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A study on behavior of producers, retailers and speculators in futures and day-ahead markets: A Nash equilibrium model

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ABSTRACT

Uncertainties in different parameters such as the output power of renewable energy sources, available capacity of generators, or the condition of grid lines in the future, face market players with financial risks in the power system. Futures contracts are used in parallel with the day-ahead electricity markets to protect market players against financial risks of undesirable price fluctuations. Supplying a demand by both futures and day-ahead markets leads to mutual impacts between these two markets. In this paper, a Nash equilibrium approach is introduced to model the interactions between the futures and day-ahead markets. The proposed model includes producers, retailers, and speculators as market players, the uncertainty in the output power of wind farms (WFs), the possibility of the financial settlement of contracts, market players' risk preferences, and transmission system limitations. Using this approach, the optimal strategy of market players in futures and day-ahead markets, the effects of transmission system congestion on the Nash equilibrium of the system, and the role of the financial settlement of contracts in dealing with the uncertainty of WFs' output power and transmission lines capacity are discussed. Eventually, the behavior of speculators and their impacts on the gaming of other market players are evaluated. Simulation results highlight the role of the financial delivery feature in the effective utilization of futures contracts and the behavior of market players.

1. Introduction

Electricity producers and retailers are always at risk of adverse price fluctuations. This risk increases by growing investment in renewable energy resources with uncertain nature which causes higher uncertainty in estimating the electricity price in the future [1]. To reduce the risk of losing money, market players use financial derivatives such as forward, option, swap, and futures contracts. Since a given load can be offered by both financial and day-ahead markets, producers and retailers can define optimal strategies for trading in both markets so that their total profits are maximized and their risk preferences are also met. In this situation, on one hand, market players' strategies are affected by prices in the futures and day-ahead markets, and on the other hand, changes in the behavior of market players in the transfer of power from one market to another market affect the prices in both markets. Moreover, in addition to producers and retailers, speculators can also participate in the futures market. Speculators are not producers or consumers of electricity and benefit from trading futures contracts with other market players. Speculators' behavior can affect the markets' prices and the optimal strategies of market players. So, there are mutual impacts among producers', retailers', and speculators' strategies and prices in the financial and day-ahead markets. Studying the interactions of these markets can be very useful for system operators and decision-makers of countries that are going to run financial markets alongside the day-ahead electricity market. This gives them an estimation of how the markets' prices, profit of market players, and transmission system loading change after running financial markets.

The interactions between financial contracts and day-ahead markets have received considerable attention in the literature. These studies can be categorized from two different viewpoints: 1) market players' viewpoint and 2) system operators' viewpoint. The market players' viewpoint studies aim to maximize the profit of a specific market player such as a power producer or an electricity retailer considering the possibility of participating in both futures and day-ahead markets. In [2], the authors proposed two models for optimal power allocation of producers

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Nomenclature

Acronyms

ACP	Average contract price
ASX	Australian securities exchange
DAM	Day-ahead market
EEX	European energy exchange
FS	Financial settlement
JEPX	Japan electrical power exchange
LMP	Locational marginal price
PD	Physical delivery
PDF	Probability density function
SFE	Supply function equilibrium
TSO	Transmission system operator
WF	Wind Farm

Indices

d	Days
i	Producers
j and b	Retailers and areas
k	Speculators
s	Uncertainty scenarios of the delivery period

Sets

A	Set of areas
D	Set of trading days
P	Set of producers
R	Set of retailers
S	Set of speculators
U_d	Set of uncertainty scenarios at trading day d

Parameters

$\overline{T}_{b,b'}$	Upper bound for transmitted power between areas b and b'
ω	The weighting factor of the mixture PDF
ρ_s^d	Probability of uncertainty scenario s at trading day d
$\xi_{i,s}^{P,d}$	Concerns of producer i about scenario s at trading day d
$\rho_{i,s}^{P,d}$	Mixed probability-concern value for producer i
$\xi_{j,s}^{R,d}$	Concerns of retailer j about scenario s at trading day d
$\rho_{j,s}^{R,d}$	Mixed probability-concern value for retailer j
a_i	The intercept of the marginal cost function of producer i
b_i	The slope of the marginal cost function of producer i
$\overline{Q}_i$	The maximum output power of the producer i
$B_{bb'}$	Susceptance of the transmission line between areas b and b'
c_j	The intercept of the marginal utility function of retailer j
d_j	The slope of the marginal utility function of retailer j
m_k	The slope of the offer function of speculator k to producers
n_k	The slope of the bid function of speculator k to retailers
$p_{i,j}^{PR,f,z}$	Agreed contract price between producer i and retailer j in the past trading day z ($z < d$)
$p_{i,k}^{PS,f,z}$	Agreed contract price between producer i and speculator k in the past trading day z ($z < d$)
$p_{j,k}^{RS,f,z}$	Agreed contract price between retailer j and speculator k in the past trading day z ($z < d$)
$q_{i,j}^{PR,f,z}$	Agreed contract power between producer i and retailer j in the past trading day z ($z < d$)
$q_{i,k}^{PS,f,z}$	Agreed contract power between producer i and speculator k in the past trading day z ($z < d$)
$q_{j,k}^{RS,f,z}$	Agreed contract power between retailer j and speculator k in the past trading day z ($z < d$)
V_b	The nominal voltage of the transmission system at area b
$QW_{b,s}^d$	The output power of the WFs in area b in scenario s at trading day d

Variables

$W_{b,s}^d$	congestion-based wheeling fee for transmitting power from hub node to area b at delivery period scenario s estimated on trading day d
$\alpha_{i,j(k)}^d$	The intercept of the bid function of producer i to retailer j (speculator k) on trading day d of the futures market
$\overline{\mu}_{i,s}^d$	The lagrangian multiplier of the producers' generation capacity constraint
$\in_{j,i(k)}^d$	The intercept of the offer function of retailer j to producer i (speculator k) on trading day d of the futures market
$\eta_{k,i}^d$	The intercept of the offer function of speculator k to producer i on trading day d of the futures market
$\zeta_{k,j}^d$	The intercept of the bid function of speculator k to speculator j on trading day d of the futures market
$\gamma_{b,s}^d$	Injected power of the day-ahead market from the hub node to area b at uncertainty scenario s estimated on trading day d from the TSO viewpoint
$\delta_{b,s}^d$	The phase angle of area b at the delivery period scenario s estimated on trading day d
$\lambda_{b,s}^d$	The market price of area b at the delivery period scenario s estimated on trading day d
$\lambda_{hub,s}^d$	Hub node price at delivery period scenario s estimated on trading day d
$\mu_{i,b,s}^{hub,d}$	The lagrangian multiplier of hub node price from the viewpoint of producer i
$\mu_{j,b,s}^{hub,d}$	The lagrangian multiplier of hub node price from the viewpoint of retailer j
$\mu_{k,b,s}^{hub,d}$	The lagrangian multiplier of hub node price from the viewpoint of speculator k
$\mu_{i,j,s}^{PR,d}$	The lagrangian multiplier of financial settlement constraint for contracts between producer i and retailer j
$\mu_{k,i,s}^{SP,d}$	The lagrangian multiplier of financial settlement constraint for contracts between speculator k and producer i
$\mu_{k,j,s}^{SR,d}$	The lagrangian multiplier of financial settlement constraint for contracts between speculator k and retailer j
$\mu_{i,s}^{x,d}$	The lagrangian multiplier of grid power balance from the viewpoint of producer i
$\mu_{j,s}^{y,d}$	The lagrangian multiplier of grid power balance from the viewpoint of retailer j
$\mu_{k,s}^{z,d}$	The lagrangian multiplier of grid power balance from the viewpoint of speculator k
$\phi_{i,j,s}^{PR,d}$	Futures contract power that is estimated to be settled financially between producer i and retailer j in delivery period uncertainty scenario s of trading day d
$\phi_{k,j,s}^{SR,d}$	Futures contract power that is estimated to be settled financially between speculator k and retailer j in delivery period uncertainty scenario s of trading day d
$\psi_{b,s}^d$	The lagrangian multiplier of the DC power flow equality constraint
$Q_{i,s}^{P,d}$	Optimal power bid of producer i estimated on trading day d for scenario s of the delivery period
$x_{i,b,s}^d$	Injected power of the day-ahead market from the hub node to area b at uncertainty scenario s estimated on trading day d from the viewpoint of producer i
$y_{j,b,s}^d$	Injected power of the day-ahead market from the hub node to area b at uncertainty scenario s estimated on trading day d from the viewpoint of retailer j
$z_{k,b,s}^d$	Injected power of the day-ahead market from the hub node to area b at uncertainty scenario s estimated on trading day d from the viewpoint of speculator k

