \leqslant \lambda_B\right) = \begin{cases} 1, & \text{when } \lambda_{\text{wp}}^{h,\omega} \leqslant \lambda_B \\ 0, & \text{when } \lambda_{\text{wp}}^{h,\omega} > \lambda_B \end{cases} \tag{6}$$

The covered time interval of the barrier option in this paper is set to 1 month. Since the pool market is cleared every 1 h, the barrier option is devised that can be exercised every 1 h within the 1-month time interval. Therefore, the barrier option for wind power is exactly an exotic barrier option instead of a standard one, since it consists of several barrier options and the amount is not constant.

In Fig. 2, the WP-traded price is depicted as the green line, and the strike price of the barrier option is depicted as the red[1] line. With the barrier option, the hedged proportion of wind power is traded at prices no less than the strike price, depicted as the black line.

Before the execution month, the WPP has to decide how many quantities to be hedged. As the DA offered quantity is the only available information regarding power quantities at that time, the WPP can determine what proportion of DA offered quantity is hedged, represented as the hedge rate.

The risk premium of the barrier option is defined as the expected value of the option during the 1-month option life, which equals to the expected increased profit in trading wind power of DA hedged quantity. The expected value of the barrier option is calculated by the scenario-based method, in which scenarios can be generated by establishing mathematical models or directly using historical data [51,52]. The mathematical functions for calculating the risk premium are

$$\rho_O(r) = \sum_{\omega}^{N_\omega} \pi^\omega \rho_O^\omega(r) \tag{7}$$

$$\text{s.t.} \quad \rho_O^\omega(r) = \sum_n^{N_n} \sum_h^H \max\left(r \cdot P_{\text{DA}}^{n,h,\omega} \cdot \left(\lambda_K - \lambda_{\text{wp}}^{h,\omega}\right), 0\right) \cdot \mathrm{I}\left(\lambda_{\text{wp}}^{h,\omega} \leqslant \lambda_B\right) \tag{8}$$

Eq. (7) indicates that the risk premium is calculated by the average value of each scenario. Eq. (8) calculates the risk premium for sce-

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[1] For interpretation of color in Figs. 2 and 3, the reader is referred to the web version of this article.

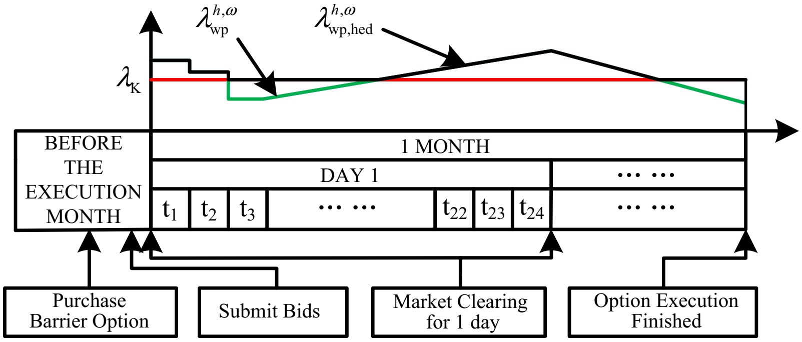

Fig. 2. Tariff structure and time frames for market clearing in pool market with barrier option.

nario ω, which equals to the expected increased profit in trading wind power of DA hedged quantity. It can be observed that the risk premium is different for different hedge rate or strike price. A greater value of strike price or hedge rate leads to a higher risk premium.

To better demonstrate the comparative relationship between the risk premium and WPP's trading profits, we express the risk premium as the percentage of WPP's trading profits with the barrier option [44,49], and define the price of barrier option as,

$$V_{\text{O}}(r) = \frac{\rho_{\text{O}}(r)}{\sum_{n}^{N_n}\sum_{h}^{H}\sum_{\omega}^{N_\omega} R_{\text{pool,O}}^{n,h,\omega}} \tag{9}$$

$$\begin{aligned}\text{s.t.}\quad R_{\text{pool,O}}^{n,h,\omega} &= \min\left(r\cdot P_{\text{DA}}^{n,h,\omega}, P_{\text{T}}^{n,h,\omega}\right)\cdot\lambda_{\text{wp,hed}}^{h,\omega}\\ &\quad + \max\left(\left(P_{\text{T}}^{n,h,\omega} - r\cdot P_{\text{DA}}^{n,h,\omega}\right)\cdot\lambda_{\text{wp}}^{h,\omega}, 0\right)\end{aligned} \tag{10}$$

Eq. (9) shows that the price of barrier option is determined by the ratio of risk premium over the WPP's profit in trading wind power with barrier option, which is calculated by (10). If the hedged proportion $r\cdot P_{\text{DA}}^{n,h,\omega}$ is smaller than the equivalent traded quantity $P_{\text{T}}^{n,h,\omega}$, the hedged proportion is paid at the hedged price $\lambda_{\text{wp,hed}}^{h,\omega}$, while rest of the equivalent traded quantity is paid at the WP-traded price $\lambda_{\text{wp}}^{h,\omega}$. However, if the hedged proportion is greater than the equivalent traded quantity, the WPP will be paid for the equivalent traded quantity at the hedged price.

