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Electricity supply chain coordination: Newsvendor model for optimal contract design

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ABSTRACT

This paper delivers an electricity supply chain coordination framework through the newsvendor model to provide an optimal contract design with the aim of maximizing profits. Given retailers' attitude towards the risk associated with the demand uncertainty, the framework optimally considers overage and underage costs, and discount policy to define the contract share and prices. A novel simulation-optimization approach has also been proposed to provide a global optimal solution for the model using the advantages of the linear transportation model. More analytically, the approach leads to some original and meaningful trade-offs among retailers' and generation companies' profits, markets share, overage and underage costs, and the all-unit discount given by retailers. By this means, an almost linear, positive relationship is found between the spot market share and the underage cost. On the contrary, retailers' sensitivity to overage cost is greater if the share of the spot market is low and the retailer is more risk-averse. In this way, the greater the overage cost, the higher the share of the spot market. And, the lower the overage and underage costs, the greater the retailers profit, and the lower the generation companies' profit due to the lower retailers' order quantity. The amount of the discount has a negligible effect on retailers' order quantity, while lowering prices. However, an increase in the amount of the discount has a negligible but negative effect on the spot market share.

1. Introduction

A competitive electricity market is essential for allowing the growth of private player participation in the market (Xuegong et al., 2013). It also makes it possible to provide services to consumers at a lower price (Woo et al., 2003). Unfortunately, this market is not as ideal as expected, primarily due to the lack of demand response, abuse of local market power, and the political resistance to high prices reflecting scarcity rents and shortages (Deng and Oren, 2006). Therefore, it is necessary to support the market by appropriate trading tools in such a way that the essential difference between electricity and other commodities is considered (Shahidehpour et al., 2003).

Trading generally makes sense only in liberalized markets (Sioshansi, 2002). The liberalization of the electricity market begins with privatization of the state-owned electricity monopolies and breakdown the traditional vertically integrated structure (Joskow, 2008). And, it is finally done with separating participants as generator, distributor, and retailer (Kuleshov et al., 2012) aiming at intensifying competition not only on the generation/supply side, but also on the retail side of the corresponding Electricity Supply Chain (ESC) network. Such a decentralization strategy (Finon and Boroumand, 2011) in the long run leads to more efficient development and in the short term leads to more efficient use of available resources (Shen and Yang, 2012). Because it allows smaller companies to enter the wholesale electricity market or retail trade (Ghazvini et al., 2019). In line with these characteristics, liberalization, in the one hand, provides more freedom for suppliers in their processing and selling strategies, while creating a unique market positioning that focuses not only on efficiency, but also on reliability and sustainability (Tanrisever et al., 2015). Competition at the bottom of the chain, on the other hand, provides customers with a wide variety of services from a wide range of retailers and allows them to select offers that best meet their needs in terms of price and quality of services (Joskow, 2008).

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Nomenclature

Indices

$i \in I = \{1, 2, ..., I\}$ Index of Generation companies (Gencos)

$j \in J = \{1, 2, ..., J\}$ Index of retailers

Parameters

$a_i, b_i, c_i\ \forall i \in I$ Positive cost coefficients of Genco i

A Linear inverse demand function parameter

C_o Overage cost

C_u Underage cost

α Spot market share and the retailer's risk aversion level

γ Fixed linear inverse demand function parameter

$\beta_j\ \forall j \in J$ The all-unit discount coefficient of retailer$j$

Independent Variables

$D_j\ \forall j \in J$ Total demand should be supplied by retailer j

$f_{d_j}\ \forall j \in J$ Density function of the j^{th} retailer's uncertain demand

$m_j\ \forall j \in J$ The amount of j^{th} retailer's purchased power from the futures market

$Q_j\ \forall j \in J$ Total power quantity supplied by retailer j

$q_{ij}^F\ \forall i \in I, j \in J$ The amount of power exchange between Genco i and retailer j in the futures market

$q_i^{Sg}\ \forall i \in I$ The sold power of Genco i in the spot market

$q_j^{Sr}\ \forall j \in J$ The purchased power by retailer j in the spot market

$R_i\ \forall i \in I$ The share of Genco i of the total sales in the futures market

$W_{ij}^F\ \forall i \in I, j \in J$ The price of power exchange between Genco i and retailer j in the futures market

$E[D]$ Expected value of demand

P The retail price

S The spot price

Dependent variables/Objective functions

$\Pi_i^g\ \forall i \in I$ Profit function of Genco i

$\Pi_j^r\ \forall j \in J$ Profit function of retailer j

Despite the aforementioned outcomes, a general double marginalization problem is arising in such a network where suppliers and buyers make self-interested production and pricing decisions (Mendelson and Tunca, 2007). The problem reflects the fact that both upstream and downstream of the chain, in a bilateral monopoly, simultaneously exert their market power against each other (Lantz, 2009). This may negatively affect the equilibrium outcome and lead to a deviation from the maximum profit of the entire Supply Chain (SC) (Lantz, 2009; Mendelson and Tunca, 2007; Oliveira et al., 2013). Solving this problem in the oligopoly case, which is the case in this paper, becomes more complex and industry dependent (Oliveira et al., 2013). Implementing one of the two types of bilateral fixed-price procurement contracts, i.e. contract for differences and the two-part tariffs, in a market that is open to all the SC participants provides an opportunity to improve the efficiency of the chain to deal with the problem (Mendelson and Tunca, 2007). A two-part tariff consists of a lump-sum access charge and a cost per unit of electricity. The first is paid for the right to buy an electricity to attain a targeted amount of market participation. And the last is paid to achieve profit maximization or economic efficiency (Oliveira et al., 2013; Yamamoto, 2017).

This paper considers two part-tariff contracts to solve the double marginalization problem. The contract trades electric power months or days ahead of delivery (Oliveira et al., 2013). In real situations, it often used to mitigate the risk of the spot price (Gökgöz and Atmaca, 2017; Martínez and Torró, 2018; Xia et al., 2019) coming from spot pool-based market that trades electricity close to delivery time (Oliveira et al., 2013). The importance of the relationship between spot and futures trading has previously been investigated in terms of the interaction between spot and futures markets in shaping investment decisions in oligopolies (Kazempour et al., 2012; Murphy and Smeers, 2005), retailer's optimal trading strategy (Carrion et al., 2007), suppliers perspective (Conejo et al., 2008), performance of the ESC (Oliveira et al., 2013), and their risk mitigations and trade-offs (Martínez and Torró, 2018).

Although different approaches are proposed in the literature to model the interaction among such ESC players, yet several gaps remain to be covered: (A) Appropriate frameworks are required to model the wholesale and the retail energy markets in the ESC, simultaneously. In such frameworks, the decision-making problem of all the players, i.e. Generation companies (Gencos), retailers, and consumers, should be modeled in such a way that they compete in wholesale and retail markets. (B) Retailers sell energy to consumers through contract prices, while the process of buying energy from the pool market is uncertain. Therefore, the risk-aversion level of retailers, which has an important impact on the decision-making, should be modeled. (C) Since there are several Gencos and retailers in wholesale energy markets, it is required to model the profit of all the players through an integrated approach. (D) In the retail energy market, retailers' competition to sell energy to consumers, as well as giving consumers the choice to choose the best retailer, should be modeled. (E) Retailers need new models to manage their purchased power from the futures market under the uncertainties of demand and spot prices.

Liberalizing the electricity market, this paper is presented to fill these gaps by introducing an ESC network design problem in such a way that the bilateral-based (futures) market under two-part tariffs contractual strategy is accompanied by the pool-based (real-time) market under the spot trading strategy. The first tier of the SC includes several Gencos that are responsible for supplying electricity to some retailers in the second tier through a two-stage electricity market scheme. Gencos and retailers initially open bilateral contracts in a futures market. And, afterward, they participate in a pool-based market so they can trade the rest of the electricity at a spot price. Finally, customers directly purchase the electricity from retailers in such a liberalized electricity market framework.

The main contributions of the paper are as follows. A) Using a novel simulation-optimization approach, the proposed model is the first to allow retailers to define their optimal contract share, while addressing their risk-aversion level. B) The optimal selling price for both the futures and spot markets, as well as retailers' energy-supply and the Gencos energy generation-distribution strategies are simultaneously modeled through an analytical approach. C) Some original, and meaningful trade-offs are presented among retailers' and Gencos profits, market share, overage and underage costs, and the all-unit discount. D) The model gives retailers the ability to use such inventory management as the single-period newsvendor inventory model to address the underage and overage costs in their corresponding cost function to be optimized. E) A novel heuristic is introduced to obtain optimal solution for the problem in an iterative manner, which uses the balance constraint to define the stopping condition. F) This is the first time that the transportation model has been used as a well-known linear programming to provide optimal final energy purchased by retailers from each Genco through a bilateral contract with a predetermined price.

The reminder of the paper is as follows. An overview of the literature is provided in Section 2, and the problem description including the general framework as well as the mathematical formulation of the SC, which is considered in this paper, is obtained in Section 3. The model reformulation is completely described in Section 4, and a numerical example in line with developing the proposed solution approach is reported in Section 5. A broad sensitivity analysis and further discussions leading to some policy implications are reported in Section 6, and the conclusion and some future directions are provided in Section 7.

2. Literature review

Since the importance of computing is due to the need for insight and not just numbers (Hamming, 2012), and the same is true for energy systems' modeling, the age of the discussion on the energy systems' modeling is comparable to the age of the models themselves (Huntington et al., 1982). In this regard, optimization is provided through linear programming models to deal with the complexity of interactions and multiple layers of energy in a modern economy (Dantzig, 2016). Relative literature has identified the issue of balancing model resolution with data availability and computational tractability as a major challenge (Pfenninger et al., 2014). Vulnerability of electric power systems to temporal variation causes the issue of constant balance between demand and supply to be the other key element of the system modeling and functioning (Machowski et al., 2011). Electricity market models are related to electric power systems models, but instead of focusing on physical properties, they are concerned about the increasingly liberalized electricity markets (Ventosa et al., 2005). Since the electric power system is a complex network consisting of generation, transmission, and distribution entities (Eto et al., 2019; Ma et al., 2017), it does not yield to compact forms of representation. However, by decoupling of processes in different scales, the complexity science paradigm may formulate the system's individual parts in a simplest way and defines the rules they follow and their interaction with the environment. Since the issue of complexity is linked to the issue of scale, such a decoupling may make the system simpler (Pfenninger et al., 2014). Electricity Market Complex Adaptive System (EMCAS) is a good example for such idea. The idea makes the system works in a five-level SC network including the physical/load flow layer, three market layers, (transmission companies, bilateral contract markets, pool markets), and the regulatory layer (Veselka et al., 2002). Forgionne and Guo (2009) also introduced the ESC as a four-layer network including electricity production, transmission, distribution, and consumption layers. Laying stress on the importance of the ESC and its coordination, Ma et al. (2017) presented a three-level network containing one Genco, multiple consumers, and competing utility companies. Considering a power plant that transmits electricity power through a transmission network to multi-customers, Wangsa and Wee (2019) proposed a production-inventory model for ESC coordination.