$\mu_{j,b,s}^{TL,d}$	The lagrangian multiplier of the transmission lines' lower bound constraint
$\mu_{j,b,s}^{TU,d}$	The lagrangian multiplier of the transmission lines' upper bound constraint
$P_{i,j}^{PR,f,d}$	Agreed contract price between producer i and retailer j on trading day d
$P_{i,k}^{PS,f,d}$	Agreed contract price between producer i and speculator k on trading day d
$P_{j,k}^{RS,f,d}$	Agreed contract price between retailer j and speculator k on trading day d
$Q_{i,j}^{PR,f,d}$	Agreed contract power between producer i and retailer j on trading day d
$Q_{i,k}^{PS,f,d}$	Agreed contract power between producer i and speculator k on trading day d
$Q_{j,k}^{RS,f,d}$	Agreed contract power between retailer j and speculator k on trading day d

and consumers in the day-ahead market and forward contract. Problems are formulated as mixed integer linear models and solved using dynamic programming. Dynamic programming was also applied in [3] to supply a load using day-ahead market, forward contracts, and self-generation. A wind hydro-pump storage unit operation was studied in [4] in which the goal was to maximize the profit considering the possibility of trading power in forward contracts and the day-ahead market. In [5], the authors proposed a stochastic model for solving the decision-making problem of a retailer in forward contracts and the day-ahead market. In [6] the bidding strategy problem for a producer in the day-ahead electricity market and weekly forward contracts were addressed. A multi-stage mixed-integer stochastic model was used to find the optimal trading strategy for a producer in the day-ahead electricity market, forward, and options contracts [7]. In [8], the optimal participation of coal-fired power plants in derivatives, bilateral contracts, and the day-ahead market is studied. The Monte Carlo method is used to make a two-way search for obtaining the best prices and capacities for contracts. In [9], a hybrid stochastic/robust approach is proposed to create a portfolio of call/put options to hedge the price and volumetric risk induced by a short position in forward contracts backed by renewable energy sources. The soft Robustness concept is used to include different degrees of aversion to ambiguity on spot price probability distribution. In [10], a multi-step risk-return method is presented to help retailers deal with the volatility of spot prices and consumption uncertainty. Retailers can trade in the futures market, bilateral physical forward contracts, and the day-head electricity market. A multi-level optimization problem is proposed to maximize profit and minimize risk. Finally, a decision support system is developed to sort the best options based on forecast results. In [11], an agent-based modeling and simulation approach is proposed to investigate the benefits of forward and contract for difference in the profit of market players. Key features for negotiating bilateral contracts considering risk management and risk sharing strategies are discussed in [12]. In [13], authors introduced a method to identify alternative swap contract designs that are more effective than conventional fixed volume swaps for trading the output power of WFs.

Market operators' viewpoint studies try to model the operation of the whole power system considering the physical properties of the grid and the rational behavior of market players. The goal is to give a better understanding of the impacts of financial derivatives and the day-ahead market on the operational point of the power system which leads to Nash equilibrium models. In [14], the authors introduced a Nash equilibrium model of a power system that operates with bilateral contracts. In this method, each producer submits bids to all retailers to agree on the volume of forward contracts. In [15], a two-layer master–slave game model is proposed to find the Nash equilibrium of an electricity market that works based on bilateral contracts. Producers, suppliers, and end-user are modeled and the game between producers and suppliers and between suppliers and end-users is formulated. A nonlinear reward and punishment mechanism is also used by suppliers to manage users' consumption. The impacts of forwards contracts on wholesale electricity markets with imperfect competition are studied [16]. A genetic algorithm is used to find the Nash equilibrium of the market. Producers are assumed to be strategic players while consumers are price-takers and modeled as constant loads. An agent-based retailer competition model is proposed in [17]. The method includes defining new strategies for retailers and a formal model for competition. Different risk attitudes of retailers are also modeled.

In [18], a Cournot-Nash equilibrium model was introduced for the parallel operation of day-ahead and forward contracts to supply the load ignoring the transmission system limitations. A supply function equilibrium (SFE) model of a power system with a day-ahead electricity market and forward contracts was proposed in [19]. The gaming of retailers and the impacts of electricity market prices on forward contracts were not considered in this model. In [20] an iterative algorithm was suggested for determining the optimal prices of bilateral contracts in a system with power producers, suppliers, and end-user consumers. In [21] the authors proposed a mathematical model for calculating the Nash equilibrium of forward contracts. The impacts of forward contracts on day-ahead market prices are not considered in this model. The SFE of the joint day-ahead and forward contract markets considering the mutual impacts of two markets, uniform and pay-as-bid pricing for electricity, strategic gaming of both producers and retailers, and uncertainty in load and wind power generation was studied in [22] and [23]. In [24] the authors investigated the impacts of day-ahead market prices on put option prices. A comprehensive model for joint put option and day-ahead markets was proposed in [25] to study the impacts of strike and premium prices of put option contracts on put option and day-ahead electricity markets. In [26] an equilibrium model was introduced for put option and day-ahead markets. Uncertainty in fuel price, the impact of premium bounds, and elasticity of consumers to strike price, premium price, and day-ahead price were taken into account and then, a new method for put option pricing is proposed. Nash equilibrium of put option and day-ahead markets with high and low elastic loads were investigated in [27]. The Black–Scholes method is used to model the option pricing. Nash equilibrium of futures and day-ahead market prices were modeled in [28]. The proposed model considers the futures market price equal to the average spot price over the time horizon and ignores the transmission system limitations and the active role of retailers in the futures market. In [29] a mixed supply function-Cournot equilibrium model is suggested to study the interactions of day-ahead and futures markets. Transmission system constraints and uncertainty in demand are considered in the model.

Futures contracts are one of the most popular derivatives for trading electricity. Among the most liquid European futures markets we can refer to European Energy Exchange (EEX) and Nord Pool [30]. EEX is the top electricity trader worldwide with an annual trading volume of 7406 *TWh* [31]. It offers trading in electricity futures contracts for 20 European power markets across Europe. Futures contracts have been traded on Nord Pool since 1995 [32]. North America Power, Japan Electric Power Exchange (JEPX), and Australian Securities Exchange (ASX) are some other markets for trading electricity futures contracts in the US, Asia, and Australia, respectively.

The review of studies in the literature shows that while futures are very popular for the electricity trade, the number of studies in this field is not significant. Also, the existing models for this market do not show the most important features of the futures market, such as the possibility of updating the contracts during the trading period, the financial delivery of contracts, and the strategic gaming of speculators, adequately.

To fill this gap in the literature, in this paper, a Nash equilibrium model for the joint operation of futures and day-ahead markets is proposed. The problem is solved from the perspective of the market operator. The main contributions of the proposed model are as follows:

- Proposing a Nash equilibrium model for parallel operation of futures and day-ahead markets considering the active role of both producers and retailers and uncertainty in output power of WFs;
- Considering the possibility of updating futures contracts on different days of the trading period taking into account the possibility of both financial and physical settlement of contracts in the delivery period;
- Modeling the behavior of speculators in the futures market and their interactions with producers and retailers.

The rest of the paper is organized as follows. In section 2 the problem is described and assumptions are presented. In section 3, the mathematical model for finding the Nash equilibrium of the system is formulated. Simulation results are presented and discussed in section 4, and finally, the paper is concluded in section 5.

2. Problem definition and assumptions

2.1. Problem definition

A futures contract is a legal agreement for trading standard sizes of a commodity at a predetermined price at a specific time in the future. The most important features of futures markets are 1) trading contracts in standard sizes 2) the possibility of the financial settlement of contracts instead of physical delivery, 3) daily mark-to-marketing settlement of contracts, and 4) the presence of different market participants such as speculators in the market along with the producers and retailers. The main advantage of the future contract compared to other derivatives are easy pricing, high liquidity, price transparency, and lack of default risk [29]. As mentioned in section 1, there are mutual impacts between futures and day-ahead markets. Hence, to study the power system operation, both futures and day-ahead markets and their interactions should be considered. In this paper, a Nash equilibrium model for a power system with both futures and day-ahead markets is proposed. The daily mark-to-marketing settlement feature of the futures market has already been investigated in [29] and we found out that the effect of this feature on the Nash equilibrium of the system is insignificant. Also, without loss of generality, we ignore the necessity of trading contracts in standard sizes to reduce the complexity of the model. So, our focus will be on other features of the futures market i.e., updating contracts on different days of the trading period, financial settlement possibility of contracts, and the presence of speculators in the market.

2.2. Financial and physical settlement

Futures contracts are usually settled by financial delivery. In some cases, it is also possible to settle the contracts by physical delivery. In this paper, it is assumed that the contracts can be settled by both financial and physical delivery. The financial settlement means offsetting futures contract obligations by cash transfers rather than physical delivery [33]. In general, both sides of the contract can perform financial settlement. However, to avoid over-complexity in the modeling and presentation, it is assumed that only one side of the contract decides the amount of the power that should be settled financially. When the contract is between a producer and retailer, it is assumed that the producer decides the financial settlement, and when a speculator is on one side of the contract, it decides on the amount of the power that is settled financially. It is also assumed that if a contract of a market player is settled financially by other parties, he/she will receive or pay the day-ahead market price of his/her area.

2.3. Structure of the power system

The power system includes several areas that are connected by transmission lines with limited power transmission capacity. In each area, there are several producers and one retailer. So, the same index can be used to refer to retailers and areas. If there is more than one retailer in each area, it can be split into separate areas that are connected by zero impedance lines and unlimited power transmission capacity. DC power flow is used to model the power system operation. It is assumed that tie-line capacities are assigned to the market participants based on their historical usage and the remainder is sold to them through annual transmission capacity auctions. To avoid complexity in the modeling, the tie-line capacity auctions process is not included in the formulation.

2.4. Market players characteristics

It is assumed that the marginal cost function of producer i for generating Q MW power is $a_i + b_i Q$ where $a_i \geqslant 0$ and $b_i \geqslant 0$ are the intercept and slope of marginal cost function, respectively. Marginal utility function of retailer j is $c_j - d_j Q$. $c_j \geqslant 0$ and $d_j \geqslant 0$ are the intercept and slope of marginal function, respectively. Since speculators are not producers or retailers of electricity, no marginal cost or utility function is defined for them.