In real-world applications, prices of the barrier option with different hedge rates are released. For diversification, we set 20 options with different hedge rates at 5%, 10%, …, 100%.

2.5.3. Optimal purchasing framework of barrier option for wind power

To decide the hedge rate, the objective of a WPP is to achieve the maximum utility $U_{\text{wpp,pool,O}}^{n}$ in trading wind power by purchasing the barrier option, represented as,

$$\begin{aligned}\max U_{\text{wpp,pool,O}}^{n} = \sum_{\omega}^{N_\omega}\sum_{h}^{H}\pi^{\omega}\cdot R_{\text{pool,O}}^{n,h,\omega}\cdot(1 - V_{\text{O}}(r)) + \beta_{\text{wpp}}^{n}\\ \cdot CVaR_{\text{wpp,pool,O}}^{n}\end{aligned} \tag{11}$$

Similar to (4), WPP's utility with barrier option is calculated as a combination of profit and risk. The first term of the right-hand side of (11) is the WPP's net profit by trading wind power, while the second term represents the risk value. In practice, the WPP calculates the corresponding utilities with the 20 barrier options considering its risk preference, and figures out which one brings it with the greatest utility.

In Fig. 2, before the execution month, the WPP properly purchases the barrier option according to (11). During the execution month, the daily market clearing process is same to most international practices. The WPP submits bids before the operating day. After collecting and optimizing all bids from suppliers and customers, the market operator releases DA prices. During the operating day, the balancing price is determined based on RT operating conditions. Once the operating day passes, the WPP will be paid.

3. Purchasing barrier option with bilateral contract

3.1. Characteristics of bilateral contract for wind power

A bilateral contract stipulates the amount and price of power exchanges in a specific time interval. Considering the stochastic and fluctuant nature of wind power, bilateral contract with floating power exchanges is adopted [53]. This bilateral contract specifies upper and lower boundaries of the instant power exchange, instead of a determined value. During the executing period, the WPP has the right to decide the quantity of power traded via the bilateral contract. The bilateral contract is successfully signed only if utilities of both parties are increased with the bilateral contract compared to trading in pool market. It is noted that pool market is still accessible to the transaction parties when executing bilateral contracts. For the sake of comparison, the covered time interval of the bilateral contract in this paper is also set to 1 month. The scenario-based method is adopted to calculate utility expectations of both parties, in which scenarios can be generated by establishing mathematical models or directly using historical data. With the utility expectations, the price and boundaries of the bilateral contract can be determined.

3.2. WPP's utility with bilateral contract

3.2.1. Without barrier option

The WPP's utility with bilateral contract is calculated as,

$$U_{\text{wpp,con}}^{n} = \sum_{\omega}^{N_\omega}\sum_{h}^{H}\pi^{\omega}\cdot R_{\text{con}}^{n,h,\omega} + \beta_{\text{wpp}}^{n}\cdot CVaR_{\text{wpp,con}}^{n} \tag{12}$$

$$\begin{aligned}R_{\text{con}}^{n,h,\omega} &= P_{\text{con}}^{n,h,\omega}\cdot\lambda_{\text{con}} + (P_{\text{DAsell}}^{n,h,\omega} - P_{\text{DAbuy}}^{n,h,\omega})\cdot\lambda_{\text{DA}}^{h,\omega} + P_{\text{RTsell}}^{n,h,\omega}\cdot\lambda_{\text{RT}}^{h,\omega}\\ \text{s.t.} &= P_{\text{con}}^{n,h,\omega}\cdot\lambda_{\text{con}} - P_{\text{DAbuy}}^{n,h,\omega}\cdot\lambda_{\text{DA}}^{h,\omega} + P_{\text{Tsell}}^{n,h,\omega}\cdot\lambda_{\text{wp}}^{h,\omega}\end{aligned} \tag{13}$$

$$P_{\text{Tsell}}^{n,h,\omega} = \frac{\lambda_{\text{DA}}^{h,\omega}\cdot P_{\text{DAsell}}^{n,h,\omega} + \lambda_{\text{RT}}^{h,\omega}\cdot P_{\text{RTsell}}^{n,h,\omega}}{\lambda_{\text{wp}}^{h,\omega}} \tag{14}$$

$$P_{\text{con}}^{n,h,\omega} + P_{\text{DAsell}}^{n,h,\omega} + P_{\text{RTsell}}^{n,h,\omega} = P_{\text{RT}}^{n,h,\omega} + P_{\text{DAbuy}}^{n,h,\omega} \tag{15}$$

$$P_{\text{conll}} \leqslant P_{\text{con}}^{n,h,\omega} \leqslant P_{\text{conul}} \tag{16}$$

$$0 \leqslant P_{\text{conll}} < P_{\text{conul}} \leqslant P_{\text{wpp,max}}^{n} \tag{17}$$

$$P_{\mathrm{DAbuy}}^{n,h,\omega} = \max(P_{\mathrm{conll}} - P_{\mathrm{f}}^{n,h,\omega}, 0) \tag{18}$$

$$P_{\mathrm{DAsell}}^{n,h,\omega} = \max(P_{\mathrm{f}}^{n,h,\omega} - P_{\mathrm{conll}}, 0) \tag{19}$$