Although emphasizing the overall benefits of a centralized SC may jeopardize the interests of its participants, in a decentralized framework, conflict of interest may be resolved through an appropriate SC coordination mechanism (Hojati et al., 2017; Jokar and Hosseini-Motlagh, 2019). The main issue in the SC coordination mechanism is the design of a kind of contract to provide the so-called win-win situation between suppliers and retailers (Wang et al., 2019). Therefore, the implementation of an option contract for the SC coordination has attracted a significant amount of research (Heydari, 2014; Jokar and Hosseini-Motlagh, 2019; Wang et al., 2015; Ye et al., 2018; Zhao et al., 2012). By this means, there are several types of contracts that can coordinate the SC, including all-unit quantity discount (Weng and Wong, 1993), sales rebate (Taylor, 2002), buy-back (Pasternack, 1985), delay in payments (Jaber and Osman, 2006), two-part tariffs (Moorthy, 1987; Zusman and Etgar, 1981), revenue sharing (Cachon and Lariviere, 2005; Wang et al., 2004), and quantity flexibility contracts (Goyal and Gupta, 1989). Cachon (2003) conducted a detailed study of coordination with contracts and examined all kinds of contracts' effect on the SC coordination for a wide range of SC models. With the increasing interest in electric power industry due to its transformation from a regular to a competitive environment, several models and pricing schemes and contracts mechanisms have also been developed to investigate pricing and competition in the relative decentralized SC (Forgionne and Guo, 2009). There are several papers investigating the impact of competition on the electricity supply efficiency (Day et al., 2002; Hobbs, 2001; Jing-Yuan and Smeers, 1999), especially along the ESC coordination (Nagurney and Matsypura, 2007; Sethi et al., 2005). Under the all-unit quantity discount contract, it is optimal for the buyer to buy more units than it needs to achieve a lower wholesale price for all units (Kalkanci et al., 2011). A few research concentrate on the spot market mechanism through the wholesale market (Chao and Peck, 1996; De Vany and Walls, 1999; Schweppe et al., 2013; Stoft and Kahn, 1991). Under these contracts, the electricity supply-side can be protected against unfavorable market prices, which may lead to financial losses due to mismatch between supply and demand in the spot market (Eydeland and Wolyniec, 2003; Wolak, 2000; Wolfram, 1999). Sales rebate contracts, for each unit purchased beyond a threshold, provide a certain rebate for retailers. In some cases, quantity discount is similar to sales rebate (Heydari and Asl-Najafi, 2016), but they are not the same because it only applies to items sold to end-users (Wong et al., 2009). Cachon (2003) claimed that this kind of contract is not capable of coordinating the SC with voluntary compliance as the supplier makes no profit in this case. Taylor (2002) concluded that a combination of a target rebate and a return contract, as a special type of buy-back contract (Xue et al., 2019), can achieve coordination in the SC. Under buy-back contracts the supplier sets a buyback value for unsold units (Luo et al., 2018; Wang and Zipkin, 2009). Sales rebate, buy-back, and quantity flexibility contracts coordinate the SC with sharing the risk of overage and/or underage among the participants, and are therefore unsuitable in a deterministic scenario (Giri et al., 2013). In quantity flexibility contracts buyer's final purchase may deviate from the previous estimate (Tsay and Lovejoy, 1999; Yazlali and Erhun, 2007). Xiong et al. (2011) studied the advantages of a composite contract based on the buy-back and quantity flexibility contracts over each of the individual contracts, in terms of coordination, profit allocation, and risk allocation. And Zhang et al. (2018) studied the advantages of integrating the buy-back and wholesale contracts. Another mechanism used in the SC coordination is called the delay in payments scheme in which the buyer is allowed to have some extra time to pay for the purchased items based on the trade credit granted by the supplier (Aljazzar et al., 2016; Heydari et al., 2018). Such a policy may change the buyer's ordering behavior, deliver short-term credit to the buyer, and provide more liquidity available to it, ultimately enabling the buyer to buy more or invest elsewhere for greater profitability (Heydari et al., 2017). According to the literature, such kind of contract have been investigated less than the other schemes (Chaharsooghi and Heydari, 2010). Two-part tariffs contract, as the other SC coordination scheme which Saggi and Vettas (2002) call it royalty, specify a fixed fee and a per-unit payment (Bonnet and Dubois, 2010; Cachon and Kök, 2010;

Chen et al., 2012). Some research works study the trade-off between such a long-run bilateral and short-run spot market contracts in the electric power transmission network (Deng and Oren, 2001; Hogan, 1992; Oliveira et al., 2013). The other very attractive SC coordination model is the revenue sharing contract, which is viewed as a valuable alternative to the wholesale/spot price contract, although the latter is commonly observed in practice due to its simplicity (El Ouardighi and Kim, 2010). Ma et al. (2017) proposed a revenue sharing contract and pricing scheme in a three-level ESC. Under such policy, the retailer's lump sum payment, which is fixed in the two-part tariffs contracts, is proportional to actual sales (Giannoccaro and Pontrandolfo, 2004). To avoid duplication of efforts, the reader is referred to the research done by Govindan et al. (2013) for further investigation on the context.

3. Electricity supply chain description and modeling

In traditional energy systems, electricity is generated by government-owned power plants to be distributed to consumers of electrical power. By changing the structure at the level of generation and distribution of energy systems, new energy actors emerge called Gencos and retailers. Retailers are the network participants that provide electricity to customers through the distribution network. Gencos are able to establish a balance between markets prices and capacity (Chattopadhyay, 2004). So, it makes sense that if Gencos can accurately predict market prices with a high accuracy, which is the case in this paper, there is no need to consider any nameplate capacity in the model formulation. Because Gencos have so much capacity that they are able to clearing the futures market as well as the remaining capacity in spot markets. Therefore, by varying the markets share and prices, Gencos will never face the problem of capacity limitation to be considered in the model formulation.

To manage the trading energy among these actors, wholesale energy markets operated by Independent System Operator (ISO) are leveraged aiming at minimizing the cost for maintaining energy balance. Each actor maximizes the profit by determining its optimal decisions in the market. In order to maximize the social welfare within the ESC framework, shown in Fig. 1, profits of all actors, i.e. Gencos and retailers, should be maximized in relation to their cooperation in the wholesale energy market including bilateral contracts and pool markets.

As shown in the figure, Gencos and retailers compete in a two-stage wholesale energy market including futures and day-ahead energy markets. At the first stage, Gencos $i \in I = \{1, 2, ..., I\}$ and retailers $j \in J = \{1, 2, ..., J\}$ trade energy with each other in the futures market through bilateral contracts. In this market, players decide on trading power in the energy market regarding which the amount of power (q_{ij}^F) and its price (W_{ij}^F) are determined. After clearing the market, results of each contract are announced to the ISO. Gencos are responsible to deliver the contracted energy quantity to each retailer in a certain time in the future. And retailers are responsible to pay contract prices to Gencos.

Given the uncertainty in electricity supply and demand, Gencos and retailers need another market for short-term power trading. For this purpose, the day-ahead energy market is cleared by the ISO in the day before the real operation. In this market, a unique energy market price (S) is determined in each period regarding which all Gencos sell their energy (q_j^{Sr}) to retailers. At the end, retailers sell their purchased power $(q_i^{Sg} + q_j^{Sr})$ to the consumers. The relative transmission network is operated by the Transmission System Operator (TSO). The power generated by Gencos is transmitted through the network to the Transmission-Distribution (T-D) substations, which are the common coupling points of the network. Then, the Distribution System Operator (DSO) transmits the power from T-D substations to consumers regarding the contracted power between retailers and consumers.

In such a system, the total profit of Genco i can be given by Eq. (1), in which the first and the second terms correspond to the energy sold in the futures and spot markets, respectively, and the last term represents the total electricity production cost.

$$\Pi_i^g = \sum_{j=1}^{J} q_{ij}^F W_{ij}^F + q_i^{Sg} S - \left(a_i + b_i \left(\sum_{j=1}^{J} q_{ij}^F + q_i^{Sg} \right) + \frac{1}{2} c_i \left(\sum_{j=1}^{J} q_{ij}^F + q_i^{Sg} \right)^2 \right), \quad \forall i \in I \tag{1}$$

As a conventional assumption for thermal generating units, the total production cost of Genco i is formulated through a quadratic function (Oliveira et al., 2013). In the equation, q_{ij}^F is the amount of power sold to retailer j by Genco i through the bilateral contract at price W_{ij}^F. So, the first term denotes the revenue obtained by Genco i in the futures market. Since q_i^{Sg} is the amount of power generated by Genco i to be sold in the spot market at spot price S, the second term calculates the revenue attained by Genco i in the spot market. Given $\sum_J q_{ij}^F + q_i^{Sg}$ as the total power supplied by Genco i, and a_i, b_i, and c_i as positive cost coefficients of the Genco, the third term is the total cost of generating electricity paid by the Genco. Accordingly, Π_i^g is the net profit obtained from Genco i, which should be maximized in the final integrated ESC network.

With an increasing penetration of renewable energies in the power grid, the use of electrical storage systems is increasing to provide valuable services to the grid in addition to their main function, both in the industrial (Golpîra et al., 2018) and domestic (Golpîra and Khan, 2019) sectors. Based on analogies between inventory management in classical industry SCs and electrical storage systems, this research is the pioneer attempt to adopt a suitable inventory model in the ESC network coordination problem. Since the cost parameters are assumed to be stationary over time and the demand is assumed to be stochastic, the single-period newsvendor inventory model can be used for the model formulation (Schneider et al., 2015). In doing so, the total profit of retailer j, denoted by Π_j^r, is formulated through Eq. (2), which should be maximized in the final coordinated network.

$$\Pi_j^r = \left\{ \left(P \left(\int_0^{Q_j} D_j f_{D_j} dDdt + \int_{Q_j}^{\infty} Q_j f_{D_j} dDdt \right) \right) - \left(\sum_i^I q_{ij}^F W_{ij}^F + q_j^{Sr} S + C_o \int_0^{Q_j} \left(Q_j - D_j \right) f_{D_j} dD + C_u \int_{Q_j}^{\infty} \left(D_j - Q_j \right) f_{D_j} dD \right) \right\}, \quad \forall j \in J \tag{2}$$

The first term, in the equation, is to calculate the profit of retailer j from selling power to the final consumer at price P. Given Q_j and D_j as the total power quantity supplied by retailer j and the total demand should be supplied by the retailer, as well as f_{D_j} as the density function of the uncertain demand D_j, the first term of the equation

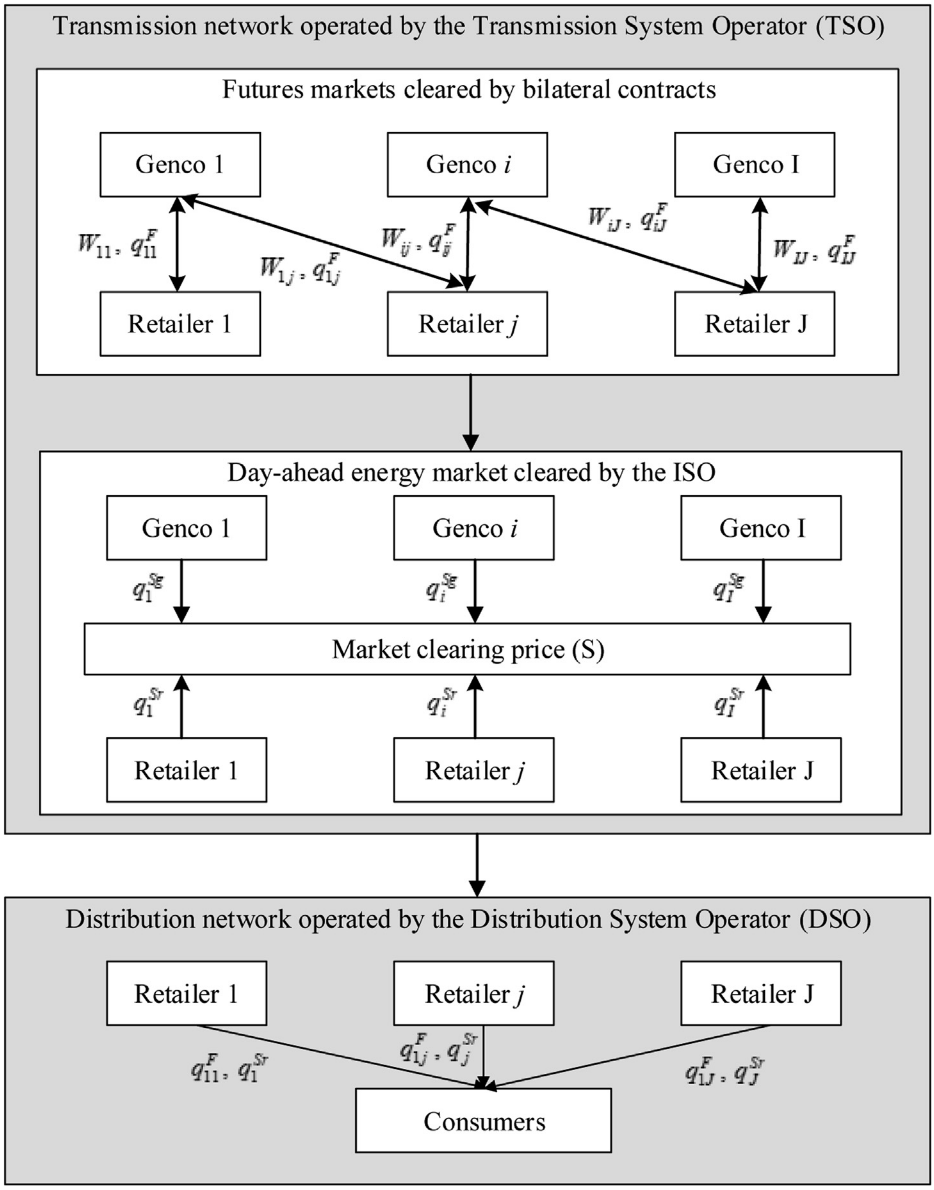

Fig. 1. The considered ESC.