2.5. Sequence of actions

It is suggested to divide the timeline into three periods, 1) the trading period, 2) one day before the delivery period, and 3) the delivery period. The futures market runs during the trading period and the day-ahead market runs one day before the delivery period. The delivery period of futures is usually one day, or several hours during peak and off-peak hours. However, for simplicity in presentation, it is assumed that the delivery period is one hour. The decision-making process on each trading day is presented in Fig. 1. On each day d of the trading period market players estimate the uncertainty scenarios and electricity price of the day-ahead market in the delivery period at each uncertainty scenario and consider concluded futures contracts in previous days of the trading period and their risk preferences. Then, they decide about the amount of power that they are going to trade in the futures market and its desirable price, the amount of power that is estimated to be traded in the day-ahead market one day before the delivery period, and the amount of power that will be settled financially in case of realizing each one of uncertainty scenarios. This process is repeated until one day before the delivery period. On this day, producers (retailers) decide about the financial or physical settlement of their contracts and then, participate in the day-ahead market to sell (buy) the rest of their capacity (demand) considering all the agreed futures contracts during the trading period that are going to be delivered physically. Speculators do not participate in the day-ahead market, and since they cannot deliver their contracts physically, they have to settle all their contracts financially.

2.6. Futures market modeling

On each day of the trading period d, all market players can participate in the futures market. The futures market is a continuous market which means that the market runs throughout the day, market players can frequently submit bids and offers, and the bids and offers that are matched in terms of price and quantity are finalized. Modeling the dynamics of such a market is not practically possible since we do not know the sequence of orders during the day. Instead, to model the futures market transactions, it is assumed that on each trading day, each market player can submit affine bids or offers to all other market players. Then, considering the orders received from other market players, it can make the best decision on the price and power of its futures contract. This leads to an operation point for the futures market that gives the most optimal position for each market player and can be used as an estimation

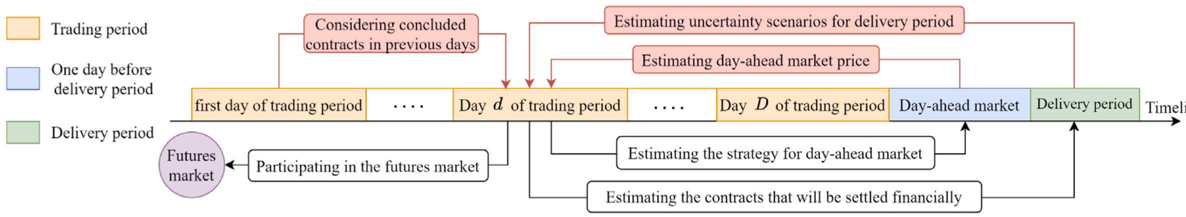

Fig. 1. Decision making process on trading day d.

of the outcome of the real futures market on that day. The decision-making variables of each market player are the intercepts of its bid or offer functions submitted to other market players. The slope of the bid (offer) function of each producer (retailer) is equal to the slope of its marginal cost (utility) function. Speculators do not have marginal cost or utility functions; however, from the perspective of producers (retailers), speculators are the same as retailers (producers). So, it is assumed that speculators submit bid functions to retailers and offer functions to producers. The slope of this bid (offer) function is assumed to be known and equal to the average of the slope of bid (offer) functions of all producers (retailers). The intersection of bid and offer functions of each two market players gives the price and quantity of futures contracts between these two market players in the trading day d.

2.7. Day-ahead electricity market modeling

The day-ahead electricity market is formulated by the Cournot model which is more straightforward than the supply function model when transmission system constraints are considered [34]. A Cournot Nash equilibrium model for the day-ahead electricity market is proposed in [35] which is upgraded to model the day-ahead electricity market operation in our work. In this approach, the authors show that a pool-co model of an electricity market is equivalent to a model in which 1) each producer sells power only to the retailer in its area and 2) there are arbitragers in the system that buy electricity from the low price areas and sell to high price areas until the price difference between every two areas gets equal to the price of the power transmission between those areas. It should be noted that the concept of arbitragers used in [35] is different from the speculators that are modeled in this paper. In [35], arbitragers are just auxiliary variables used to achieve the pool-co model from a bilateral model for the day-ahead market, while, in this paper, speculators are independent market players that participate only in the futures market. It is also assumed that all the power injected into the grid passes through a virtual hub node. The transmission system operator (TSO) charges producers a congestion-based wheeling fee $W^d_{b,s}$ for transmitting power from the hub node to area b. The TSO is modeled as a market player that maximizes its profit from power transmission in the grid considering the transmission system constraints. The following upgrades are applied to this method in our work: 1) Using affine marginal cost functions instead of fixed marginal functions in [34], 2) considering the effects of futures contracts on the day-ahead market, and 3) involving the uncertainties in the model. Producers are assumed to be strategic market players in both day-ahead and futures markets. However, since retailers must supply their loads at any price, they are price takers in the day-ahead market. Speculators are not allowed to bid into the day-ahead market.

2.8. Uncertainty scenarios

WFs' output power during the delivery period is considered as the source of uncertainty in the system which is modeled by some discrete scenarios [36]. There can be different WFs in different areas. The uncertainty in different days of the trading period and consequently the number of scenarios at each day d i.e., $n^{W,d}_s$, can also be different. So, the uncertainty scenario s at trading day d is defined as $QW^d_s = [QW^d_{1,s}, \cdots, QW^d_{b,s}, \cdots, QW^d_{n_b,s}]$ where n_b is the number of areas. It is assumed that the uncertainty scenarios are sorted increasingly, i.e., $QW^d_s \leqslant QW^d_{s+1}$.

2.9. Market players' risk preferences

Market players have different risk appetites. So, their risk management preferences should be included in the model. In general, to model risk preferences, a risk assessment measure such as value at risk (VaR) or conditional value at risk (CVaR) is defined and added to the objective function as a weighted penalty. This penalty represents the undesirable scenarios and the profit lost due to the realization of these scenarios. To formulate these methods, we should include a term to the objective function, add new constraints and define new variables. This increases the complexity of the model and the risk of convergence failure of the method, considerably. In this paper, it is suggested to use the concept of concern scenarios introduced in [29] to model the risk preferences of the market players. We know that the concerns of market players about realizing a scenario affect their behavior in the system. For instance, since by increasing the output power of WFs the electricity price decreases, producers (retailers) are more worried about scenarios that lead to high (low) wind power generation and trade futures contracts in prices greater (lower) than the prices in scenarios that they are most concerned about. In the concern scenario method, it is suggested to model these concerns as penalties that are included in the probability of scenarios in the objective function such that the scenarios lead to reducing the profit being penalized more than other scenarios. More precisely, for producers (retailers), we define these penalties such that their values increases as the output power of WFs increases (decreases) or equivalently, the electricity price decreases (increases), and consequently the profits of both producers and consumers decrease. Modeling the concerns in this way is similar to the VaR and CVaR methods where the scenarios that cause profit loss are included in the penalty term. Taking into account the above explanations, to include concerns into the probability of uncertainty scenarios it is suggested to replace the probability of each scenario with a mixed probability-concern value which is defined as the weighted sum of the probability and a penalty that reflects the concern of market players about that scenario [29]. The probability of each uncertainty scenario i.e., ρ^d_s is determined based on the viewpoint of the system operator on occurring that scenario. The exponential distribution is used to model the concerns of market players about different scenarios as below:

$$e(x,\beta) = \beta e^{-\beta x}. \tag{1}$$

The exponential distribution is a monotonically decreasing function. Since we have $QW^d_s \leqslant QW^d_{s+1}$, to model the concerns of retailer j (producer i) we can use $\xi^{R,d}_{j,s} = e(s,\beta^R_j)$ ($\xi^{P,d}_{i,s} = e(n^{W,d}_s - s, \beta^P_i)$) where β^R_j (β^P_i) represents the concern of retailer j (producer i).

compared to other retailers (producers). So, the mixed probability-concern value for retailer j is calculated as below:

$$\rho^{R,d}_{j,s} = \omega \xi^{R,d}_{j,s} + (1-\omega)\rho^d_s. \tag{2}$$

Similarly, the mixed probability-concern value for producer i is formulated as below:

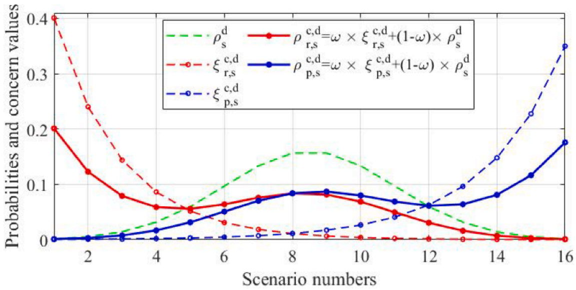

Fig. 2. Illustrative example of calculating mixed probability-concern values for one producer and consumer (w = 0.5).

$$\rho_{i,s}^{P,d} = \omega \xi_{i,s}^{P,d} + (1-\omega)\rho_s^d \tag{3}$$

This process is illustrated in Fig. 2 assuming that the probabilities of uncertainty scenarios are calculated by Normal distribution. Now, to consider producers' and consumers' risk preferences, it is enough to replace uncertainty probabilities with mixed probability-concern values [29]. The performance of the concern scenario method in modeling the risk preferences of market players in comparison with the CVaR method has been investigated and confirmed in [22]. Since speculators are not worried about decreasing and increasing the price and can make profit in both situations, mixed probability-concern values are not defined for them.

3. Problem formulation

In this section, the proposed method for calculating the Nash equilibrium of the system for 1) an arbitrary day during the trading period and 2) one day before the delivery period in the day-ahead market is formulated.

3.1. Obtaining the Nash equilibrium on trading day d

During the trading period, market players participate only in the futures market. However, they consider the estimations of the day-ahead market and interaction between two markets in different scenarios and maximize their expected profit in the aggregation of futures and day-ahead markets. To find the Nash equilibrium of the system, first, the futures and day-ahead market operations are formulated. Then, optimization problems of producers, retailers, and speculators are formulated, and finally, the process of obtaining the Nash equilibrium of the system is explained.