In (12), the WPP's utility is defined as a combination of trading profit and risk, similar to (4). The WPP's profit in trading with bilateral contract is calculated by (13). The first term of the middle-hand side in (13) represents profit in bilateral contract trading. The second term represents profit in DA market, noting that the WPP is allowed to purchase/sell energy when the forecast quantity is lower/higher than the lower boundary of the bilateral contract, as illustrated in (18) and (19). The third term represents profit in trading wind power in balancing market. Eq. (14) demonstrates how the equivalent WPP-traded quantity with bilateral contract is calculated, similar to (3). Power quantity constraint is represented in (15), as the sum of RT generated and DA purchased quantities equals to the sum of DA, RT and bilateral contract sold quantities. Eq. (16) assures the traded power quantity is within the boundary range of bilateral contract. Eq. (17) provides constraints of the boundary range.

Fig. 3 further shows the time frames for executing bilateral contract, where the boundary range is depicted as the grey block. The blue and red dot lines represent the DA predicted quantity P_{f} and the RT generated quantity P_{RT}, respectively.

The WPP allocates scheduled power based on predictions of wind power generation and market price before an operating day. In most cases, the DA price is higher than the contract price. For higher profit, in hours (e.g. t_1, t_2, t_{22}, t_{23} in Fig. 3) when the predicted quantity is higher than the lower boundary of bilateral contract, the WPP allocates power into the bilateral contract at quantity of the lower boundary, while the rest is submitted in DA market (parts of blue solid line where its value is higher than 0), as Eq. (19). In hours (e.g. t_3, t_{24} in Fig. 3) when the predicted quantity is lower than the lower boundary of bilateral contract, the WPP has to purchase power in DA market (parts of blue solid line where its value is lower than 0), as Eq. (18).

Within the operating day, in hours (eg. t_1, t_2, t_3 in Fig. 3) when the RT generated quantity is greater than the DA predicted, the WPP has to decide whether to trade the excess power in balancing market or via bilateral contract. In most cases, the contract price is higher than the balancing price. For higher profit, the WPP trades the excess power via bilateral contract, depicted as the green solid line. On the contrary, in hours (e.g. t_{22}, t_{23}, t_{24} in Fig. 3) when the RT generated quantity is lower than the DA predicted, the WPP has to purchase power in balancing market to compensate for the unsatisfied quantity in bilateral contract, depicted as the orange solid line. The relationship of power traded in balancing market and via bilateral contract is referred to as Eq. (15).

3.2.2. With barrier option

The barrier option affects WPP's profit in pool market, and thus affects WPP's utility with bilateral contract. With both barrier option and bilateral contract, WPP's utility is defined as,

$$U_{\mathrm{wpp,con,O}}^{n} = \sum_{\omega}^{N_\omega}\sum_{h}^{H}\pi^{\omega}\cdot R_{\mathrm{con,O}}^{n,h,\omega} + \beta_{\mathrm{wpp}}^{n}\cdot CVaR_{\mathrm{wpp,con,O}}^{n} \tag{20}$$

s.t.

$$\begin{aligned} R_{\mathrm{con,O}}^{n,h,\omega} = {} & P_{\mathrm{con}}^{n,h,\omega}\cdot\lambda_{\mathrm{con}} - P_{\mathrm{DAbuy}}^{n,h,\omega}\cdot\lambda_{\mathrm{DA}}^{h,\omega} \\ & + \left(r\cdot P_{\mathrm{DAsell}}^{n,h,\omega}\cdot\lambda_{\mathrm{wp,hed}}^{h,\omega} + \left(P_{\mathrm{Tsell}}^{n,h,\omega} - r\cdot P_{\mathrm{DAsell}}^{n,h,\omega}\right)\cdot\lambda_{\mathrm{wp}}^{h,\omega}\right)(1 - V_{\mathrm{O}}(r)) \end{aligned} \tag{21}$$

(14)–(19)

The difference between (21) and (13) is the third term of the right-hand side. In (21), it calculates the net profit in trading wind power in pool market considering the cost of purchasing the barrier option.

3.3. Customer's utility

3.3.1. Utility in energy consumption

The quadratic utility function [54,55] is adopted to describe the customer's utility in energy consumption and confirmed to be non-decreasing and concave, as

$$U_{\mathrm{c}}(e) = \begin{cases} \theta_{\mathrm{c}}e - \frac{\gamma_{\mathrm{c}}}{2}e^2, & \text{if } 0 \leqslant e \leqslant \frac{\theta_{\mathrm{c}}}{\gamma_{\mathrm{c}}} \\ \frac{\theta_{\mathrm{c}}^2}{2\gamma_{\mathrm{c}}}, & \text{if } e \geqslant \frac{\theta_{\mathrm{c}}}{\gamma_{\mathrm{c}}} \end{cases} \tag{22}$$

To value the different utilities in different times of a day, three different parameters are chosen for peak, flat and valley hours, respectively. In this case, e in (22) is replaced by $\sum_{h\in peak\ hours}x^{h,\omega}$, $\sum_{h\in flat\ hours}x^{h,\omega}$ and $\sum_{h\in valley\ hours}x^{h,\omega}$.