calculates the expected value of the retailer's income. Since in the futures market, what benefits Gencos is the cost to retailers, the term $\sum_I q_{ij}^F W_{ij}^F$ is included, in addition to the cost imposed from the spot market, $q_j^{Sr}S$. Further, if the retailer orders more power than the realized market demand, it faces with the overage cost C_o for the unsold power. Yet, if the retailer orders fewer power than the realized market demand, it faces with the underage cost C_u for the power it could have sold if it had been on stock. As for optimizing retailers' objective function using a derivative-based hierarchical approach, it can be simplified as Eq. (3) by adding four terms as $\pm P\int_{Q_j}^{\infty} D_j f_{D_j} dDdt$ and $\pm C_o\int_{Q_j}^{\infty}(Q_j - D_j) f_{D_j} dD$ to Eq. (2). In the equation, $E[D]$ is the expected value of the demand and P is the retailer's selling price, which can be obtained from customers' preferences given by Eq. (4) (Oliveira et al., 2013), where conditions $\gamma \geq 0$ and $\beta_j \geq 0, \ \forall j \in J$ are necessary.

$$\Pi_j^r = P \times E[D] - \sum_i^I q_{ij}^F W_{ij}^F - q_j^{Sr} S - C_o \times (Q_j - E[D]) - (C_u + C_o + P)\int_{Q_j}^{\infty} (D_j - Q_j) f_{D_j} dD, \quad \forall j \in J \tag{3}$$

$$P = \gamma - A\sum_{j=1}^{J} \beta_j (Q_j), \quad j \in J \tag{4}$$

According to Eqs. (1), (2) and (4), futures and the spot markets are fully interrelated. So, it is necessary to first determine the equilibrium condition in the spot market, provided by Eq. (5) considering that bilateral contracts are settled. Then in a backward perspective, futures market is analyzed to find the final global equilibrium in the overall ESC.

$$\sum_{i=1}^{I} q_i^{Sg} = \sum_{j=1}^{J} q_j^{Sr} \tag{5}$$

The equilibrium means that the energy sold by a Genco must be equal to the energy purchased by retailers in the spot market. If $0 < \alpha < 1$ is assumed to be the fraction of the retailer's order, which is provided from the spot market, Eq. (6) can be logically written. Accordingly, given $Q_j = \sum_{i=1}^{I} q_{ij}^F + q_j^{Sr}$, Eq. (7) can be conducted, where m_j is the amount of power purchased from the futures market.

$$q_j^{Sr} = \alpha \times Q_j, \quad \forall j \in J \tag{6}$$

$$m_j = \sum_{i=1}^{I} q_{ij}^F = (1-\alpha) Q_j, \quad \forall j \in J \tag{7}$$

In the perspective of the risk management, the term $(1-\alpha)$ is the futures market share that is claimed as retailers' risk-aversion level, in this paper. Because, in the futures market a retailer can negotiate with more than one Genco, simultaneously. In this case, any Genco that is satisfied from the negotiation outcome will sign a bilateral contract with a retailer that yields the highest degree of mutual agreement. It is, therefore, acceptable that the risk of the bilateral contract is significantly lower than the risk obtained from the spot market. So, a conservative retailer is more ready to sacrifice the mean profit, while the parameter $(1-\alpha)$ increases to avoid the risk (Golpîra, 2017; Golpîra et al., 2017) obtained from the spot market. This may of interest for the Decision Maker (DM), because considering the DMs risk-aversion level is an important issue in the process of decision-making under uncertainty and risk (Golpîra, 2018).

4. Model reformulation

Following the model formulation presented in Section 3, in the current section, after examining the concavity of Gencos and retailers objective functions formulated in Eqs. (1) and (3), the model is completely reformulated, subject to Eqs. (4)–(7), to be ready for solving by the solution algorithm presented in Section 5.

As for examining the concavity of Gencos profit function, formulated through Eq. (1), the first and the second derivatives of Π_i^g on q_i^{Sg} have been calculated through Eqs. (8) and (9).

$$\frac{\partial \Pi_i^g}{\partial q_i^{Sg}} = S + q_i^{Sg} \frac{\partial S}{\partial q_i^{Sg}} - b_i - c_i \left(\sum_j^J q_{ij}^F + q_i^{Sg} \right), \quad i \in I \tag{8}$$

$$\frac{\partial^2 \Pi_i^g}{\partial {q_i^{Sg}}^2} = 2 \frac{\partial S}{\partial q_i^{Sg}} + q_i^{Sg} \frac{\partial^2 S}{\partial {q_i^{Sg}}^2} - c_i, \quad i \in I \tag{9}$$

Since $\frac{\partial^2 \Pi_i^g}{\partial {q_i^{Sg}}^2}$ is negative, objective function Π_i^g is concave with respect to q_i^{Sg}, hence the value of q_i^{Sg} obtained from setting Eq. (8) to zero is global optimal.

As for examining the concavity of retailers profit function obtained by Eq. (3), its relative Hessian matrix should be determined (Alfares and Ghaithan, 2016) through Eq. (10).

$$H\left(Q_j, q_j^{Sr}\right) = \begin{bmatrix} \frac{\partial^2 \Pi_j^r}{\partial Q_j^2} & \frac{\partial^2 \Pi_j^r}{\partial Q_j \partial P} \\ \frac{\partial^2 \Pi_j^r}{\partial P \partial Q_j} & \frac{\partial^2 \Pi_j^r}{\partial P^2} \end{bmatrix} \tag{10}$$

The elements of the Hessian matrix can be directly calculated through Eqs. 11–14.

$$\frac{\partial \Pi_j^r}{\partial Q_j} = 0 \Rightarrow \left\{ \frac{\partial P}{\partial Q_j} \times E[D] - \frac{\partial}{\partial Q_j} \left(\sum_i^I \left(W_{ij}^F q_{ij}^F \right) + q_j^{Sr} S \right) - C_o + (C_u + C_o + P) \times \int_{Q_j}^{\infty} f_{D_j} dD - \frac{\partial P}{\partial Q_j} \int_{Q_j}^{\infty} (D_j - Q_j) f_{D_j} dD = 0 \right\}, j \in J \tag{11}$$

$$\frac{\partial^2 \Pi_j^r}{\partial Q_j^2} = - \left[(C_u + C_o + P) \times f_{D_j}(Q_j) + A \times \beta_j \times \int_{Q_j}^{\infty} f_{D_j} dD \right], j \in J \tag{12}$$

$$\frac{\partial^2 \Pi_j^r}{\partial P^2} = \frac{\partial^2 \Pi_j^r}{\partial Q_j^2} \times \frac{\partial^2 Q_j}{\partial P^2} = \frac{\partial^2 \Pi_j^r}{\partial Q_j^2} \times (0) = 0 \quad , \forall j \in J \tag{13}$$

$$\frac{\partial^2 \Pi_j^r}{\partial q_j^{Sr} \partial P} = -(C_u + C_o + P) \times \int_{Q_j}^{\infty} f_{D_j} dD - \frac{1}{A \times \beta_j} \times f_{D_j}(Q_j), \ j \in J \tag{14}$$

Retailers objective function is concave if $\frac{\partial^2 \Pi_j^r}{\partial Q_j^2} \le 0$, $\frac{\partial^2 \Pi_j^r}{\partial P^2} \le 0$ and $H(Q_j, q_j^{Sr}) \le 0$. According to Eqs. (12) and (13), it is obvious that $\frac{\partial^2 \Pi_j^r}{\partial Q_j^2} \le 0$ and $\frac{\partial^2 \Pi_j^r}{\partial P^2} \le 0$. Accordingly, the value of the determinant obtained in Eq. (10) is less than or equal to zero, hence Π_j^r is concave on both Q_j and q_j^{Sr}, and Q_j^* denotes the optimal value of Q_j that maximizes Eq. (3).

To determine Q_j^*, the partial derivatives of Π_j^r with respect to Q_j $\forall j \in J$ should be calculated and set to zero to be solved, simultaneously using Eq. (11), while $f_{D_j}(Q_j^*)$ can be formulated as $f_{D_j}(Q_j^*) = c_u / (c_u + c_o)$, given C_o and C_u (Axsäter, 2015). To solve Eq. (11), it is needed to calculate the value of $\frac{\partial P}{\partial Q_j}$ in which P denotes the retail price and Q_j is the total power quantity supplied by retailer j. In this way, calculating the first derivative of Eq. (4) may obtain the value of $\frac{\partial P}{\partial Q_j}$ as shown in Eq. (15).

$$\frac{\partial P}{\partial Q_j} = -A \times \beta_j \tag{15}$$

Further, the value of $\frac{\partial}{\partial Q_j}(\sum_i^I (W_{ij}^F q_{ij}^F) + q_j^{Sr} S)$, which is included in Eq. (11), can also be calculated by Eq. (16), given $\sum_{i=1}^{I} (W_{ij}^F q_{ij}^F) + q_j^{Sr} S = k, \ j \in J$ for further simplifying the calculation.

$$\frac{\partial K}{\partial Q_j}=\left(\frac{\partial q_{1j}^F}{\partial Q_j}\times\frac{\partial q_{2j}^F}{\partial Q_j}\times\ldots\times\frac{\partial q_{Ij}^F}{\partial Q_j}\times\frac{\partial q_j^{sr}}{\partial Q_j}\times\frac{\partial K}{\partial q_{1j}^F}\times\frac{\partial K}{\partial q_{2j}^F}\times\ldots\times\frac{\partial K}{\partial q_{Ij}^F}\times\frac{\partial K}{\partial q_j^{sr}}\right)^{\frac{1}{I+1}}=\left(S\times\prod_{i=1}^{I}W_{ij}^F\right)^{\frac{1}{I+1}} \tag{16}$$

Given Eqs. (15) and (16), Eq. (11) can be transformed into Eq. (17), and the value of Q_j^* can be obtained.

$$\frac{\partial \Pi_j^r}{\partial Q_j}=\left\{-A\times\beta_j\times E[D]-\left(S\times\prod_{i=1}^{I}W_{ij}^F\right)^{\frac{1}{I+1}}-C_o+(C_u+C_o+P)\times\int_{Q_j}^{\infty}f_{D_j}dD+A\times\beta_j\times\int_{Q_j}^{\infty}(D_j-Q_j)f_{D_j}dD\right\}=0,j\in J \tag{17}$$

Now, it is time to consider Gencos profit function obtained by Eq. (1). In doing so, first the optimal values of q_i^{Sg} should be obtained by setting the first derivative of Eq. (1) equal to zero as shown in Eq. (18)

$$\frac{\partial \Pi_i^g}{\partial q_i^{Sg}}=S+q_i^{Sg}\frac{\partial S}{\partial q_i^{Sg}}-b_i-c_i\left(\sum_j^J q_{ij}^F+q_i^{Sg}\right)=0,\quad i\in I \tag{18}$$

To simplify the equation, both sides of the equation are multiplied by ∂q_i^{Sg} that resulting in Eq. (19).

$$\frac{\partial \Pi_i^g}{\partial q_i^{Sg}}=S\partial q_i^{Sg}+q_i^{Sg}\partial S-b_i\partial q_i^{Sg}-c_i\left(\sum_j^J q_{ij}^F+q_i^{Sg}\right)\partial q_i^{Sg}=0,\quad i\in I \tag{19}$$

The transference of the term $q_i^{Sg}\partial S$ from the left- to the right-hand side of the equation and dividing both the two sides by $-q_i^{Sg}$ results in Eq. (20).

$$\frac{\partial S}{\partial q_i^{Sg}}=\frac{S-c_i\left(\sum_j^J q_{ij}^F+q_i^{Sg}\right)-b_i}{-q_i^{Sg}}=\frac{S-c_iq_i^{Sg}-\left[c_i\sum_j^J q_{ij}^F+b_i\right]}{-q_i^{Sg}},\quad i\in I \tag{20}$$

Given $S=s+s_0$ and $q_i^{Sg}=Q_i^{Sg}+Q_i^{Sg}0$, Eq. (20) is transformed into Eq. (21).