3.1.1. Futures market transactions modeling

To model the futures market, we focus on the outcome of the futures market at the end of the day and ignore the dynamics of market players' actions during the day. As mentioned in section 2.6, prices and quantities for futures contract between each two market players are obtained

$$H_{b,s}^{R,d} = \sum_{i \in P}\left(\sum_{z=1}^{d-1} q_{i,b}^{PR,f,z} + Q_{i,b}^{PR,f,z} - \phi_{i,b,s}^{PR,z}\right) + \sum_{k \in S}\left(\sum_{z=1}^{d-1} q_{b,k}^{RS,f,z} + Q_{b,k}^{RS,f,z} - \phi_{k,b,s}^{SR,z}\right) \quad \forall b \in R(A) \tag{11}$$

$$H_{i,s}^{P,d} = \sum_{j \in R}\left(\sum_{z=1}^{d-1} q_{i,j}^{PR,f,z} + Q_{i,j}^{PR,f,z} - \phi_{i,j,s}^{PR,z}\right) + \sum_{k \in S}\left(\sum_{z=1}^{d-1} q_{i,k}^{PS,f,z} + Q_{i,k}^{PS,f,z} - \phi_{k,i,s}^{SP,z}\right) \quad \forall i \in P \tag{12}$$

by calculating the intersection of their affine bid and offer functions [23]. Each producer i submits bid function $\alpha_{ij}^d + b_i Q_{ij}^f$ to each retailer $j \in R$ and bid function $\alpha_{i,k}^d + b_i Q_{i,k}^f$ to each speculator $k \in S$. α_{ij}^d and $\alpha_{i,k}^d$ are decision making variables of producer i in contract with retailer j and speculator k at trading day d, respectively. Similarly, decision making variables of retailer j (speculator k) in contract with producers and speculators (retailers) are $\epsilon_{\mathrm{j,i}}^{\mathrm{d}}$ and $\epsilon_{\mathrm{j,k}}^{\mathrm{d}}$ ($\eta_{k,i}^d$ and $\zeta_{k,j}^d$), respectively. So, by calculating the intersections of bid and offer functions, quantities and prices of the producer i-retailer j (PR), producer i-speculator k (PS), and retailer j-speculator k (RS) contracts on trading day d are formulated as below [23].

$$Q_{i,j}^{PR,f,d} = \frac{\epsilon_{\mathrm{j,i}}^{\mathrm{d}} - \alpha_{\mathrm{i,j}}^{\mathrm{d}}}{b_i + d_j}, \quad P_{i,j}^{PR,f,d} = \frac{b_i \epsilon_{\mathrm{j,i}}^{\mathrm{d}} + \mathrm{d_j} \alpha_{\mathrm{i,j}}^{\mathrm{d}}}{b_i + d_j} \tag{4}$$

$$Q_{i,k}^{PS,f,d} = \frac{\eta_{k,i}^d - \alpha_{i,k}^d}{b_i + m_k}, \quad P_{i,k}^{PS,f,d} = \frac{b_i \eta_{k,i}^d + m_k \alpha_{i,k}^d}{b_i + m_k} \tag{5}$$

$$Q_{j,k}^{RS,f,d} = \frac{\epsilon_{\mathrm{j,k}}^{\mathrm{d}} - \zeta_{\mathrm{k,j}}^{\mathrm{d}}}{n_k + d_j}, \quad P_{j,k}^{RS,f,d} = \frac{n_k \epsilon_{\mathrm{j,k}}^{\mathrm{d}} + \mathrm{d_j} \zeta_{\mathrm{k,j}}^{\mathrm{d}}}{n_k + d_j} \tag{6}$$

It should be noted that $Q_{i,j}^{PR,f,d}$, $Q_{i,k}^{PS,f,d}$, and $Q_{j,k}^{RS,f,d}$ can take any real values. This means that a market player can be both buyer and seller of power in the futures market. Fig. 3 illustrates this fact for a specific producer and retailer. It can be seen that both market players adjust their decision variables $\alpha_{i,k}^d$ and $\epsilon_{\mathrm{j,i}}^{\mathrm{d}}$ such that their contract quantity be positive or negative. In case the contract quantity is negative, the retailer is the seller of the power and the producer is the buyer of power in the futures market.

3.1.2. Estimating the day-ahead market operation during the trading period

As mentioned in Sections 2.5 And 3.1, the estimations of the day-ahead market during the delivery period and its interaction with futures contracts should be considered in formulating the operation during the trading period. This estimation should be performed for each uncertainty scenario s, separately. According to the proposed method in [35] and explanations in section 2.7, the optimization problem of the TSO in the day-ahead market at uncertainty scenario s of the trading day d is formulated as below:

$$\max_{\delta_{b,s}^d, \gamma_{b,s}^d \forall b \in A} \sum_{b \in A} W_{b,s}^d \left(\gamma_{b,s}^d + H_{b,s}^{R,d} - \sum_{i \in P_b} H_{i,s}^{P,d}\right) \tag{7}$$

s.t.

$$V_b V_{b^`} B_{b,b^`} \left(\delta_{b,s}^d - \delta_{b^`,s}^d\right) \leqslant \overline{T}_{b,b^`} \left(\mu_{b,b^`,s}^{TU,d}\right) \forall \{b, b^`\} \in L \tag{8}$$

$$V_b V_{b^`} B_{b,b^`} \left(\delta_{b,s}^d - \delta_{b,s}^d\right) \geqslant - \overline{T}_{b,b^`} \left(\mu_{b,b^`,s}^{TL,d}\right) \forall \{b, b^`\} \in L \tag{9}$$

$$\sum_{b' \in A} V_{b'} V_b B_{b',b} \left(\delta_{b',s}^d - \delta_{b,s}^d\right) = \gamma_{b,s}^d + H_{b,s}^{R,d} - \sum_{i \in P_b} H_{i,s}^{P,d} \left(\psi_{b,s}^d\right) \forall b \in A \tag{10}$$

The objective function (7) maximizes the revenue of TSO in transmitting day-ahead and futures markets' powers among areas. Variable $\gamma_{b,s}^d$ represents the injected power to area b in the day-ahead market from the viewpoint of the TSO. Variables $H_{b,s}^{R,d}$ and $H_{i,s}^{P,d}$ represent the physically delivered power to the retailer b and produced power by producer i in the futures market until the trading day d, respectively. P_b represents the set of producers in area b. Parameters $q_{b,k}^{RS,f,z}$, $q_{i,b}^{PR,f,z}$, and $q_{i,k}^{PS,f,z} \forall z = 1,\ldots,d-1$ are retailer-speculator, producer-retailer, and producer-speculator contract quantities for trading days before the trading day d. Since these parameters are known on trading day d, they should be considered constant parameters in optimization problems. Constraints (8) and (9) model the power transmission limitations of the grid lines. V_b is the voltage in area b. The parameter $B_{b',b}$ is the susceptance of the transmission line between area b and b'. Variable $\delta_{b,s}^d$ represents the voltage phase in area b. Constraint (10) represents the DC power flow equations. Equations (11) and (12) formulate variables $H_{b,s}^{R,d}$ and $H_{i,s}^{P,d}$, respectively. Variables $\mu_{b,b',s}^{TL,d}$, $\mu_{b,b',s}^{TU,d}$, and $\psi_{b,s}^d$ are lagrangian multipliers of constraints (8)-(10). The decision-making variables of the TSO optimization problem are $\gamma_{b,s}^d$ and $\delta_{b,s}^d$.

3.1.3. Optimization problem of producers

The optimization problem of producer i at trading day d is formulated as below:

$$\max_{Q_{i,s}^{P,d},\alpha_{i,j}^d,\alpha_{i,k}^d,\phi_{i,j,s}^{PR,d},x_{i,b,s}^d} \sum_{s\in U_d}\rho_{i,s}^{P,d}\Big(\lambda_{b(i),s}^d\Big(Q_{i,s}^{P,d}-\sum_{k\in S}\phi_{k,i,s}^{SP,d}\Big)+M_i^{P,d}-\sum_{j\in R}\lambda_{j,s}^d\phi_{i,j,s}^{PR,d}$$

$$-a_i\big(Q_{i,s}^{P,d}+H_{i,s}^{P,d}\big)-\frac{1}{2}b_i\big(Q_{i,s}^{P,d}+H_{i,s}^{P,d}\big)^2\Big) \tag{13}$$

s.t.

$$M_i^{P,d}=\sum_{z=1}^{d-1}\Big(\sum_{j\in R}p_{i,j}^{PR,f,z}q_{i,j}^{PR,f,z}+\sum_{e\in S}p_{i,k}^{PS,f,z}q_{i,k}^{PS,f,z}\Big)+\sum_{j\in R}P_{i,j}^{PR,f,d}Q_{i,j}^{PR,f,d}+\sum_{k\in S}P_{i,k}^{PS,f,d}Q_{i,k}^{PS,f,d} \tag{14}$$

$$\sum_{j\in R}\Big(\sum_{z=1}^{d-1}q_{i,j}^{PR,f,z}+Q_{i,j}^{PR,f,d}\Big)+\sum_{k\in S}\Big(\sum_{z=1}^{d-1}q_{i,k}^{PS,f,z}+Q_{i,k}^{PS,f,d}\Big)+Q_{i,s}^{P,d}\leqslant\overline{Q}_i\ \ \big(\overline{\mu}_{i,s}^d\big)\ \forall s\in U_d \tag{15}$$

$$\lambda_{b,s}^d=c_b-d_b\Big(\sum_{i\in P_b}Q_{i,s}^{P,d}+x_{i,b,s}^d+H_{b,s}^{R,d}\Big)\quad \forall s\in U_d, b\in A \tag{16}$$

$$\lambda_{b,s}^d-\lambda_{hub,s}^d-W_{j,s}^d=0\quad \big(\mu_{j,i,s}^{hub,d}\big)\forall b\in A,\forall s\in U_d \tag{17}$$

$$\sum_{b\in A}x_{i,b,s}^d=0\qquad \big(\mu_{i,s}^{x,d}\big)\ \forall s\in U_d \tag{18}$$

$$\phi_{i,j,s}^{PR,d}\leqslant\sum_{z=1}^{d-1}q_{i,j}^{PR,f,z}+Q_{i,j}^{PR,f,d}\quad \big(\mu_{i,j,s}^{PR,d}\big)\ \forall j\in R,\forall s\in U_d \tag{19}$$

$$Q_{i,s}^{P,d}\geqslant 0\qquad \forall s\in U_d \tag{20}$$

where U_d is the set of uncertainty scenarios at trading day d. $\lambda_{b(i),s}^d$ gives the locational marginal price (LMP) of area b in scenario s of trading day d. The index $b(i)$ represents the area b that producer i is located in. $Q_{i,s}^{P,d}$ is the scheduled power of producer i in the day-ahead market. $\phi_{k,i,s}^{SP,d}$ is the