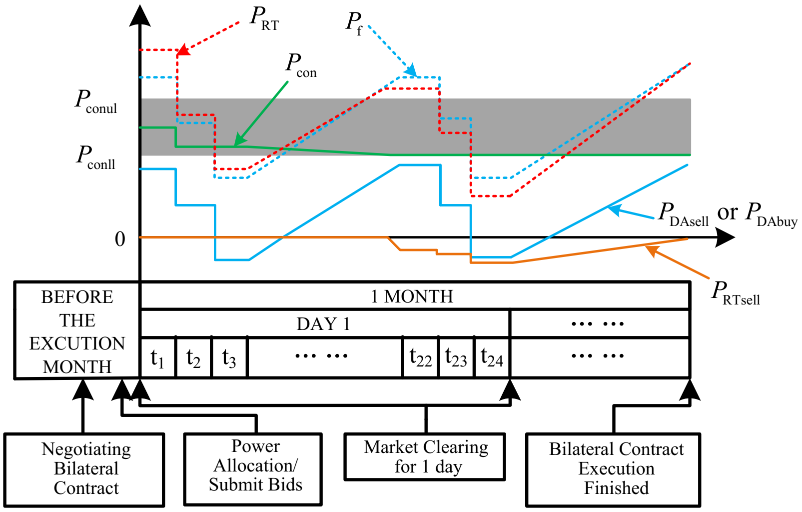

Fig. 3. Time frames for executing bilateral contract.

3.3.2. Utility in pool market

The customer's utility in pool market is calculated as energy consumption utility minus energy purchasing cost and plus risk, represented as,

$$U_{\text{csm,pool}} = \sum_{\omega}^{N_\omega}\sum_{h}^{H}\pi^{\omega}\cdot U_{\text{c}}\left(x_{\text{pool}}^{h,\omega}\right) - \sum_{\omega}^{N_\omega}\sum_{h}^{H}\pi^{\omega}\cdot x_{\text{pool}}^{h,\omega}\cdot\lambda_{\text{RTP}}^{h,\omega} + \beta_{\text{csm}}\cdot CVaR_{\text{csm,pool}} \tag{23}$$

$$\text{s.t. } x_{\text{pool}}^{h,\omega} = x^{h,\omega} + \sum_{i}^{H}\varepsilon_{h,i}\cdot\frac{\lambda_{\text{RTP}}^{h,\omega}-\lambda_{\text{RTPbase}}^{h,\omega}}{\lambda_{\text{RTPbase}}^{h,\omega}} \tag{24}$$

$$\lambda_{\text{RTP}}^{h,\omega} = \lambda_{\text{DA}}^{h,\omega} + \lambda_{\text{TD}}^{h,\omega} \tag{25}$$

Eq. (24) shows that the real demand of the customer is changed for the varying Real Time Price (RTP) considering the electricity price elasticity. In (25), the RTP is formed by the DA price plus a fixed T&D price [44].

3.3.3. Utility with bilateral contract

With bilateral contract, the customer has the obligation to receive the power supplied by the WPP at any quantity level within the stipulated boundary range and at the determined price. The customer's utility is,

$$U_{\text{csm,con}} = \sum_{\omega}^{N_\omega}\sum_{h}^{H}\pi^{\omega}\cdot U_{\text{c}}\left(x_{\text{con}}^{h,\omega}\right) - \sum_{\omega}^{N_\omega}\sum_{h}^{H}\pi^{\omega}\cdot max\left(x_{\text{con}}^{h,\omega},P_{\text{con}}^{h,\omega}\right)\cdot\lambda_{\text{RTP,con}}^{h,\omega} + \beta_{\text{csm}}\cdot CVaR_{\text{csm,con}} \tag{26}$$

s.t. (25), (27), and (28).

A Stackelberg model is utilized to determine the changed demand via bilateral contract $x_{\text{con}}^{h,\omega}$. In a Stackelberg model, the leader moves firstly and the follower moves subsequently. The leader must consider how the follower may act before taking a move. Since the follower can take a move after fully observing the leader's move, the leader must consider how the follower should act before taking actions. Here, as the equivalent RTP $\lambda_{\text{RTP,con}}^{h,\omega}$ results from the customer's changed demand $x_{\text{con}}^{h,\omega}$, the determination of $x_{\text{con}}^{h,\omega}$ is the leader; while $\lambda_{\text{RTP,con}}^{h,\omega}$ acts as the follower. The model is illustrated as,

$$x_{\text{con}}^{h,\omega} = x^{h,\omega} + \sum_{i\in H\wedge i\neq h}^{H}\varepsilon_{h,i}\cdot\frac{\lambda_{\text{RTP}}^{h,\omega}-\lambda_{\text{RTPbase}}^{h,\omega}}{\lambda_{\text{RTPbase}}^{h,\omega}} + \varepsilon_{h,h}\cdot\frac{\lambda_{\text{RTP,con}}^{h,\omega}-\lambda_{\text{RTPbase}}^{h,\omega}}{\lambda_{\text{RTPbase}}^{h,\omega}} \tag{27}$$

$$\lambda_{\text{RTP,con}}^{h,\omega} = \frac{\lambda_{\text{RTP}}^{h,\omega}\cdot\max\left(x_{\text{con}}^{h,\omega}-P_{\text{con}}^{h,\omega},0\right)+\left(\lambda_{\text{con}}+\lambda_{\text{TD}}^{h,\omega}\right)\cdot P_{\text{con}}^{h,\omega}}{\max\left(x_{\text{con}}^{h,\omega},P_{\text{con}}^{h,\omega}\right)} \tag{28}$$