$$\frac{\partial S}{\partial q_i^{Sg}}=\frac{s+s_0-c_iQ_i^{Sg}-c_iQ_i^{Sg}0-\left[c_i\sum_j^J q_{ij}^F+b_i\right]}{-\left(Q_i^{Sg}+Q_i^{Sg}0\right)},\quad i\in I \tag{21}$$

Further, given $Q_i^{Sg}0=0$ and $s_0-c_iQ_i^{Sg}0-(c_i\sum_{j=1}^{J}q_{ij}^F+b_i)=0$, Eq. (21) can be transformed into Eq. (22).

$$\frac{\partial s}{\partial Q_i^{Sg}}=\frac{s-c_iQ_i^{Sg}}{-Q_i^{Sg}},\quad i\in I \tag{22}$$

Given $\frac{s}{Q_i^{Sg}}=V$, the homogeneous differential equation approach may result in $\frac{\partial s}{\partial Q_i^{Sg}}=V+Q_i^{Sg}\frac{\partial V}{\partial Q_i^{Sg}}$ and from Eq. (22), result in $\frac{\partial s}{\partial Q_i^{Sg}}=\frac{VQ_i^{Sg}-c_iQ_i^{Sg}}{-Q_i^{Sg}}=V-c_i$, hence Eq. (23) is provided.

$$-V+c_i=V+Q_i^{Sg}\frac{\partial V}{\partial Q_i^{Sg}}\Rightarrow c_i-2V=Q_i^{Sg}\frac{\partial V}{\partial Q_i^{Sg}},\quad i\in I \tag{23}$$

By reversing the equation and further multiplying it's both sides by ∂V, Eq. (24) is obtained.

$$\frac{1}{c_i-2V}\partial V=\frac{1}{Q_i^{Sg}}\partial Q_i^{Sg},\quad i\in I \tag{24}$$

Integrating both sides of the equation may result in $\frac{1}{\sqrt{2V-c_i}}=Q_i^{Sg}$. Given $\frac{s}{Q_i^{Sg}}=V$, $s=S-s_0$, and $Q_i^{Sg}=q_i^{Sg}-Q_i^{Sg}{}_0$ the equation may transform into $\left(2\frac{S-s_0}{q_i^{Sg}-Q_i^{Sg}0}-c_i\right)^{-1/2}=q_i^{Sg}-Q_i^{Sg}0$, and further given $Q_i^{Sg}0=0$ and $s_0=(c_i\sum_{j=1}^{J}q_{ij}^F+b_i)$, Eq. (25) is finally obtained, in which the spot price and the power quantity generated by Genco i are directly interrelated.

$$q_i^{Sg^*}=\frac{\left(2S-2\left[c_i\sum_j^J q_{ij}^F+b_i\right]\right)\pm\sqrt{\left(2S-2\left[c_i\sum_j^J q_{ij}^F+b_i\right]\right)^2-4c_i}}{2c_i},i\in I \tag{25}$$

Eq. (25) needs the optimal value of S. In this way, the derivative of Π_j^r from Eq. (3) on q_j^{Sr} is calculated and set to zero as shown in Eq. (26). Because Π_j^r is also concave in the amount of soled power to retailer j, shown in Eq. (27), so that a global optimal solution can be provided from the first-order conditions.

$$\frac{\partial \Pi_j^r}{\partial q_j^{Sr}}=0\Rightarrow-A\times\beta_j\times E[D]-\left(S\times\prod_{i=1}^{I}W_{ij}^F\right)^{\frac{1}{I+1}}-C_o+(C_u+C_o+P)\times\int_{Q_j}^{\infty}f_{D_j}dD=0,\ j\in J \tag{26}$$

$$\frac{\partial^2 \Pi_j^r}{\partial q_j^{Sr^2}}=-A\times\beta_j\times\int_{Q_j}^{\infty}f_{D_j}dD-(C_u+C_o+P)\times f_{D_j}(Q_j)\quad,\quad j\in J \tag{27}$$

Accordingly, the optimal value of S can be attained as Eq. (28).

$$S^* = \left(\frac{1}{|J|} \sum_{j=1}^{J} \left(-A \times \beta_j \times E[D] - C_o + (C_u + C_o + P) \times (1 - F(Q_j)) \right) \Big/ \left(\prod_{i=1}^{I} W_{ij}^F \right)^{\frac{1}{I+1}} \right)^{I+1} \tag{28}$$

The optimal values needed for the spot market are now obtained. To obtain the optimal value for bilateral price, derivatives of Π_i^g and Π_j^r on q_{ij}^F are simultaneously needed, which can be calculated through Eqs. (29) and (30).

$$\frac{\partial \Pi_i^g}{\partial q_{ij}^F} = W_{ij}^F + q_i^{Sg} \frac{\partial S}{\partial q_{ij}^F} + \frac{\partial q_i^{Sg}}{\partial q_{ij}^F} S - b_i \left(\frac{\partial q_i^{Sg}}{\partial q_{ij}^F} + 1 \right) - c_i \left(q_i^{Sg} + \sum_j^J q_{ij}^F \right) \times \left(\frac{\partial q_i^{Sg}}{\partial q_{ij}^F} + 1 \right) = 0 \tag{29}$$

Eqs. (29) and (30) need the optimal value of q_i^{Sg}, which is obtained from Eq. (25). Further, they need $\frac{\partial S}{\partial q_{ij}^F}$ and $\frac{\partial q_i^{Sg}}{\partial q_{ij}^F}$ that can be calculated through Eq. (31) and Eq. (32), respectively.

$$\frac{\partial \Pi_j^r}{\partial q_{ij}^F} = 0 \Rightarrow \left\{ \begin{array}{l} -A \times \beta_j \times E[D] - W_{ij}^F - \frac{\alpha}{1-\delta} \times S - q_j^{sr} \times \frac{\partial S}{\partial q_{ij}^F} - C_o \times (1-\alpha) + \\ (1-\alpha) \times (C_u + C_o + P) \times \int_{Q_j}^{\infty} f_{D_j} dD + A \times \beta_j \int_{Q_j}^{\infty} (D_j - Q_j) f_{D_j} dD \end{array} \right\} = 0 \tag{30}$$

$$\frac{\partial S}{\partial q_{ij}^F} = \left(I + 1 \right) \times \left(\frac{1}{|J|} \sum_{j=1}^{J} \frac{\left(-A \times \beta_j \times E[D] - C_o + (C_u + C_o + P) \times (1 - F(Q_j)) \right)}{\left(\prod_{i=1}^{I} W_{ij}^F \right)^{\frac{1}{I+1}}} \right)^{I} \times \sum_{j=1}^{J} \frac{\left(1-\alpha\right) \times \left(-f\left(Q_j\right) + \frac{\partial P}{\partial q_{ij}^F} \left(1 - F\left(Q_j\right) \right) \right)}{J \times \left(\prod_{i=1}^{I} W_{ij}^F \right)^{\frac{1}{I+1}}} \tag{31}$$

$$\frac{\partial q_i^{Sg}}{\partial q_{ij}^F} = -q_i^{Sg} \times \left(-2 \frac{\partial S}{\partial q_{ij}^F} + 2C_i \right) \Big/ \left(2C_i q_i^{Sg} + \left(-2S + 2 \left(C_i \sum_{j=1}^{J} q_{ij}^F + b_i \right) \right) \right), \quad i \in I \tag{32}$$

Calculating Eqs. (29) and (30) based on Eqs. (31) and (32), may resulting in W_{ij}^{*} as Eq. (33).

$$W_{ij}^{F^*}=\frac{1}{2}\times\left(\begin{array}{l}-A\times\beta_j\times E[D]-\frac{\alpha}{1-\delta}\times S-q_j^{sr}\times\frac{\partial S}{\partial q_{ij}^F}-C_o\times(1-\alpha)+(1-\alpha)\times(C_u+C_o+P)\times\int_{Q_j}^{\infty}f_{D_j}dD+\\ A\times\beta_j\int_{Q_j}^{\infty}(D_j-Q_j)f_{D_j}dD-\left(q_i^{Sg}\frac{\partial S}{\partial q_{ij}^F}+\frac{\partial q_i^{Sg}}{\partial q_{ij}^F}S-b_i\left(\frac{\partial q_i^{Sg}}{\partial q_{ij}^F}+1\right)-c_i\left(q_i^{Sg}+\sum_j^J q_{ij}^F\right)\left(\frac{\partial q_i^{Sg}}{\partial q_{ij}^F}+1\right)\right)\end{array}\right) \tag{33}$$

It is noticeable that Eqs. (25) and (33) need the value of $\sum_{j=1}^{J}q_{ij}^F\ \forall i\in I$ as the share of Genco i of total sales in futures market. Since, this share depends on the selling price of the Genco in such a competitive situation, it is estimated through Eq. (34), named as R_i, in which m_j is calculated by Eq. (34).

$$R_i=\sum_{j=1}^{J}q_{ij}^F=\sum_{j=1}^{J}\left(\left(W_{ij}^F\right)^{-1}\Big/\left(\sum_{i'=1}^{I}\left(W_{i'j}^F\right)^{-1}\right)\right)\times m_j\ ,\qquad i\in I \tag{34}$$

5. Solution approach with a numerical example

Due to the complexity of the approach introduced in Sections 3 and 4 and the interrelationship among a large number of decision variables included in the proposed framework, it is hard to obtain an optimal solution for the model. Therefore, in this section a heuristic approach is designed to intelligently enumerate various values of variables as well as corresponding optimal solutions. Recall that due to the concavity of retailers and Gencos profit functions on relative variables, presented in Section 4, the final solution, obtained through the iterative analytical approach introduced in following paragraphs is guaranteed to be global optimal.

First, although any distribution and any values of parameters are allowed, suppose that customers' demand D_j is determined by a normal distribution function with mean 400 and variance 20, $f_{D_j}=(400,20)\ \forall j\in J$, in a three-supplier, four-retailer ESC network, which means $I=3$ and $J=4$. The values of other parameters are those given in Table 1.

In summary, an initial solution should be chosen for α, S, Q_j, and W_{ij}^F. Then, for each iteration, a new solution is generated based on the proposed solution mechanism till the final optimal solution is obtained. For instance, based on the mean value randomly chosen for D_j, one can set the initial value of $Q_j\ \forall j\in J$at 400, and also set α, S, and $W_{ij}^F\ \ \forall i\in I, j\in J$ at 0.3, 200, and 180, randomly. Based on variables' current values, and values of the parameters given in Table 1, the model is solved in Wolfrom Mathematica 11 and the resulting optimal values are considered as the input data to be used for further providing optimal values of the q_{ij}^F using LINGO-17.0 Software. Simulation process, which is run on an Intel(R) Core (TM) i7-6700HQ CPU @ 2.60 GHz with 16 GB memory, is completely discussed, by detail, in the following paragraphs.