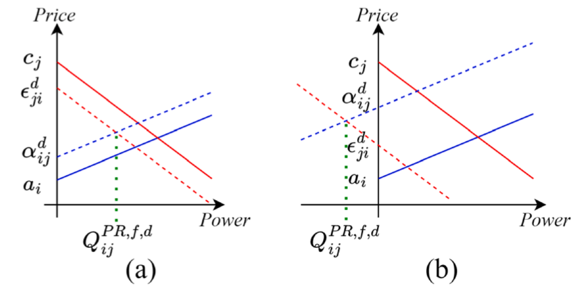

Fig. 3. Comparing two cases of interaction between a producer and retailer in the futures market, a) $Q_{i,j}^{PR,f,d}\geqslant 0$ b) $Q_{i,j}^{PR,f,d}\leqslant 0$.

amount of contract powers that are estimated to be settled financially by speculator k if scenario s of trading day d occurs. $\overline{Q}_i$ is the maximum generation capacity of the producer i. $\lambda_{hub,s}^d$ is the virtual hub node price. $x_{i,b,s}^d$ is the injected power to area b from the viewpoint of producer i. Parameters $p_{i,j}^{PR,f,d}$ and $p_{i,k}^{PS,f,d}$ are producer-retailer and producer-speculator contract prices for trading days before the trading day d which are known on trading day d. Variables $\overline{\mu}_{i,s}^d$, $\mu_{j,i,s}^{hub,d}$, $\mu_{i,s}^{x,d}$, and $\mu_{i,j,s}^{PR,d}$ are lagrangian multipliers of constraints (15), (17)-(19).

The first term in the objective function (13) represents the estimated revenue from the day-ahead market and the cost related to the financial settlement of contracts with speculators. The second term which is defined in (14) is the revenue from contracts until the trading day d. The third term is the cost of settling the contracts with retailers, financially, and the last two terms are the operation cost of the producer. Constraint (15) limits the scheduled power of the producer to its maximum generation capacity. Constraints (16) and (17) define the LMP of area b and the relation between the LMP of areas and the virtual hub node price, respectively. Constraint (18) indicates that the sum of injected power to the areas from the viewpoint of producer i is zero. Constraint (19) limits the financial settlement of contracts with each retailer to the quantity of futures contracts agreed with that retailer during the trading period. Decision-making variables of producer i at trading day d are $Q_{i,s}^{P,d}$, $\alpha_{i,j}^d$ $\forall j\in R\cup S$, $\phi_{i,j,s}^{PR,d}$ $\forall j\in R$, and $x_{i,b,s}^d$.

If a producer is not willing to participate in the futures market, variables $\phi_{k,i,s}^{SP,d}$, $\phi_{i,j,s}^{PR,d}$, $H_{i,s}^{P,d}$ and the constraint (19) are removed from its optimization problem.

3.1.4. Optimization problem of retailers

The optimization problem of retailer j on trading day d is formulated as below:

$$\max_{\epsilon_{j,i}^d,\epsilon_{j,k}^d,y_{j,b,s}^d}\sum_{s\in U_d}\rho_{j,s}^{R,d}\Big(-\lambda_{j,s}^d\Big(Q_{j,s}^{C,d}-\sum_{p\in P}\phi_{i,j,s}^{PR,d}-\sum_{k\in S}\phi_{k,j,s}^{SR,d}\Big)-G_j^{R,d}$$

$$+c_j\big(Q_{j,s}^{C,d}+H_{j,s}^{R,d}\big)-\frac{1}{2}d_j\big(Q_{j,s}^{C,d}+H_{j,s}^{R,d}\big)^2\Big) \tag{21}$$

s.t.

$$G_j^{R,d} = \sum_{z=1}^{d-1}\left(\sum_{i\in P} p_{i,j}^{PR,f,z} q_{i,j}^{PR,f,z} + \sum_{k\in S} p_{j,k}^{RS,f,z} q_{j,k}^{RS,f,z}\right) + \sum_{i\in P} P_{i,j}^{PR,f,d} Q_{i,j}^{PR,f,d} + \sum_{k\in S} P_{j,k}^{RS,f,d} Q_{j,k}^{RS,f,d} \tag{22}$$

$$Q_{j,s}^{C,d} = \sum_{i\in P_j} Q_{i,s}^{P,d} + QW_{j,s}^{d} + y_{j,j,s}^{d} \qquad \forall s \in U_d \tag{23}$$

$$\lambda_{b,s}^{d} = c_b - d_b\left(\sum_{i\in P_b} Q_{i,s}^{P,d} + y_{j,b,s}^{d} + H_{b,s}^{R,d}\right) \quad \forall s \in U_d, b \in A \tag{24}$$

$$\lambda_{b,s}^{d} - \lambda_{hub,s}^{d} - W_{b,s}^{d} = 0 \quad \left(\mu_{j,b,s}^{hub,d}\right) \forall b \in A, \forall s \in U_d \tag{25}$$

$$\sum_{b\in A} y_{j,b,s}^{d} = 0\left(\mu_{j,s}^{y,d}\right) \quad \forall s \in U_d \tag{26}$$

where $\phi_{k,j,s}^{SR,d}$ is the financially settled contracts of speculator k with retailer j estimated for scenario s of the trading day d. $y_{j,b,s}^{d}$ is the injected power to area b from the viewpoint of the retailer j. Variables $\mu_{j,b,s}^{hub,d}$ and $\mu_{j,s}^{y,d}$ are lagrangian multipliers of constraints (25) and (26). The parameter $p_{j,k}^{RS,f,d}$ is the retailer-speculator contract price for trading days before trading day d and is known on trading day d. The first term in the objective function (21) is the cost of buying electricity from the day-ahead market minus the revenue from the financial settlement of contracts by producers and speculators. The second term represents the cost of buying electricity through futures until the trading day d which is defined in (22). The last two terms of the objective function are the utility of the retailer of the delivered power. Equation (23) formulates the total delivered power to the retailer in the day-ahead market. Constraints (24) and (25) are the same as constraints (16) and (17) in section 3.1.3. Constraint (26) indicates that the sum of injected power to the areas from the viewpoint of retailer j is zero. The decision-making variables of retailer j on trading day d are $\epsilon_{j,i}^{d} \forall i \in P \cup S$ and $y_{j,b,s}^{d}$. If a retailer is not willing to participate in the futures market, variables $\phi_{k,j,s}^{SR,d}$, $\phi_{i,j,s}^{PR,d}$, and $H_{j,s}^{R,d}$ are removed from the optimization problem of this retailer.

3.1.5. Optimization problem of speculators

Speculators benefit from trading electricity with producers and retailers at different prices on different trading days of the futures market. At the end of the trading period, speculators must settle the net positive or negative power imbalance of their portfolio, financially. The optimization problem of speculator k at trading day d is formulated as below:

$$\max_{\zeta_{e,j}^{d},\eta_{e,i}^{d},\phi_{j,e,s}^{SR,d},\phi_{i,e,s}^{SP,d}} H_k^{S,d} - G_k^{S,d} + \sum_{s\in U}\rho_s^{d}\left(\sum_{i\in P}\lambda_{b_i,s}^{d}\phi_{k,i}^{SP} - \sum_{j\in R}\lambda_{j,s}^{d}\phi_{k,j}^{SR}\right) \tag{27}$$

s.t.

$$H_k^{S,d} = \sum_{j\in R} P_{j,k}^{RS,f,d} Q_{j,k}^{RS,f,d} + \sum_{z=1}^{d-1}\left(\sum_{j\in R} p_{j,k}^{RS,f,z} q_{j,k}^{RS,f,z}\right) \tag{28}$$

$$G_k^{S,d} = \sum_{i\in P} P_{i,k}^{PS,f,d} Q_{i,k}^{PS,f,d} + \sum_{z=1}^{d-1}\left(\sum_{i\in P} p_{i,k}^{PS,f,z} q_{i,k}^{PS,f,z}\right) \tag{29}$$

$$\sum_{z=1}^{d-1}\left(\sum_{j\in R} q_{j,k}^{RS,f,z} - \sum_{i\in P} q_{i,k}^{PS,f,z}\right) + \sum_{j\in R}\left(Q_{j,k}^{RS,d} - \phi_{j,k,s}^{SR,d}\right) - \sum_{i\in P}\left(Q_{i,k}^{PS,d} - \phi_{i,k,s}^{SP,d}\right) = 0 \tag{30}$$

$$\phi_{j,k,s}^{SR,d} \leqslant \sum_{z=1}^{d-1} q_{j,k}^{RS,f,z} + Q_{j,k}^{RS,f,d} \qquad \left(\mu_{k,j,s}^{SR,d}\right) \forall j \in R \tag{31}$$