In (27), the customer reacts to the RTP and changes its demand, while in executing hour h of the bilateral contract, the customer reacts to the equivalent RTP defined by (28). The numerator of the right-hand side in (28) represents the power purchasing cost (in pool market and with bilateral contract), while the denominator represents the total purchased quantity.

3.4. Bilateral contract negotiation

The Nash bargaining theory is adopted for negotiation process of the bilateral contract. The Nash bargaining theory is a cooperative-game modeling that constrains negotiated outcomes to satisfy basic fairness and efficient criteria, assuming that participants in strategic situations are able to bargain directly with each other to reach binding decisions [56]. The negotiation of bilateral contract can be treated as a cooperative game, in which both parties take into account their perceived trade-off between expected return and risk, represented as utility in this paper. The two utility-seeking players (WPP and customer in this paper) agree on a sweet point that leads to the maximum value of product of changes in utility after executing the bilateral contract:

(1) Without barrier option

$$\max F_1 = \left(U_{\text{wpp,con}}^{n} - U_{\text{wpp,pool}}^{n}\right)\left(U_{\text{csm,con}} - U_{\text{csm,pool}}\right) \tag{29}$$

(2) With barrier option

$$\max F_2 = \left(U_{\text{wpp,con,O}}^{n} - U_{\text{wpp,pool}}^{n}\right)\left(U_{\text{csm,con}} - U_{\text{csm,pool}}\right) \tag{30}$$

4. Case study

4.1. Data and approach

In this section, we conduct case studies based on real-world data from the Iberian electricity market [57]. The barrier option is devised for trading wind power in October 2015. The market price data of 12 months from October 2014 to September 2015 are adopted as sets of scenarios. To be consistent, forecast and RT wind speed of six wind farms during the same period, i.e. 12 months within October 2014 to September 2015 are adopted [58]. Their installed capacities are set to 100 MW. Wind speeds are transformed into wind power generation using the wind-speed/wind power curve of a Nordex N90/2500 turbine [59]. The averaged profiles of the wind power outputs for the six wind farms are shown in Fig. 4, and Table 2 illustrates the average forecast errors, which is calculated by the averaged value of difference between RT generated and forecast quantities:

$$P_{\text{error}}^{n} = \frac{1}{H}\sum_{h}^{H}\sum_{\omega}^{N_\omega}\pi_{\omega}\left|P_{\text{RT}}^{n,h,\omega}-P_{\text{f}}^{n,h,\omega}\right| \tag{31}$$

The customer's demand is acquired from the total Spanish demand of the same 12 months and modified as the peak value is 221 MW considering the capacities of the wind farms. Overall, to consider the uncertainties of electricity market price, wind power generation, and load demand, the total number of scenarios utilized is $12^3 = 1728$, with each scenario being assumed to have the same weight. Time period is classified: 22:00–8:00 as valley hours, 8:00–12:00 and 18:00–22:00 as peak hours, 12:00–18:00 as flat hours [44]. θ_{c} is valued as 80, 60, and 50 for peak, flat, and

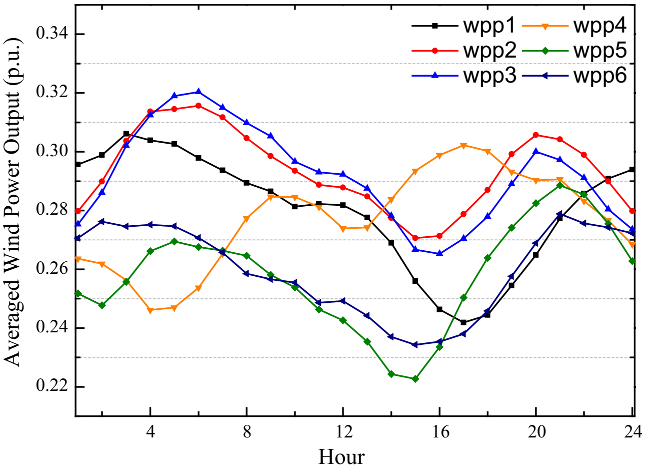

Fig. 4. Averaged profiles of wind power output for the six wind farms.

Table 2
Average forecast errors of the six wind farms.

Wind farms no.	1	2	3	4	5	6
Forecast error	28.43%	19.10%	30.78%	23.94%	21.64%	27.37%

valley hours, respectively. γ_c is 0.03. Risk preference factors are set to 0.5 for both WPP and customer. We assume that barrier price equals to the strike price.