After setting the initial values in **Step 1**, as for **Step 2**, the retail price can be calculated by using Eq. (4). For the example at hand, the value of the retail price is calculated as $P=303.16$. This value for the retail price is not optimal and considered only as an initial value for P. As for **Step 3**, given the value of P, order quantities of the retailers $Q_j\ \forall j\in J$, which depends on the retail price, can be updated by using Eq. (17). For the above example, resulting values for $Q_j\ \forall j\in J$ are calculated as $Q_1=393.00$, $Q_2=395.55$, $Q_3=395.55$, and $Q_4=395.36$. The value of $q_j^{Sr}\ \ \forall j\in J$ is directly related to the value of $Q_j\ \ \forall j\in J$, regarding Eq. (6). So, as for **Step 4** of the algorithm, the value of $q_j^{Sr}\ \ \forall j\in J$ should be also calculated based on the updated values obtained for $Q_j\ \ \forall j\in J$, given the initial value of α. Since each retailer supplies all its electricity needs from futures and spot markets, updating the amount of power purchased from the spot market in line with updating the total power purchased by the retailer may affect the amount of power purchased from the futures market, regarding Eq. (7). For the example at hand, given $\alpha=0.3$ the values of q_j^{Sr} and $m_j\ \forall j\in J$ are calculated as $q_1^{Sr}=117.900$, $q_2^{Sr}=118.665$, $q_3^{Sr}=118.665$, $q_4^{Sr}=118.608$, $m_1=275.100$, $m_2=276.885$, $m_3=276.885$, and $m_4=276.752$. Given the updated values of $Q_j\ \ \forall j\in J$ and P, and the other initial values at hand, the spot market price can be updated, using Eq. (28), as for **Step 5** of the proposed solution mechanism. For the above example, the updated spot price is calculated as $S=165.804$. Now, critical variables of the spot market are determined and it is time to look

Table 2
Provided optimal values obtained for the numerical example.

j	Q_j^*	m_j^*	q_j^{Sr*}	i	R_i^*	q_i^{Sg*}
1	412.2	363.336	48.8638	1	484.598	81.9272
2	414.7	365.540	49.1602	2	490.481	74.5690
3	414.7	365.540	49.1602	3	484.613	84.0630
4	414.4	365.275	49.1246			

Table 1
Sample data for the numerical example.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
A	0.55	γ	330	a_3	4.50	b_3	3.0	c_3	0.018	β_3	0.013
C_o	1.00	a_1	3.00	b_1	5.0	c_1	0.019	β_1	0.080	β_4	0.017
C_u	2.00	a_2	4.00	b_2	2.0	c_2	0.04	β_2	0.012		

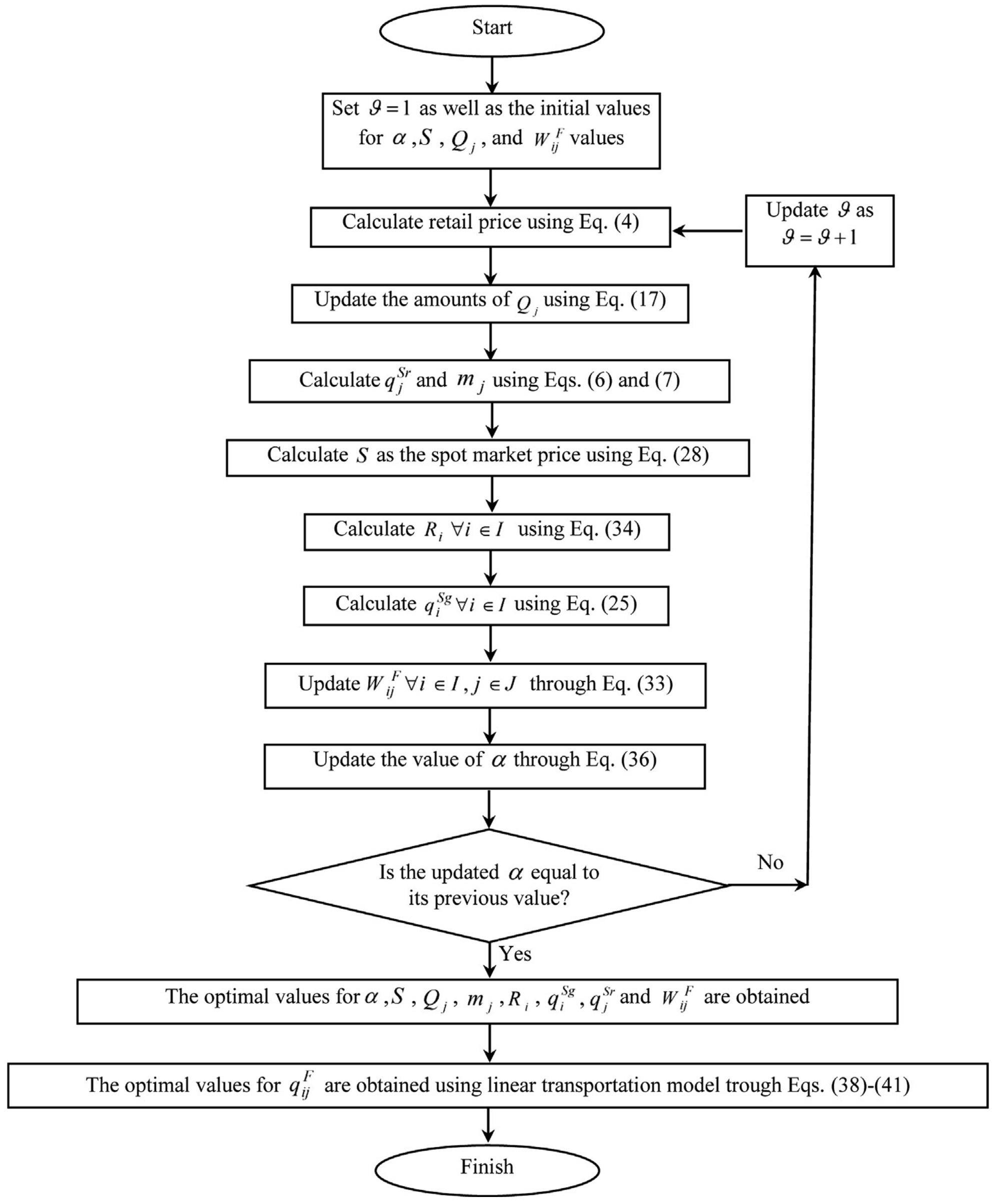

Fig. 2. Procedure for developing the proposed solution algorithm.

backward to the futures market.

As for **Step 6**, given the initial price of bilateral contract W_{ij}^F, from **Step 1**, and based on the values of m_j $\forall j \in J$ obtained from **Step 4**, the share of Genco i of total sales in the futures market R_i $\forall i \in I$ can be calculated by Eq. (34). For the example at hand, the values of R_i $\forall i \in I$ are calculated as $R_i = 368.541$ $i = 1, 2, 3$. Since, the initial price of all bilateral contracts was considered the same in **step 1**, it makes sense, from Eq. (34), that the share of all Gencos in total sales in the futures market is the same. Now, it is time to recalculate bilateral prices based on the updated spot price, obtained from **Step 5.** However, as shown in Eq. (33), bilateral prices are directly related to values of $q_i^{Sg} \forall i \in I$. So, as for **Step 7** of the proposed solution approach, values of $q_i^{Sg} \forall i \in I$ should be first calculated by Eq. (25). For the above example, using the updated value of the spot market price obtained from **Step 5**, values of $q_i^{Sg} \forall i \in I$ are calculated as $q_1^{Sg} = 8.422$, $q_2^{Sg} = 4.325$, and $q_3^{Sg} = 5.640$. Given values of $q_i^{Sg} \forall i \in I$, and values of the other parameters and variables needed for calculating $W_{ij}^F \forall i \in I, j \in J$, it is time to recalculate bilateral prices through Eq. (33), as for **Step 8** of the proposed solution mechanism. For the numerical example at hand, these values are calculated as shown in Eq. (35).

$$W_{ij}^F = \begin{bmatrix} 55.408 & 57.774 & 57.664 & 57.612 \\ 54.743 & 57.110 & 57.000 & 56.947 \\ 55.077 & 57.444 & 57.334 & 57.281 \end{bmatrix} \quad (35)$$

As for the final step, a stopping criterion is needed to terminate automatically the process of the proposed solution algorithm to save computational resources. So, as for **Step 9**, Eq. (36) is designed as the stopping criterion, in line with the final global equilibrium condition in the overall ESC, introduced through Eq. (5).

$$\alpha = \sum_{i=1}^{I} q_i^{Sg} \Bigg/ \sum_{j=1}^{J} Q_j \quad (36)$$

Table 3
Optimal results obtained from the proposed framework corresponding to various values of C_0.

Parameters			Decision variables										
C_o	C_u	β_1	Π_j^r	P	S	W_{ij}^F, $I=3$, $J=4$				q_i^{Sg}	Π_i^g	Q_j	α
						W_{i1}^F	W_{i2}^F	W_{i3}^F	W_{i4}^F				
1	2	0.08	94114.3	302.286	112.826	53.9796	56.2887	56.1787	56.3360	81.9272	29211.9	412.2	14.53%
			93409.8			53.3118	55.6209	55.5109	55.6681	74.5687	27731.6	414.7	
			93368.0			53.9779	56.2870	56.1770	56.3343	84.0630	31470.9	414.7	
			93546.5									414.4	
5	2	0.08	89846.4	302.454	130.349	62.9211	66.9968	66.8842	66.4504	84.7650	36467.9	410.0	15.20%
			88317.7			62.4331	66.5390	66.4402	66.0095	78.6570	32821.6	411.5	
			88315.7			63.0145	67.1129	67.0047	66.5639	86.6086	37787.8	411.5	
			88427.3									411.5	
15	2	0.08	85005.6	302.673	141.493	73.3938	76.6226	76.5126	76.5654	85.1258	41521.0	406.7	15.40%
			84045.9			72.8768	76.1057	75.9957	76.0486	79.5222	39359.4	408.4	
			84080.4			73.4179	76.6468	76.5368	76.5897	86.8219	43013.5	408.4	
			57254.0									408.2	
50	2	0.08	80242.4	303.008	157.194	84.1903	84.8590	84.7490	84.8967	84.0590	45863.9	401.5	15.54%
			80384.9			82.7691	83.4378	83.3278	83.4755	77.8237	44300.9	403.8	
			80093.8			84.2243	84.8930	84.7830	84.9307	85.5895	47083.9	403.8	
			80376.7									403.6	

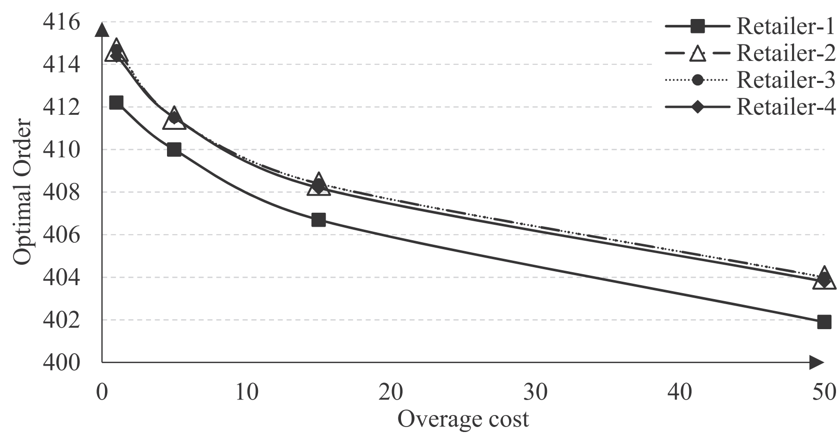

Fig. 3. Optimal order quantity Q_j with respect to the various values of the overage cost C_o.

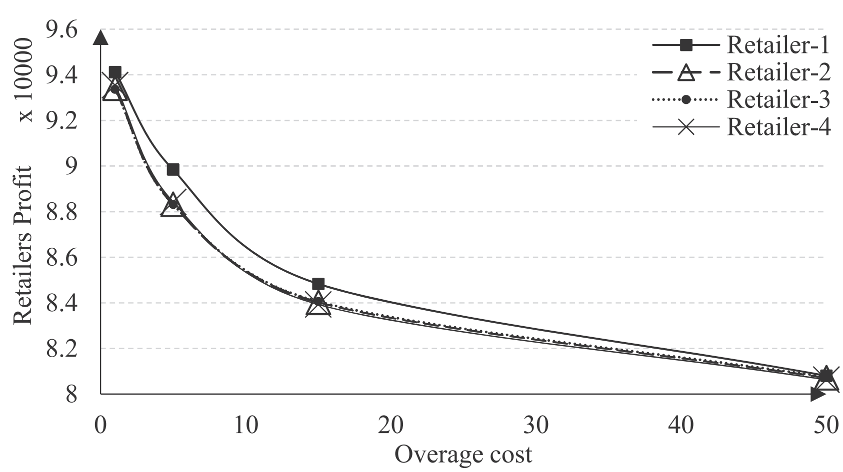

Fig. 4. Retailers profit Π_j^r with respect to the various values of the overage cost C_o.

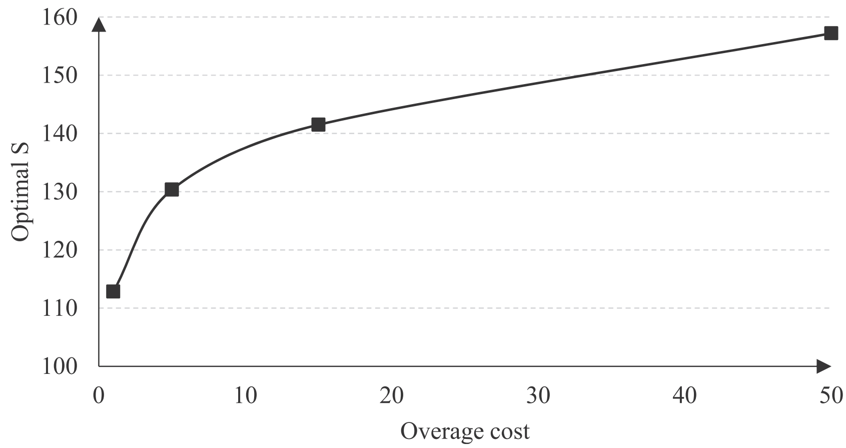

Fig. 5. Spot price S with respect to the various values of the overage cost C_o.