$$\phi_{i,k,s}^{SP,d} \leqslant \sum_{z=1}^{d-1} q_{i,k}^{PS,f,z} + Q_{i,k}^{PS,f,d} \qquad \left(\mu_{k,i,s}^{SP,d}\right) \forall i \in P \tag{32}$$

$$\lambda_{b,s}^{d} = c_b - d_b\left(\sum_{i\in P_b} Q_{i,s}^{P,d} + z_{j,b,s}^{d} + H_{b,s}^{R,d}\right) \quad \forall s \in U_d, b \in A \tag{33}$$

$$\lambda_{b,s}^{d} - \lambda_{hub,s}^{d} - W_{b,s}^{d} = 0 \quad \left(\mu_{k,b,s}^{hub,d}\right) \forall b \in A, \forall s \in U_d \tag{34}$$

$$\sum_{b\in A} z_{k,b,s}^{d} = 0 \qquad \left(\mu_{k,s}^{z,d}\right) \tag{35}$$

The first two terms in the objective function (27) represent the revenue and cost of contracts with retailers and producers, which are formulated in (28) and (29), respectively. The last term in the objective function is the revenue of financial settlement of contracts with producers and retailers at the end of the trading period. Constraint (30) guarantees settling the net power imbalance of the speculators' portfolio with financial delivery at the end of the trading period. Constraint (31) (Constraint (32)) limits the power quantity of the financial settlement between a speculator and a retailer (producer) to the total concluded contract quantities between the speculator and that retailer (producer) during the trading period. Constraints (33)-(35) are defined similar to constraints (24)-(26). Variable $z_{j,b,s}^{d}$ is the injected power to area b from the viewpoint of the speculator k. The decision-making variables of the speculators are their bids and offers to retailers and producers during the trading period, i.e., $\zeta_{k,j}^{d} \forall j \in R$ and $\eta_{k,i}^{d} \forall i \in P$, and the quantity of power that is financially settled with retailers and producers, i.e. $\phi_{j,k,s}^{SR,d} \forall j \in R$ and $\phi_{i,k,s}^{SP,d} \forall i \in P$, respectively.

3.1.6. Finding the Nash equilibrium of the system

The proposed method in [35] and [29] is used to find the Nash equilibrium of the system. At first, since all the optimization problems are convex, Karush Kuhn Tucker (KKT) conditions of all optimization problems (7)-(12), (13)-(20), (21)-(26), (27)-(35) are written. Considering the fact that injected power to each area from the viewpoint of TSO, producers, retailers, and speculators should be the same, i.e., $\gamma_{b,s}^{d} = x_{i,b,s}^{d} = y_{j,b,s}^{d} = z_{k,b,s}^{d}$, repetitive equations i.e., 1) (16), (24) and (33), 2) (17), (25) and (34), and 3) (18), (26) and (35) are replaced with one equation. Finally, by solving the remained quality and inequality constraints of KKT optimally conditions the Nash equilibrium of the system

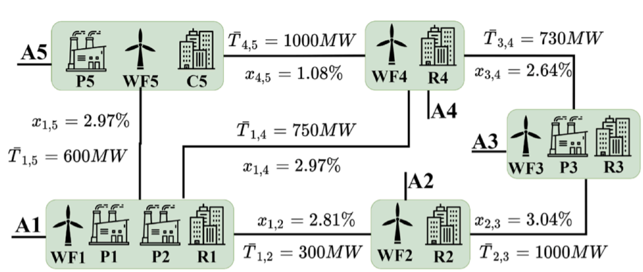

Fig. 4. Test system structure.

will be found.

3.2. Obtaining the Nash equilibrium of the day-ahead market

One day before the delivery period, market players participate in the day-ahead market. It is assumed that the futures market is closed at the end of the trading period. Hence, when market players participate in the day-ahead market the quantities and prices of concluded contracts are known. Moreover, retailers are price takers in the day-ahead market, and speculators are not allowed to participate in this market. So, to find the Nash equilibrium of the system, the contract prices and quantities in (4)-(6) are set fixed as parameters and the proposed approach in section 3.1.6 is repeated for TSO and producers, i.e., (7)-(12) and (13)-(20), respectively.

4. Numerical results

The test system is modified from the PJM 5-bus system as depicted in Fig. 4 [37]. Areas, producers, retailers, and WFs are introduced by characters A, P, R, and WF, respectively. It is assumed that the trading period includes 8 days. It is worth mentioning that the trading period can be up to several years. However, to provide analytical results, we focus only on a few days of the trading period in which significant changes in the uncertainty scenarios happen. The installed capacity of WF1, WF2, WF3, WF4, and WF5 are 0.2 GW, 1 GW, 1 GW, 2 GW, and 1.1 GW, respectively. The correlations between the output power of WFs are assumed to be 0.85. The uncertainty in the output power of WFs and the number of uncertainty scenarios on different days of the trading period varies and decreases as the delivery period approaches. The total output power of WFs in different uncertainty scenarios of all trading days are presented in Fig. 5. The green area in Fig. 5 indicates how the range of uncertainty changes on different trading days. Producers' and retailers' parameters are presented in Table 1 and Table 2, respectively. It is assumed that producer P4 and retailer R5 do not participate in the futures market. Only one speculator is considered for the system. Parameters b_k and d_k of the speculator are assumed to be equal to 0.014 $\$/MW^2$ and 0.013 $\$/MW^2$, respectively.

4.1. Simulation results

The expected value of estimated LMPs and their uncertainty range at different trading days are presented in Fig. 6. Transmission Lines L1,2 and L1,5 are congested in the delivery period which affects the prices in areas A1 and A5. Low (high) demand compared to high (low) generation capacity in Areas A1 (A5) leads to a low (high) LMP in this area compared to other areas. It can also be seen that by decreasing the estimated output power of WFs at the last trading days, the congestion in the grid increases due to the lack of power supply compared to the required demand in areas such as A2, A4 and A5 and necessity to import power from other areas. Cumulative contracted powers during the trading period, the contract settled by physical delivery (PD), and

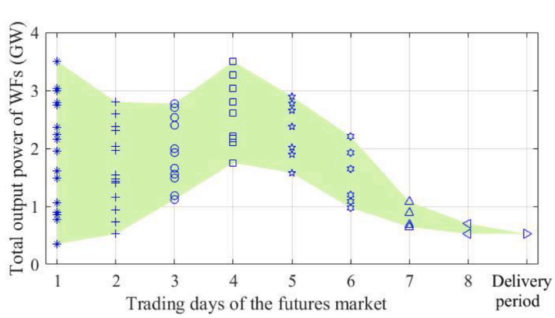

Fig. 5. Total output power of all WFs in uncertainty scenarios of each day of the trading period.

Table 1
Parameters of producers.

	P1	P2	P3	P4
$a_i(\$/MW)$	16	10.8	24	5.6
$b_i(\$/MW^2)$	0.012	0.011	0.007	0.026
$\overline{Q}_i(GW)$	2.5	4	3.5	5
β_i^P	0.75	0.40	0.65	0

Table 2
Parameters of retailers.

	R1	R2	R3	R4	R5
$c_j(\$/MW)$	82	60	90	71	78
$d_j(\$/MW^2)$	0.010	0.017	0.016	0.020	0.008
β_i^R	0.60	0.45	0.60	0.70	0

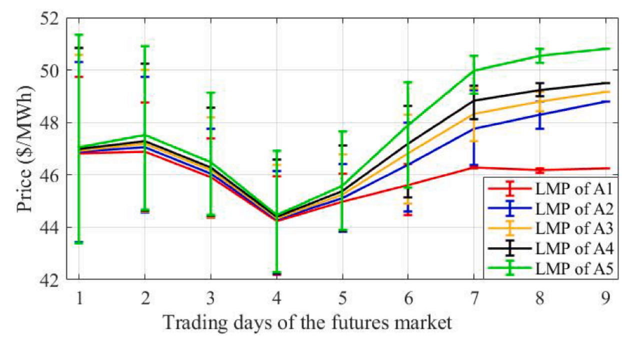

Fig. 6. Variations in the LMP of areas during the trading period.

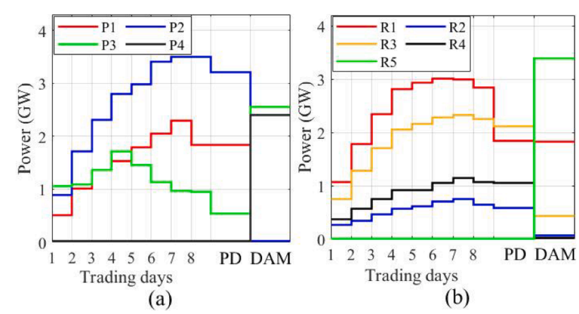

Fig. 7. Cumulative contract quantities of a) producers and b) retailers.

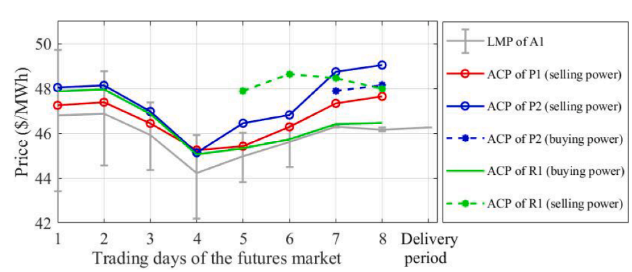

Fig. 8. Comparing the LMP and contract prices in Area A1.

scheduled powers in the day-ahead market (DAM) for producers and retailers are depicted in Fig. 7. Since the LMP in area A1 is low, producers P1 and P2 try to sell their available capacity in the futures market and settle the contracts as physically as possible. From trading day 4, expectations of the estimated LMP in area A3 increased. Hence, producer P3 decides to sell its futures contracts in the futures market, settle the remained contracts on the last trading day, financially, and trade all capacity in the day-ahead market. Retailers are willing to buy their required demand mostly through futures contracts. 100% of the demand of R2 and 86% of the demand of R3 are traded in the futures contract. This happens because the LMP of the areas of these retailers are higher than the LMP of area A1 and they decide to benefit from signing contracts with P 1 and P2 at lower prices. Market players trade most of their powers in the first five days of the trading period and then try to correct their position in the market by both selling and buying futures contracts in the rest of the trading days.