The utility functions referred to in Sections 2 and 3 aim to maximize the expected utility with consideration of risks, indicated by CVaR. It is defined as the expected profit of the $(1-\alpha)100\%$ least profitable scenarios. The CVaR is acknowledged to have better mathematical properties than Value at Risk (VaR), since it reflects the extent of risk associated with the scenarios whose profits fall below the threshold determined by VaR [14,29,44,60]. The CVaR can be expressed linearly within an optimization problem and is easy to handle, because it is convex as long as the profit function is convex[2] [60]. For a mathematical model

$$\max \ F = \sum_{\omega}^{N_\omega} \pi^{\omega} \cdot R^{\omega} + \beta \cdot CVaR \tag{32}$$

where R^{ω} is the profit function. The CVaR value can be calculated as

$$\max_{\eta^{\omega},\xi} \quad CVaR = \xi - \frac{1}{1-\alpha}\sum_{\omega}^{N_\omega} \pi^{\omega} \cdot \eta^{\omega} \tag{33}$$

$$\text{s.t.} \quad -R^{\omega} + \xi - \eta^{\omega} \leqslant 0 \tag{34}$$

$$\eta^{\omega} \geqslant 0 \tag{35}$$

As illustrated in [60], the value of ξ represents the VaR value of R^{ω} and the optimal value of function (33) represents the CVaR value of R^{ω}. In this paper, the confidence level α is set as 0.95 in all cases.

4.2. Price of barrier option

The strike price are set as 32, 35, 38, 41 €/MW h, respectively. The price of barrier option can then be identified by solving (9), as shown in Fig. 5. Therefore, higher strike price leads to higher price of barrier option, and with the increasing hedge rate, the price of barrier option increases accordingly.

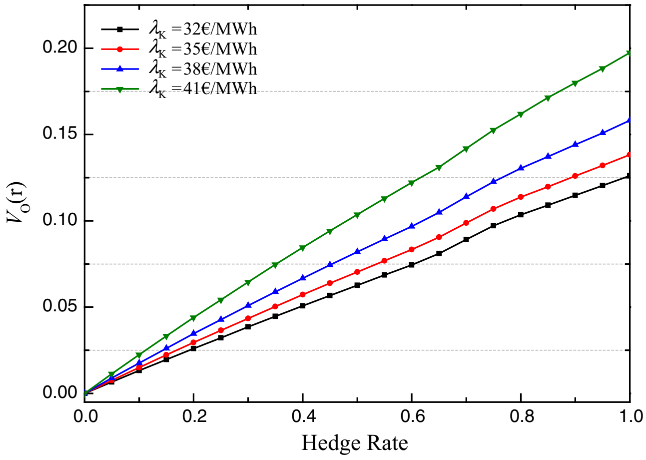

Fig. 5. Price of barrier option as a function of hedge rate for different strike prices.

4.3. Impact on price of barrier option by new comers

Wind power has its inherent nature of intermittence and variability. Those properties such as a smaller forecast error or a smoother and stable generation are more beneficial for the system operation. These properties are referred to as *good-to-system* properties in this paper. Therefore, WPPs with *good-to-system* properties should be more encouraged to the electricity market. In this subsection, we focus on how the price of barrier option is affected by the new arrival of WPPs with *good-to-system* properties. Among the aforementioned six WPPs, WPP2 and WPP4 have the *good-to-system* properties, since WPP2 has the lowest level of forecast errors and WPP4 has the property of peak load regulation. We assume two more WPPs with the same properties of WPP2 and WPP4 come to the electricity market, respectively. Setting the strike price as 35 €/MW h, the price of barrier option with the new comers can be acquired by solving (9), as shown in Fig. 6.

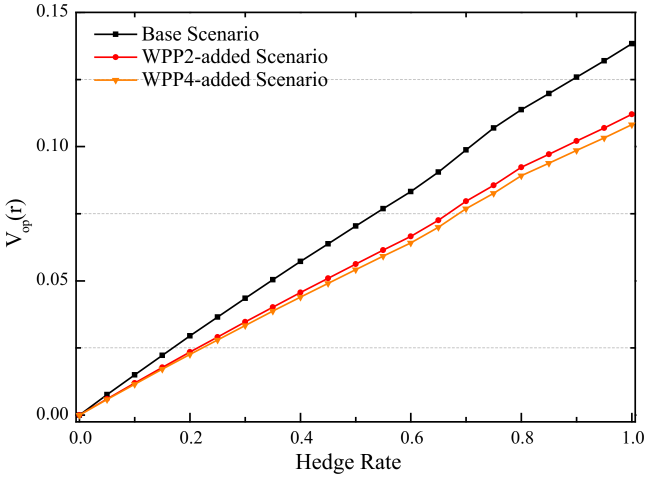

Fig. 6. Impact on price of barrier option by different new-comers.

In Fig. 6, the coming of two WPPs with *good-to-system* properties drives down the price of barrier option. To be specific, when the hedge rate is 1.0, the price of barrier option is reduced by approximately 1/5. This validates that with barrier options, WPPs with *good-to-system* properties are more encouraged to the electricity market because not only that they are beneficial for system operation but also that they reduces the price of barrier option.