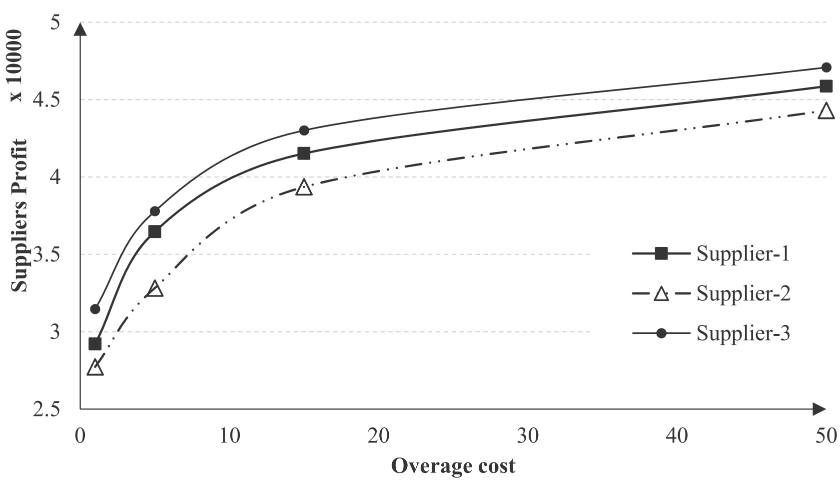

Fig. 6. Suppliers profit Π_i^g with respect to the various values of the overage cost C_o.

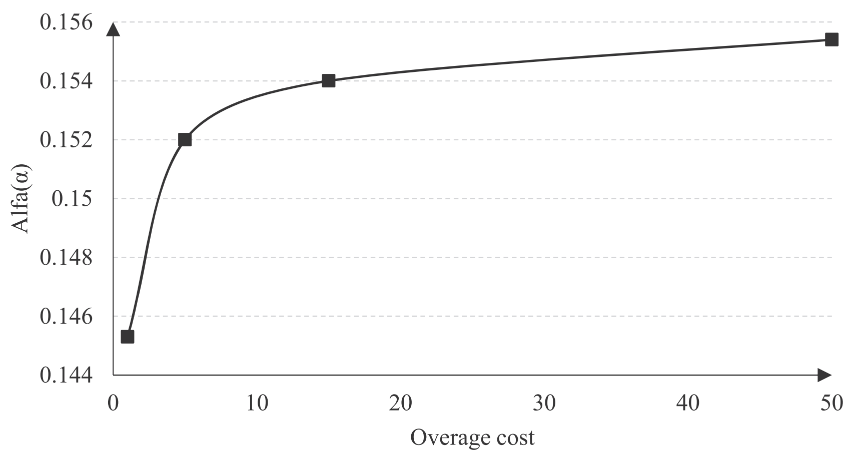

Fig. 7. Amount of α with respect to the various values of the overage cost C_o.

$$W_{ij}^{F^*} = \begin{bmatrix} 53.9796 & 56.2887 & 56.1787 & 56.3360 \\ 53.3118 & 55.6209 & 55.5109 & 55.6681 \\ 53.9779 & 56.2870 & 56.1770 & 56.3343 \end{bmatrix} \tag{37}$$

It is because of the fact that, in Eq. (5) the amount of power purchased by retailers should be logically equal to the amount of power generated by Gencos. In addition, Eq. (5) makes relationships between q_j^{Sr} and Q_j, using variable α as the spot market share for each retailer. For the example at hand, given Q_j $j \in J$ from **Step 3** and q_i^{Sg} $i \in I$ from **Step 7**, variable α takes the value of 0.0120, which

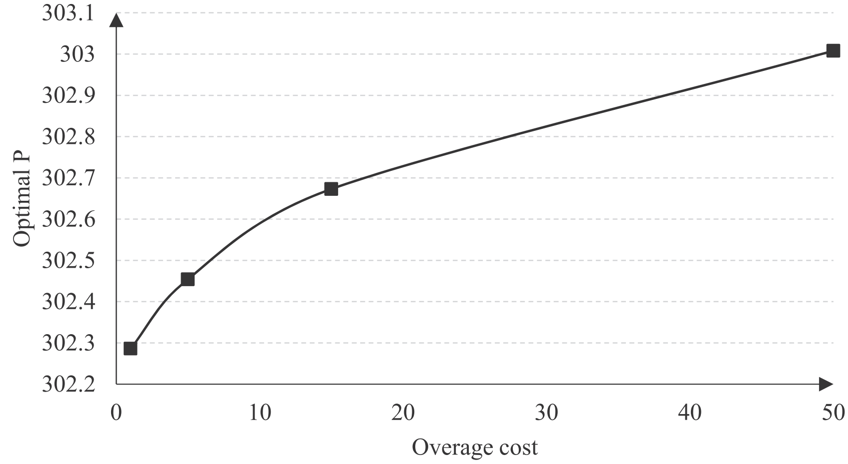

Fig. 8. Retail price P with respect to the various values of the overage cost C_o.

Table 4
Optimal results obtained from the proposed framework corresponding to various values of C_u.

Parameters			Decision variables											
C_o	C_u	β_1	Π_j^r	P	S	W_{ij}^F, $I = 3, J = 4$				q_i^{Sg}	Π_i^g	Q_j	α
						W_{i1}^F	W_{i2}^F	W_{i3}^F	W_{i4}^F				
1	**2**	0.08	94114.3	302.286	112.826	53.9796	56.2887	56.1787	56.3360	81.9272	29211.9	412.2	14.53%
			93409.8			53.3118	55.6209	55.5109	55.6681	74.5687	27731.6	414.7	
			93368.0			53.9779	56.2870	56.1770	56.3343	84.0630	31470.9	414.7	
			93546.5									414.4	
1	**10**	0.08	92140.5	302.327	118.346	58.7436	61.0027	60.8927	60.6621	83.4184	32672.7	411.6	14.85%
			91471.3			58.3430	60.6021	60.4921	60.2615	76.6499	29982.1	414.0	
			91415.1			58.7568	61.0159	60.9059	60.6753	85.4335	33463.9	414.0	
			91589.2									413.9	
1	**15**	0.08	89409.9	302.387	127.315	64.4419	66.7393	66.6359	66.8583	84.1830	35394.1	410.7	15.01%
			88745.9			63.9671	66.2608	66.1543	66.3739	77.1078	33837.5	413.0	
			96461.3			64.5037	66.7963	66.6888	66.9076	86.3028	31420.8	413.0	
			88573.2									412.7	
1	**50**	0.08	83343.0	302.447	140.022	81.5123	78.6881	81.0644	80.9544	87.7167	43627.1	410.0	15.70%
			83152.4			76.9879	79.3641	79.2541	79.8121	81.1752	42192.7	412.0	
			82825.8			78.7370	81.1133	81.0033	81.5613	89.4899	44069.5	412.0	
			82403.6									411.6	

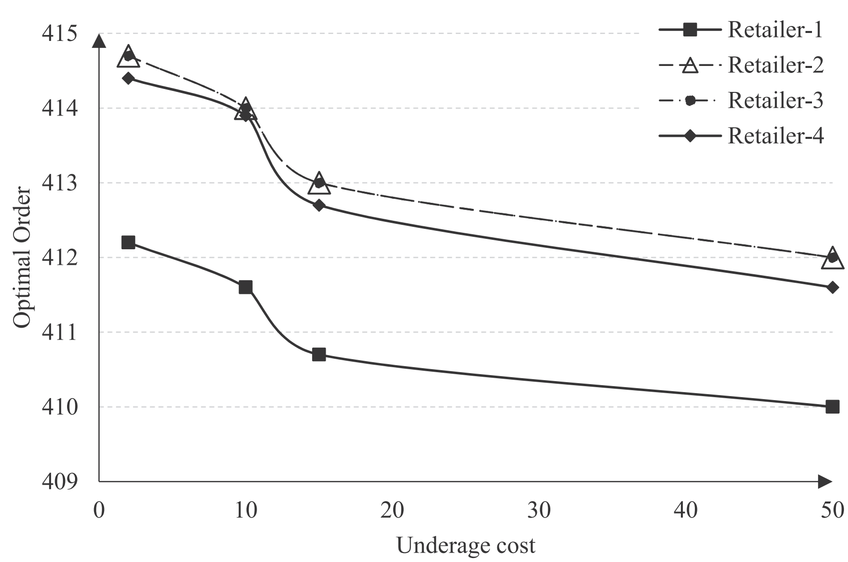

Fig. 9. Optimal order quantity Q_j with respect to the various values of the underage cost C_u.

differs from its initial value, i.e. $\alpha = 0.3000$. By this means, the stopping criterion is not satisfied, hence the algorithm goes back to **Step 2**. This process will not end until the difference between two consecutive values of α is less than or equal to the predefined acceptable tolerance. For the example at hand, the optimal solution is obtained after 6 iterations of the algorithm and optimal values of P, S and α are calculated as 301.645, 63.145, and 0.1200. Other results are also shown in Table 2 and Eq. (37).

Using optimal values obtained in **Step 9** as input parameters for **Step 10**, final optimal values of q_{ij}^F are provided through the linear transportation model, shown through Eqs. (38)–(41), to further guarantee the global optimality of the solution. In Eq. (38), dependent variable Π is provided as the total cost of bilateral contracts, which is obtained through the perspective of retailers. Using LINGO-17.0, final optimal values of the q_{ij}^F are provided as shown in Eq. (42). To obtain more clarity, the proposed solution algorithm is represented in Fig. 2.

$$Min\Pi = \sum_{i=1}^{I}\sum_{j=1}^{j} W_{ij}^F q_{ij}^F \tag{38}$$

$$\sum_{i=1}^{I} q_{ij}^F = m_j \quad \forall j \in J \tag{39}$$

$$\sum_{j=1}^{J} q_{ij}^F = R_i \quad \forall i \in I \tag{40}$$

$$q_{ij}^F \geq 0 \quad \forall i \in I, j \in J \tag{41}$$

$$q_{ij}^{F^*} = \begin{bmatrix} 352.307 & 117.272 & 0.000 & 0.000 \\ 0.000 & 121.613 & 0.000 & 354.188 \\ 0.000 & 115.559 & 354.444 & 0.000 \end{bmatrix} \tag{42}$$

6. Sensitivity analysis and further discussions

The approach presented in this paper adapts a suitable inventory model to the ESC network coordination problem, based on analogies between inventory management in classic SCs and electrical storage systems. According to the model formulation and reformulation presented in Sections 3 and 4, the overage cost C_o, underage cost C_u, and the all-unit discount coefficient $\beta_j \ \forall j \in J$ are important parameters that are able to influence final results. So, the results obtained for different values of parameters have been investigated to show the profit-efficiency and planning accuracy of the proposed framework. However, due to time and computer resource limitations, only a few values of each parameter are used.

6.1. Analysis of results and discussions with respect to change in the overage cost

The results obtained for various values of $C_o (C_o = 1, 5, 15, 50)$ are summarized in Table 3, given $C_u = 2$ and $\beta_1 = 0.8$. Fig. 3-Fig. 8 are also provided based on the values reported in Table 3 to further obtain clearer insight into the results.

From Fig. 3, the higher the overage cost, the lower the amount of the order quantity. This is because of the fact that increasing the order quantity at a higher overage cost will impose far greater inventory costs on retailers and further reduce their profit. This is completely consistent with what is outlined in Fig. 4 in full agreement with what is concluded by Altug (2017). Because the higher the overage cost, the lower the order quantity, shown in Fig. 3, and the lower the retailers' profit, shown in Fig. 4.

From Fig. 4, the higher the overage cost, while everything else remaining equal, the lower the retailers profit. This is perfectly reasonable because the increase in overage costs leads to an excess inventory cost, which includes the cost of physical inventory holding, the cost of devaluation of inventory, and opportunity cost of inventory-related funds (Kaya and Özer, 2012). This in turn will reduce retailers' income and further reduce their profits.