The daily average contract price (ACP) of producers P1 and P2 and retailer R1 that are located in area A1 are depicted in Fig. 8 as an example to understand how different prices change during the trading period. As shown in Fig. 8 contract prices are slightly greater than the average day-ahead market price. Since the LMP in area A1 is lower than other areas, producers P1 and P2 can sign contracts with retailers in other areas at higher prices. In this situation, retailer A1 is also forced to agree in higher prices for futures contracts because its low-price offers will not be accepted by producers. In some of the last four trading days, producers and retailers get opposite roles in the market to adjust their position in the market. This means that producers sell negative power to retailers (buy power from retailers) and retailers buy negative power from producers (sell power to producers). Prices of these negative power contracts for retailer A1 are greater than its positive power contract prices. This helps the retailer to cover some of the costs imposed by increasing the estimated day-ahead market price in the last trading days. Producers benefit from the financial settlement of their contracts depending on their location in the grid and congestion in the lines. For the studied case, it can be seen that considering the financial settlement possibility in the model increases the profit of producers P1, P2, and P3 about 1.7%, 2.9%, and 9.7%, respectively. The profit of producer P 4 that does not participate in the futures market decreases about 1% after considering financial settlement in the futures market.

The behavior of the speculator during the trading period is illustrated in Fig. 9. For the studied case, according to Fig. 9(a), the speculator contracts more power with retailers than producers which causes a power imbalance in its portfolio. This power imbalance is covered by the financial settlement of 445 *MW* of contracts with retailers. On the first trading days, the contract prices of the speculator with retailers are lower than its contract price with producers which increases the profit of the speculator. However, in the last trading days, as try to create a power balance in the portfolio the speculator has to agree on higher prices with producers which reduces the profit slightly. Finally, the financial settlement of contracts with retailers for providing the power balance in the speculators' portfolio causes 88% reduction in its profit and the speculator closes the not position with 2854 *$* profit. The profit of the speculator is about 6.1% of the average profit of producers.

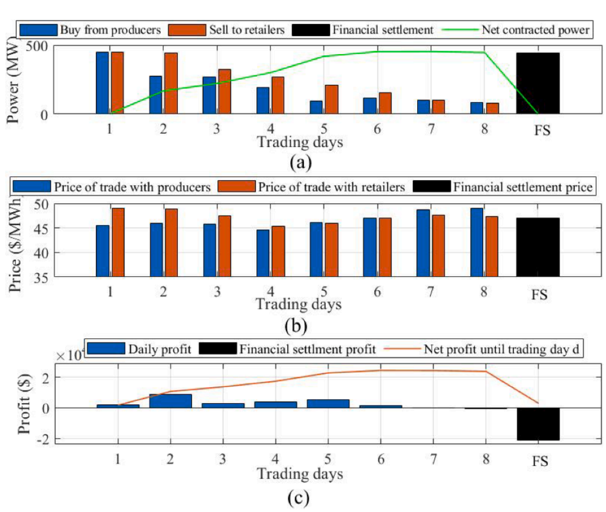

Fig. 9. Speculator's behavior during the trading period.

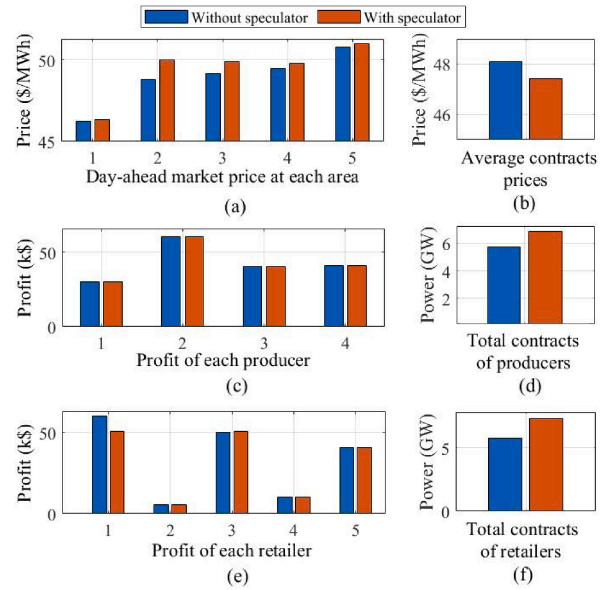

Fig. 10. Impacts of presence of speculators in the market on a) day-ahead market prices, b) futures contract prices, c) producers' profit, d) producers' contract powers, e) retailers profit f) retailers' contract powers.

4.2. Impacts of the speculator on the futures and day-ahead markets

Different parameters of the day-ahead and futures market with and without considering the presence of the speculators in the system are compared in Fig. 10. It can be seen that for the studied case, considering a speculator increases the day-ahead market prices and reduces the futures market prices. In fact, adding speculators to the futures market reduces market power and increases the competition and liquidity in this market, and leads to a reduction in the contract prices. The presence of speculator also causes a minor reduction in the profit of both producers and retailers. Retailer R1 receives the most impact from the presence of a speculator in the system. This happens because the speculator performs the financial settlement of contracts mostly with retailer A1. The the volume of futures contracts increases in the presence of speculators, which is expected as a result of adding a new market player.

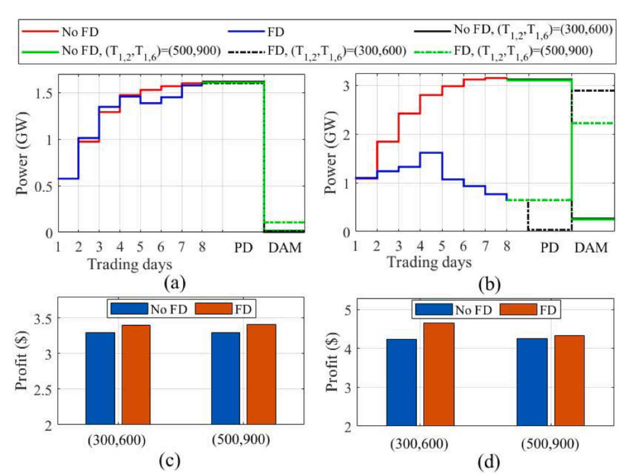

Fig. 11. Impacts of uncertainty in transmission lines capacity on a) behavior of P 1, b) behavior of P3, c) profit of P1, d) profit of P3, with and without considering financial delivery possibility.

4.3. Impacts of transmission system congestion uncertainty on market players' behavior

There might be some ongoing transmission system expansion projects during the trading period that there are uncertainties about their status in the delivery period. In this section, impacts of including these uncertainties on the market players' behaviors are studied. To this end, it is assumed that lines with capacity uncertainty are $T_{1,2}$ and $T_{1,6}$. Two uncertainty scenarios are defined for these lines as $\overline{T}(T_{1,2}, T_{1,6}) = \{(300, 600), (500, 900)\}$ and the probability of each scenario is assumed to be 0.5. To add these new uncertainties, it is suggested to replace uncertainty scenarios QW_s^d with $\{QW_s^d, \overline{T}_s\}$. This increases the number of uncertainty scenarios to $2n_s^{W,d}$. Values of mixed probability-concern parameters should be multiplied by the probability of transmission capacity uncertainty scenarios, i.e., 0.5. It is also assumed that these new uncertainties are included in the model from trading day 5. Simulation results are compared for two cases with and without considering financial settlement possibility in the futures market. Cumulative contract powers over all trading days, scheduled power in the day-ahead market, and profit of producers P1 and P3 with and without considering financial settlement possibility in the model are presented in Fig. 11. Comparing Fig. 11(a) and Fig. 11(b) shows that while P1 is not significantly affected by the possibility of financial settlement, P3 is greatly affected by it. The behavior of P3 in financial settlement of contracts and participating in the day-ahead market is different in each realization of the transmission lines capacity in the delivery period. Fig. 11(c) and Fig. 11(d) indicate that all producers benefit from the possibility of financial settlement of contracts in different realizations of the transmission lines' capacity in the delivery period.

Remark: It is worth noting that while Nash equilibrium models can provide an estimation of electricity markets operation, computation of it for real power systems has some limitations. The most important issue is that the Nash equilibrium problem is from the viewpoint of the TSO and the TSO that does not know exactly the cost function parameters of producers and the utility function of retailers. To overcome this issue, system operators can use the market players' bids and offers when their bids are close to their marginal cost and marginal utility to have an estimation of their cost function parameters. For instance, marginal pricing of producers can happen in off-peak hours.

5. Conclusion

In this paper, a Nash equilibrium model for the joint operation of the day-ahead electricity market and futures market is proposed. The introduced model considers the WFs' output power as the main source of uncertainty, strategic gaming of both producers and retailers in the futures market, transmission system structure, and main features of the futures market i.e., financial settlement of contracts and presence of speculators in the market. Simulation results approve the capability of the model in following real-world rules which makes it suitable for modeling the power systems operation and analyzing the impacts of different parameters on the markets and market players. Simulation results highlight the role of financial settlement possibility of futures contracts in affecting the behavior of market players and their profit, however, its impacts is dependent on the location of each market player in the system and the level of congestion in the grid. Simulation results also show that the presence of a speculator can increase the volume of transactions in the futures market and reduce the contract prices as a result of increasing market liquidity. For the studied case, the profits of producers did not considerably change after the presence of speculators, however, some retailers were affected by speculators and their profits were reduced. Based on the results, more than 70% of the total demand of the system is traded by the futures contracts which highlights the importance of considering the futures market in the power system analysis studies.