4.4. Pool market trading with barrier option

Setting the strike price as 35 €/MW h, optimal hedge rates of different WPPs and the corresponding utilities are generated by solving (11), Fig. 7 shows how the utilities in trading per-unit energy vary with different hedge rates of the 6 WPPs. The optimal hedge rates of the 6 WPPs range from 0.7 to 0.8. Larger hedge rate does not necessarily leads to higher utility. This is due to the forecast error of wind power. If the hedge rate is at a higher level, there is a possibility that the hedged proportion of power exceeds the actual RT generation considering the forecast error. In this case, wind power is over-hedged as the WPP has to pay an extra barrier option price for part of power that is not generated. As WPP2 has a lower level of forecast errors, its optimal hedge rate is 0.8, larger than other WPPs, because a lower level of forecast errors indicates less possibility on over-hedging. The optimal hedge rate of WPP4 is higher than others. This is due to the peak load property of WPP4's power output as the output is higher in peak hours with higher

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[2] Profit functions in (29) and (30) are convex, since it can be proved that their Hessian Matrices exist and the order principal minor determinants of their Hessian Matrices are greater than zero [61].

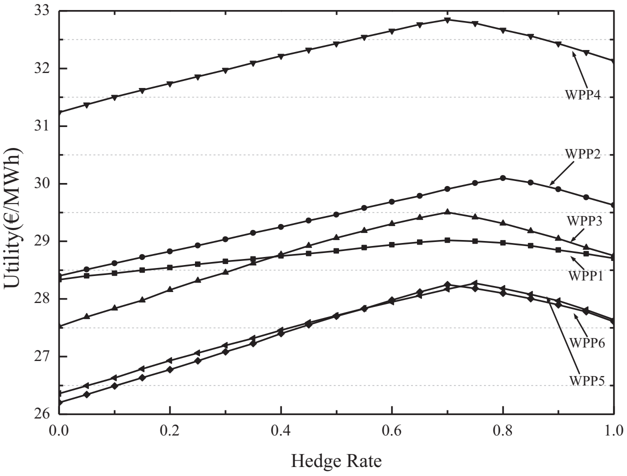

Fig. 7. Utility of per unit energy as a function of hedge rate for the WPPs.

market price. With optimally purchased barrier options, the utilities of the 6 WPPs are improved by 1.14 €/MW h on average.

4.5. Bilateral contract trading without barrier option

We focus on a situation that without barrier option, the WPP1 and the customer negotiate a bilateral contract. Setting the strike price as 35 €/MW h, the negotiation results are illustrated in Table 3 by employing (29). The lower and upper boundaries of the bilateral contract are 23.2 MW and 57.7 MW, respectively. The bilateral contract price is 33.1 €/MW h. Compared to the utilities in pool market (4.29×10^4 € for WPP1 and 1.288×10^5 € for the customer), with the help of bilateral contract, utilities of WPP1 (4.64×10^4 €) and the customer (1.332×10^5 €) are elevated by 8.16% and 3.42%, respectively.

Figs. 8 and 9 demonstrate how WPP1 and customer's utilities vary along with different boundaries of the bilateral contract when the price is constant. From Fig. 8, we figure out that a larger boundary range leads to a greater utility for WPP1. This is reasonable since a larger boundary range countervails more wind power deviations. In Fig. 9, there is a sweet point of the boundary values where the customer achieves the greatest utility. If the boundary range is at a smaller level, even though the customer may reduce energy consumption, but the decreased utility in energy consumption can be recovered by the reduced cost in purchasing energy with the bilateral contract. On the contrary, if the boundary range is at a higher level, the customer may reduce energy consumption as well, while the decreased utility can be much greater and can no longer be recovered by the reduced cost with the bilateral contract.

4.6. Bilateral contract trading with barrier option

Setting the strike price as 35 €/MW h, negotiation results of the bilateral contract are generated by solving (30), as illustrated in Table 4. The bilateral contract price is reduced to 30.9 €/MW h, because with barrier option, WPP1 could achieve greater utility in pool market and give up more utility to the customer. Thanks to the more *risk-free* way of trading, the WPP1's utility

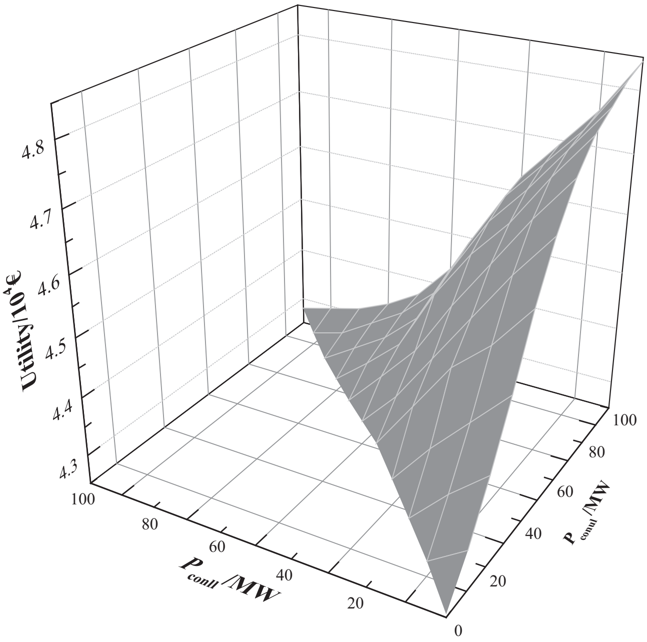

Fig. 8. Utility of the WPP1 as a function of lower and upper boundaries of the bilateral contract ($\lambda_{con} = 33.1$ €/MW h).