On the other point of view, the lower order quantity due to the higher retailers' overage cost, shown in Fig. 3, can rise selling prices, i.e. spot price, outlined in Fig. 5 and bilateral prices, reported in Table 3, to compensate for the lost profits of suppliers, shown in Fig. 6, which is in full agreement with what is concluded by Wu et al. (2014).

As outlined in Fig. 6, when the loss ratio of a retailer is high, its benefit of ordering more quantity to save the underage cost is larger than its benefit of ordering less to save the overage cost (see row 1 of Table 3 as well as Fig. 3). This positively affects the retailer's profit due to the decrease in its need to buy from the spot market, which in turn decreases the spot price, as shown in Fig. 5. This happens since the spot price is far more than bilateral prices, as shown in Table 3. As the supplier makes the most profit from the spot market,

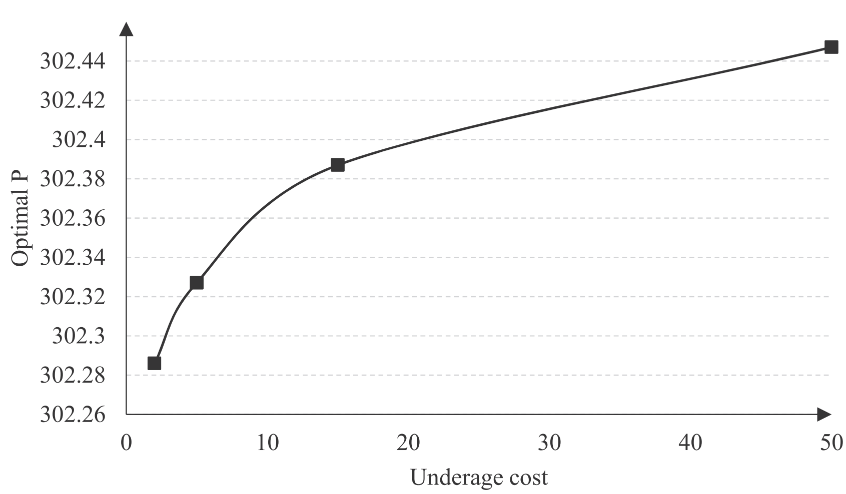

Fig. 10. Retail price P with respect to the various values of the underage cost C_u.

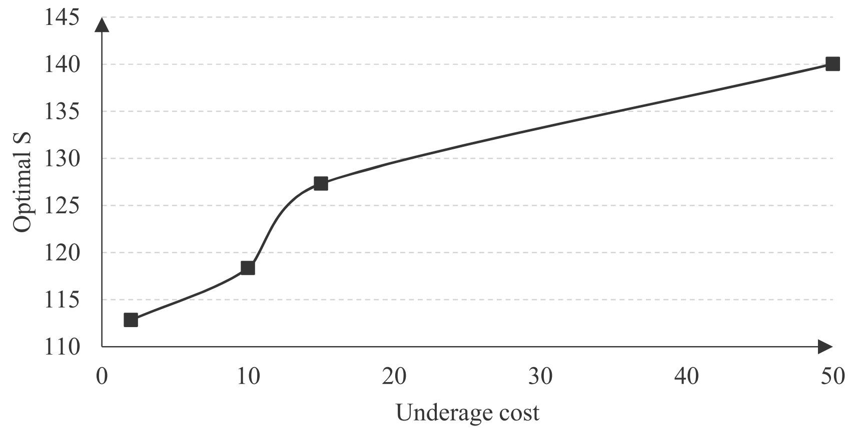

Fig. 11. Spot price S with respect to the various values of the underage cost C_u.

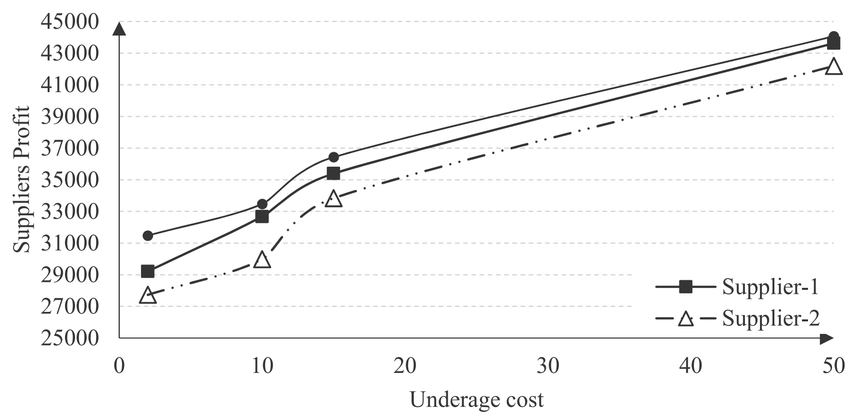

Fig. 12. Suppliers profit Π_i^g with respect to the various values of the underage cost C_u.

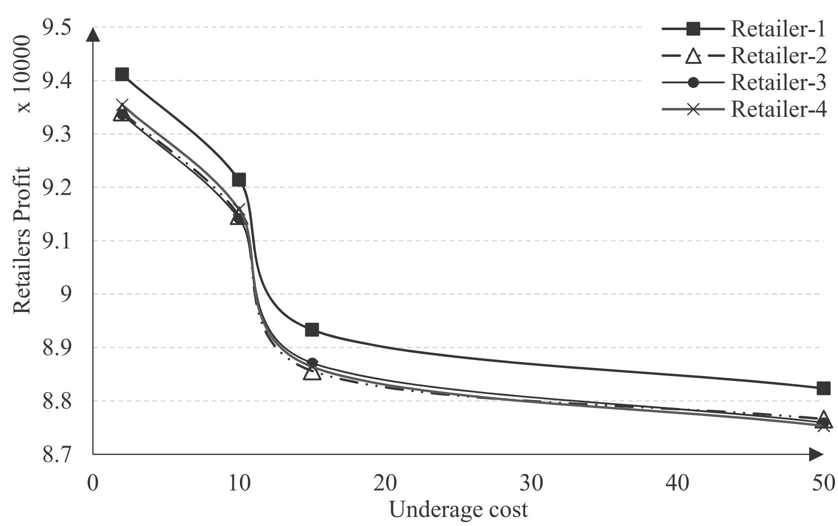

Fig. 13. Retailers profit Π_j^r with respect to the various values of the underage cost C_u.

reducing the retailer's need to this market will reduce the supplier's profit, illustrated in Fig. 6. Correspondingly, the higher the overage cost, the lower the optimal supply level (Petruzzi and Dada, 2010). This in turn increases the retailer's need to buy from the spot market, shown in Fig. 7, and it hence increases the spot price, shown in Fig. 5, and rises the suppliers' profit, shown in Fig. 6. The sharp slope at the beginning of the figures is due to the fact that at the first point, with $C_o = 1$, the overage cost is less than the underage cost, while from the second point, with $C_o = 5$, the underage cost is more than the overage cost, which influences the behavior of the retailer.

From Fig. 7, the higher the amount of the overage cost, the higher the share of the spot market. This increase in the spot market share has initially shown a sharp rise in the overage cost

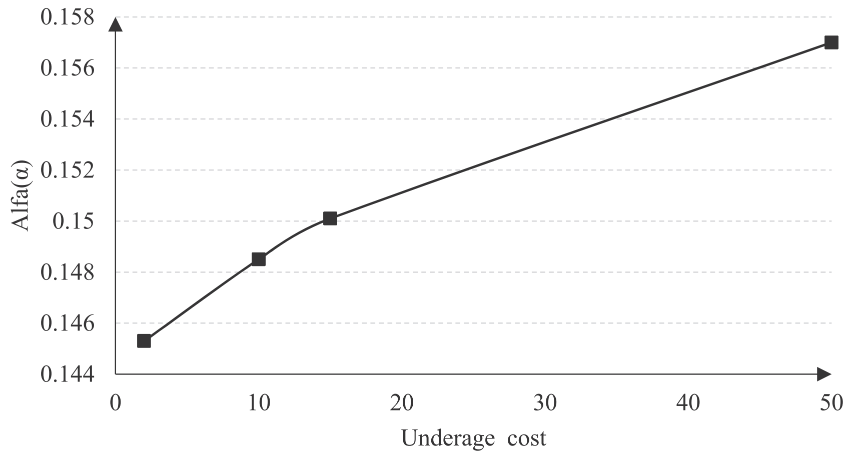

Fig. 14. Amount of α with respect to the various values of the underage cost C_u.

Table 5
Optimal results obtained from the proposed framework corresponding to discount coefficient of 1st retailer β_1.

Parameters			Decision variables										
C_o	C_u	β_1	Π_j^r	P	S	W_{ij}^F, $I = 3, J = 4$				q_i^{Sg}	Π_i^g	Q_j	α
						W_{i1}^F	W_{i2}^F	W_{i3}^F	W_{i4}^F				
1	2	**0.00**	99159.5	320.416	114.367	59.7380	58.8270	58.7170	59.9441	83.6171	31658.7	415.4	14.79%
			99593.9			59.2521	58.3411	58.2311	59.4582	76.1385	29143.2	415.2	
			99512.5			59.7594	58.8484	58.7384	59.9655	85.8391	32648.2	415.2	
			99196.7									414.4	
1	2	**0.02**	97988.4	315.859	114.116	58.5184	58.7800	58.7315	58.6622	83.4607	31443.1	414.56	14.79%
			97765.5			57.9627	58.2243	58.1758	58.1064	76.2875	29059.1	414.86	
			97718.3			58.5448	58.8064	58.7579	58.6885	85.5882	32894.2	414.83	
			97732.5									414.65	
1	2	**0.08**	94114.3	302.286	112.826	53.9796	56.2887	56.1787	56.3360	81.9272	29211.9	412.2	14.53%
			93409.8			53.3118	55.6209	55.5109	55.6681	74.5687	27731.6	414.7	
			93368.0			53.9779	56.2870	56.1770	56.3343	84.0630	31470.9	414.7	
			93546.5									414.4	
1	2	**0.10**	93131.5	297.779	111.73	51.8645	56.0000	55.9491	56.4832	81.7935	27885.0	409.1	14.51%
			91698.9			51.2111	55.3466	55.2957	55.8297	74.5666	25528.6	414.57	
			91796.4			51.8963	56.0317	55.9808	56.5149	83.9328	29372.8	414.55	
			91770.8									414.38	
1	2	**0.15**	89721.7	286.675	110.683	49.3124	53.3230	53.2508	53.1908	81.1667	26863.5	406.85	14.29%
			88316.4			48.5674	52.5780	52.5058	52.4458	73.9993	23877.9	414.65	
			88354.2			49.3470	53.3576	53.2854	53.2254	83.2800	27242.2	414.65	
			88643.2									414.45	

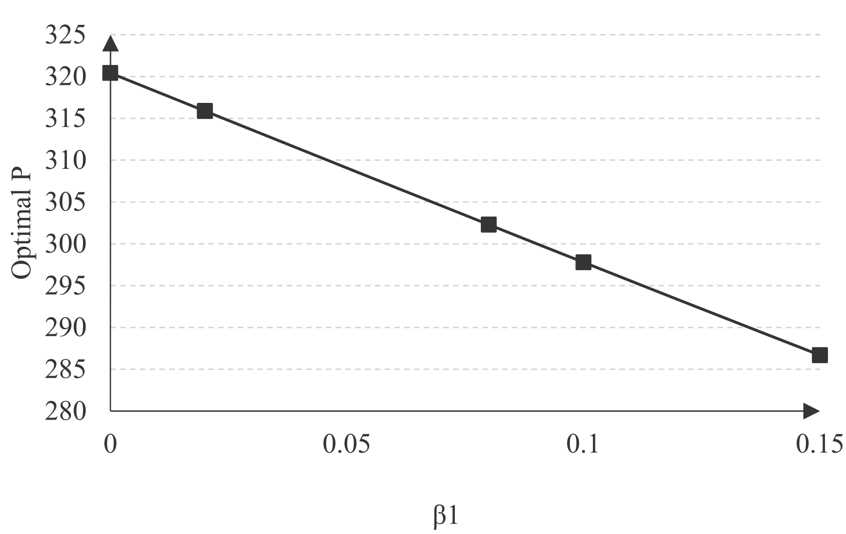

Fig. 15. Retail price P with respect to the discount coefficient of 1st retailer β_1.