Providing a detailed model of retailers including flexible and inflexible loads, and considering their strategic behavior in the day-ahead market can be the future directions of this study. It is also worth noting that the possibility of financial and physical settlement of contracts in different markets could be different and also new regulations could be defined for the physical and financial settlement of futures. Each of these methods could be the subject of future studies in this field.

CRediT authorship contribution statement

Mohsen Banaei: Conceptualization, Methodology, Software, Writing – original draft, Validation, Visualization. **Hani Raouf-Sheybani:** Conceptualization, Writing – review & editing. **Majid Oloomi-Buygi:** Conceptualization, Writing – review & editing. **Razgar Ebrahimy:** Writing – review & editing. **Henrik Madsen:** Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

[1] Y. Xiao, X. Wang, C. Du, S. Liu, Hedging against uncertainties for wind power producer with block futures contracts, in: 2015 IEEE Power Energy Society General Meeting, 2015, pp. 1–5. doi:10.1109/PESGM.2015.7285850.
[2] Palamarchuk S. Dynamic programming approach to the bilateral contract scheduling. IET Gener Transm Distrib 2010;4(2):211–20.
[3] Carrion M, Philpott AB, Conejo AJ, Arroyo JM. A stochastic programming approach to electric energy procurement for large consumers. IEEE Trans Power Syst 2007;22(2):744–54. https://doi.org/10.1109/TPWRS.2007.895164.
[4] de la Nieta AAS, Contreras J, Catalao JPS. Optimal single wind hydro-pump storage bidding in day-ahead markets including bilateral contracts. IEEE Trans Sustain Energy 2016;7(3):1284–94. https://doi.org/10.1109/TSTE.2016.2544704.
[5] Safdarian A, Fotuhi-Firuzabad M, Lehtonen M. A medium-term decision model for discos: forward contracting and tou pricing. Power Systems, IEEE Transactions on 2015;30:1143–54. https://doi.org/10.1109/TPWRS.2014.2342373.
[6] Garces LP, Conejo AJ. Weekly self-scheduling, forward contracting, and offering strategy for a producer. IEEE Trans Power Syst 2010;25(2):657–66. https://doi.org/10.1109/TPWRS.2009.2032658.
[7] Pineda S, Conejo A. Managing the financial risks of electricity producers using options. Energy Econ 2012;34(6):2216–27. https://doi.org/10.1016/j.eneco.2012.03.016.
[8] Yucekaya A. Electricity trading for coal-fired power plants in turkish power market considering uncertainty in spot, derivatives and bilateral contract market. Renew Sustain Energy Rev 2022;159:112189. https://doi.org/10.1016/j.rser.2022.112189.
[9] Brigatto A, Fanzeres B. A soft robust methodology to devise hedging strategies in renewable energy trading based on electricity options. Electric Power Systems Research 2022;207:107852. https://doi.org/10.1016/j.epsr.2022.107852.
[10] Algarvio H. Multi-step optimization of the purchasing options of power retailers to feed their portfolios of consumers. Int J Electr Power Energy Syst 2022;142:108260. https://doi.org/10.1016/j.ijepes.2022.108260.
[11] Lopes F, Algarvio H, Santana J. Agent-based simulation of electricity mar- kets: Risk management and contracts for difference. In: Understanding Complex Systems. Springer International Publishing; 2017. p. 207–25. https://doi.org/10.1007/978-3-319-46331-5_10.
[12] Algarvio H, Lopes F. Risk management and bilateral contracts in multi-agent electricity markets. In: Corchado JM, Bajo J, Kozlak J, Pawlewski P, Molina JM, Gaudou B, Julian V, Unland R, Lopes F, Hallenborg K, Garc ́ıa Teodoro P, editors. Highlights of Practical Applications of Heterogeneous Multi-Agent Systems. The PAAMS Collection. Cham: Springer International Publishing; 2014. p. 297–308.

[13] Lucy Z, Kern J. Analysis of fixed volume swaps for hedging financial risk at large-scale wind projects. Energy Econ 2021;103:105603. https://doi.org/10.1016/j.eneco.2021.105603.

[14] Song H, Liu C-C, Lawarree J. Nash equilibrium bidding strategies in a bilateral electricity market. IEEE Trans Power Syst 2002;17(1):73–9. https://doi.org/10.1109/59.982195.

[15] Wang L, Jiao P, Chen J, Zhao Y, Wang Y. Dynamic two-layer game for striking the balance of interest in multi-agent electricity market considering bilateral contracts and reward-punishment mechanism. Sustain Cities Soc 2022;76:103488. https://doi.org/10.1016/j.scs.2021.103488.

[16] Gallego CA. Intertemporal effects of imperfect competition through forward contracts in wholesale electricity markets. Energy Econ 2022;107:105835. https://doi.org/10.1016/j.eneco.2022.105835.

[17] Algarvio H, Lopes F. Agent-based retail competition and portfolio optimiza- tion in liberalized electricity markets: a study involving real-world consumers. Int J Electr Power Energy Syst 2022;137:107687. https://doi.org/10.1016/j.ijepes.2021.107687.

[18] Zhang D, Xu H, Wu Y. A two stage stochastic equilibrium model for electricity markets with two way contracts. Math Methods Oper Res 2010;71:1–45. https://doi.org/10.1007/s00186-009-0283-8.

[19] Niu H, Baldick R, Zhu G. Supply function equilibrium bidding strategies with fixed forward contracts. IEEE Trans Power Syst 2005;20(4):1859–67. https://doi.org/10.1109/TPWRS.2005.857272.

[20] Morstyn T, Teytelboym A, Mcculloch MD. Bilateral contract networks for peer-to-peer energy trading. IEEE Trans Smart Grid 2019;10(2):2026–35. https://doi.org/10.1109/TSG.2017.2786668.

[21] Banaei M, Oloomi-Buygi M. Forward contract negotiation equilibrium in uncongested electricity markets. In: Iranian Conference on Electrical Engineering (ICEE); 2019. p. 497–502. https://doi.org/10.1109/IranianCEE.2019.8786756.

[22] Banaei M, Oloomi M, Raouf Sheybani H. Supply function nash equilibrium of joint day-ahead electricity markets and forward contracts. Int J Electr Power Energy Syst 2019;113:104–16. https://doi.org/10.1016/j.ijepes.2019.05.036.

[23] Banaei M, Raouf-Sheybani H, Oloomi-Buygi M, Boudjadar J. Impacts of large- scale penetration of wind power on day-ahead electricity markets and forward contracts. Int J Electr Power Energy Syst 2021;125:106450. https://doi.org/10.1016/j.ijepes.2020.106450.

[24] Raouf Sheybani H, Oloomi buygi M. How does pricing of day-ahead electricity market affect put option pricing? Iran J Electr Electron Eng 2016;12(3). https://doi.org/10.22068/IJEEE.12.3.230.

[25] Sheybani HR, Oloomi Buygi M. Put option pricing and its effects on day-ahead electricity markets. IEEE Syst J 2018;12(3):2821–31. https://doi.org/10.1109/JSYST.2017.2764738.

[26] Raouf Sheybani H, Oloomi Buygi M. Impacts of premium bounds on the operation of put option and day-ahead electricity markets. Int J Eng 2017;(11):1752–61.

[27] Sheybani HR, Buygi MO. Equilibrium-based black-scholes option pricing in electricity markets. IEEE Syst J 2021:1–11. https://doi.org/10.1109/JSYST.2021.3131938.

[28] Ruiz C, Kazempour SJ, Conejo AJ. Equilibria in futures and spot electricity markets. Electr Pow Syst Res 2012;84(1):1–9. https://doi.org/10.1016/j.epsr.2011.09.019.

[29] Banaei M, Oloomi-buygi M, Raouf-Sheybani H, Khooban M-H. Mixed supply function-cournot equilibrium model of futures and day-ahead electricity markets. IET Gener Transm Distrib 2021;15(10):1640–54. https://doi.org/10.1049/gtd2.12123.

[30] Zanotti G, Gabbi G, Geranio M. Hedging with futures: Efficacy of garch correlation models to european electricity markets. J Int Finan Markets Inst Money 2010;20(2):135–48. https://doi.org/10.1016/j.intfin.2009.12.001.

[31] European energy exchange, power, [Online]. Available: (2023). URL https://www.eex.com/en/markets/power.

[32] Botterud A, Kristiansen T, Ilic MD. The relationship between spot and futures prices in the nord pool electricity market. Energy Econ 2010;32(5):967–78. https://doi.org/10.1016/j.eneco.2009.11.009.

[33] Lien D, Tse YK. A survey on physical delivery versus cash settlement in futures contracts. Int Rev Econ Financ 2006;15(1):15–29. https://doi.org/10.1016/j.iref.2004.08.001.

[34] Banaei M, Oloomi Buygi M, Zareipour H. Impacts of strategic bidding of wind power producers on electricity markets. IEEE Trans Power Syst 2016;31(6):4544–53. https://doi.org/10.1109/TPWRS.2016.2524993.

[35] Hobbs B. Linear complementarity models of nash-cournot competition in bilateral and poolco power markets. IEEE Trans Power Syst 2001;16(2):194–202. https://doi.org/10.1109/59.918286.

[36] Pinson P, Madsen H, Nielsen HA, Papaefthymiou G, Klöckl B. From probabilistic forecasts to statistical scenarios of short-term wind power production. Wind Energ 2009;12(1):51–62.

[37] Esmalifalak M, Shi G, Han Z, Song L. Bad data injection attack and defense in electricity market using game theory study. IEEE Trans Smart Grid 2013;4(1):160–9. https://doi.org/10.1109/TSG.2012.2224391.