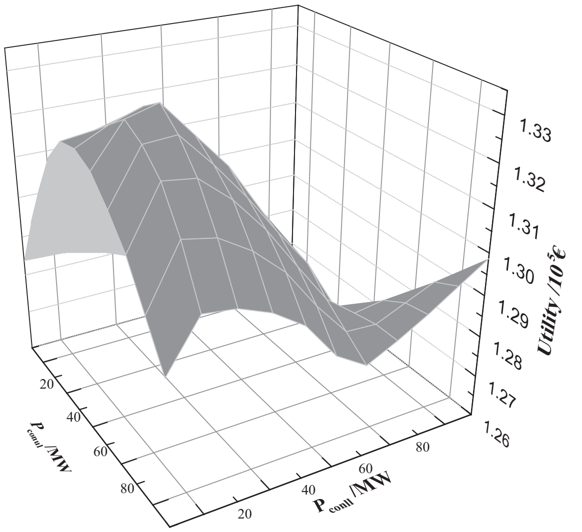

Fig. 9. Utility of the customer as a function of lower and upper boundaries of the bilateral contract ($\lambda_{con} = 33.1$ €/MW h).

Table 4
Negotiation results of bilateral contract with barrier option.

λ_{con} (€/MW h)	P_{conll} (MW)	P_{conul} (MW)	r	$U^n_{wpp,con,O}$ (€)	$U_{csm,con}$ (€)
30.9	18.0	67.1	0.95	4.98×10^4	1.360×10^5

Table 3
Negotiation results of bilateral contract without barrier option.

λ_{con} (€/MW h)	P_{conll} (MW)	P_{conul} (MW)	$U^n_{wpp,pool}$ (€)	$U^n_{wpp,con}$ (€)	$U_{csm,pool}$ (€)	$U_{csm,con}$ (€)
33.1	23.2	57.7	4.29×10^4	4.64×10^4	1.288×10^5	1.332×10^5

(4.98×10^4 €) is further increased by 7.33%. Furthermore, the lower contract price leads to a larger boundary range, resulted from deeper utilization of the customer's elastic demand. The customer's utility (1.360×10^5 €) is further increased by 2.02% consequently. The optimal hedge rate for WPP1 is 0.95, higher than that when trading only in pool market. This is due to the equivalent pool market traded quantity $P_{\text{Tsell}}^{n,h,\omega}$ can be adjusted with the help of the larger boundary range of bilateral contract, so the possibility on over-hedging is reduced. Therefore, it is concluded that efficiencies of the barrier option and bilateral contract are mutually promoted, as the barrier option leads to lower price and larger boundary range of the bilateral contract, while the bilateral contract leads to less possibility on over-hedging and better utilization of barrier option.

Concerning computational issues, all problems are solved using GAMS with an average time of 1373 s on a PC with Intel Core i5-6500 3.2-GHz CPU and 16 GB of RAM.

5. Conclusion

This paper devises a barrier option for wind power to hedge against risks of both market price and power generation. To devise the barrier option, concepts of the WP-traded price and equivalent WPP-traded quantity are introduced. Based on the WP-traded price, tariff structure and price of barrier option are proposed. The purchasing strategies of barrier option for the WPPs are studied both in pool market and with bilateral contract. Data from the Iberian market are adopted for case studies. The results indicate that,

(1) The barrier option improves WPPs' utility and thus promotes market-oriented integration of wind power. Both higher strike price and higher hedge rate lead to higher price of barrier option. However, to avoid over-hedging, the hedge rate is often chosen in a range of 0.7–0.8 for different WPPs in the case study. The optimal hedge rate brings an increase of 1.14 €/MW h in utility on average.

(2) The new arrival of WPPs with certain *good-to-system* properties such as smaller forecast errors and a property of peak load regulation drives down the price of barrier option by approximately 1/5. WPPs with *good-to-system* properties are more encouraged to the electricity market because not only they are beneficial for system operation but also they reduce the price of barrier option.

(3) The bilateral contract improves the WPP and customer's utilities by 8.16% and 3.42%, respectively. The WPP's utility is increased as the bilateral contract countervails part of its power deviations, while the customer's utility is increased as its demand elasticity is utilized and the power purchasing price is reduced. The bilateral contract attracts more elastic demand for lower-cost purchase of wind power.

(4) Efficiencies of the barrier option and the bilateral contract are mutually promoted. The barrier option results in lower price and larger boundary range of the bilateral contract, while the bilateral contract leads to less possibility on over-hedging and better utilization of the barrier option.

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