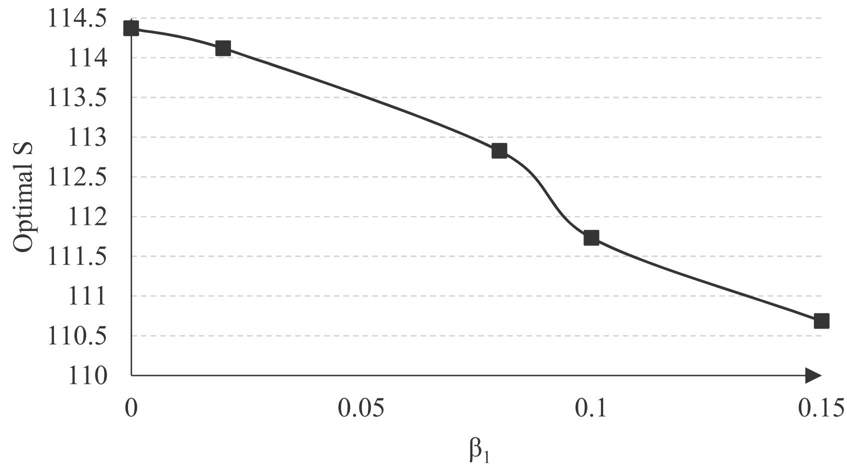

Fig. 16. Spot price S with respect to the discount coefficient of 1[st] retailer β_1.

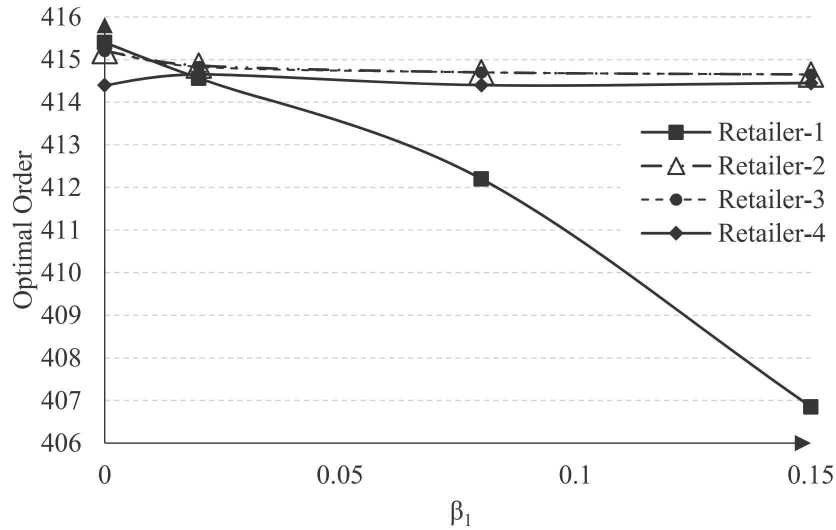

Fig. 17. Optimal order quantity Q_j with respect to the discount coefficient of 1[st] retailer β_1.

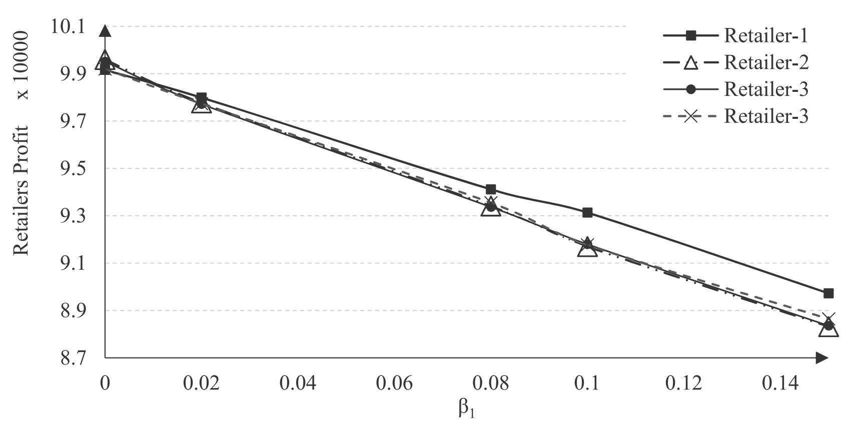

Fig. 18. Retailers profit Π_j^r with respect to the discount coefficient of 1[st] retailer β_1.

and it has been moderated after point (5,15.20%). This is quite logical, since the lower share of the spot market at lower α allows retailers to move more quickly towards purchasing further power from the spot market even with the slightest increase in the overage cost. In other words, retailers' sensitivity to the overage cost is much higher when the share of the spot market is small enough.

Accordingly, Fig. 8 clearly shows that the lower the order

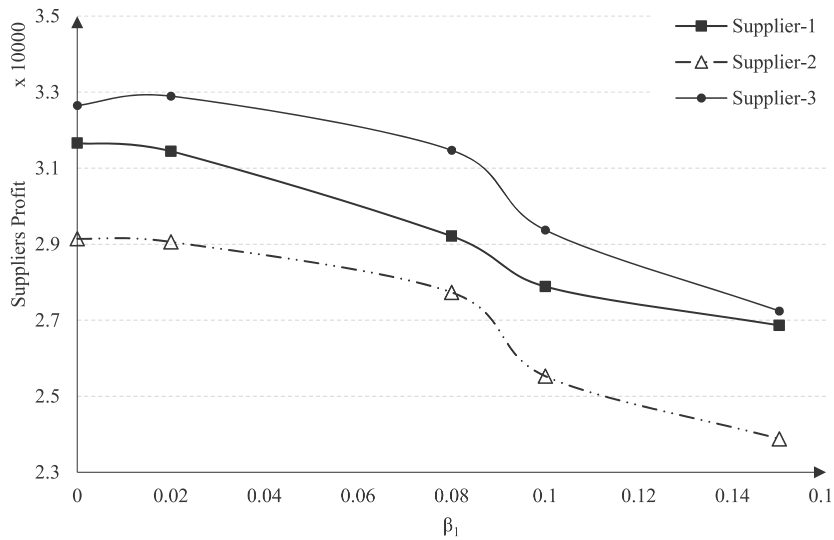

Fig. 19. Suppliers profit Π_i^g with respect to the discount coefficient of 1st retailer β_1.

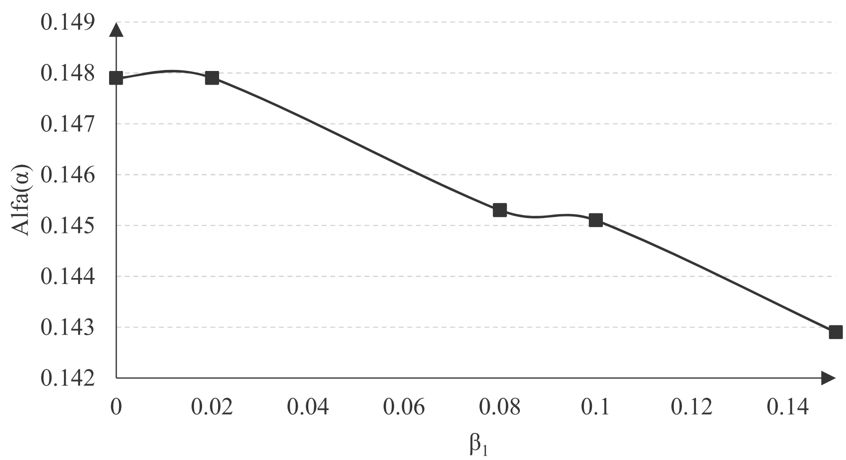

Fig. 20. Amount of α with respect to t the discount coefficient of 1st retailer β_1.

quantity due to the higher overage cost, the higher the retailer's selling price regarding its pricing policy given by Eq. (4). Because, in full agreement with what is reported in (Chen, 2012), as the overage cost increases, the order quantity decreases, hence retailers supply decreases which in turn rises the optimal retail price. Besides, regarding the relative literature (Mathewson and Winter 1987), with a drop in suppliers' wholesale price, the retail price must drop, which is clearly reported in Fig. 8 in line with the results obtained in Table 3.

6.2. Analysis of results and discussions with respect to change in the underage cost

The results obtained for various values of $C_u(C_u = 2, 10,\ 15,\ 50)$ are summarized in Table 4, given $C_o = 1$ and $\beta_1\ = 0.8$. Fig. 9-Fig. 14 are also provided based on the values reported in Table 4 to further obtain clearer insight into the results.

Fig. 9 shows that the greater the underage cost, the lower the order quantity. This is completely in agreement with what is reported in (Wang and Webster, 2009). The explanation for this behavior is that, with the increase in the underage cost, retailers' selling price changes subtly, shown in Fig. 10, while retailers' purchase price, i.e. the spot price regarding Eq. (28) and the bilateral price according to Eq. (33), shows a sharp increase, outlined in Fig. 11 and Table 4. This will increase the retail cost and Gencos profit, outlined in Fig. 12, while it reduces retailers' profit, illustrated in Fig. 13. On the one hand, the logical reaction of a retailer to an increase in purchase cost is to reduce the order quantity. On the other hand, since it must meet customers' demand, the reduction of the order quantity cannot be too high.

The retail price and the order quantity are inversely related, concluded by Du et al. (2018). This is because in the high retail price, retailers are not willing to accept the high risk of buying under the uncertainty in demand at a higher retail price. In addition, retailers' order quantity decreases as the wholesale price increases (Tsao, 2017; Xinsheng et al., 2015). Therefore, since there is a positive relationship between the wholesale price and the underage cost, reported in Table 4, the retail price will increase as the underage cost increases, shown in Fig. 10.

Since the spot market is considered to tackle the risk of the futures market, it makes sense to Gencos to increase the spot price, outlined in Fig. 11, to further increase their profit as the underage cost of retailers increases, shown in Fig. 12.

Accordingly, suppliers/Gencos charge retailers a higher wholesale price when the spot price increases, reported in Table 4 in full coordination with what is concluded by Chen and Liu (2007). This may increase suppliers final profit, shown in Fig. 12, while decreasing retailers profit, outlined in Fig. 13. Similar results are also reported by Seifert et al. (2012) considering a general three-echelone SC. The results also agree with what is reported in (Chen et al., 2017), where they claimed that with an increase in the wholesale price, which occures with an increase in the underage cost, reported in Table 4, retailers will generate a lower expected profit, shown in Fig. 13. Given a decline in the retail profit and an increase in the supplier's profit, it can be expected that the total profit of the chain will remain almost unchanged. This is also claimed by Seifert et al. (2012).

Similar to what has been reported in Fig. 7, from Fig. 14, the higher the amount of the underage cost, the higher the share of the spot market. Contrary to what has been claimed about an increase in the spot market share against the overage cost, an increase in the spot market share is almost linear with an increase in the underage cost. This is only because the underage cost is deliberately chosen so that it is always more than the overage cost. Therefore, the behavioral change that was expected to occur in the spot market share, shown in Fig. 7, which was supposed to happen due to a change in the position of the underage and overage costs, did not occur.

6.3. Analysis of results and discussions with respect to change in the discount coefficient

After providing the analysis regarding overage and underage costs, it is time to analyze the results obtained from various values of the discount coefficient β_j, $j \in J$. Before analyzing the results, it is necessary to describe that according to similar trends for both suppliers and retailers observed in the aforementioned figures, only β_1 is taken to be changed to study the effects of discounts to final customers related variables. The results obtained for various values of β_1 $(\beta_1 = 0.00, 0.02\ , 0.08,\ 0.10,\ \text{and}\ 0.15)$ are summarized in Table 5, given $C_o = 1$ and $C_u\ = 2$. Figs. 15–20 are also provided based on the values reported in Table 5 to further obtain clearer insight into the results.

Since the discount of the first retailer linearly reduces the sales price of all retailers, shown in Fig. 15, they try to maximize their profits by lowering the spot price, illustrated in Fig. 16. Reducing the spot price, suppliers try to adjust their bilateral prices to motivate retailers to make a major purchase from the futures market as outlined in Table 5. This is completely consistent with retailers' total order quantity that remains almost constant and with first retailer's lower order quantity as shown in Fig. 17. Clearly, as prices decrease and sales remain almost constant, retailers' and consequently suppliers' profits will also decline as shown respectively in Figs. 18 and 19.

From other point of view, although Fig. 20 shows a drop in the spot market share in response to an increase in discounts, the decline is negligible, i.e. approximately 0.5%. Thus, in general, it can be said that an increase in discounts has a negligible but decreasing effect on the spot market share. This slight reduction is due to a decrease in the retailer's order quantity that has driven the rebate (the first retailer in the solved example).

6.4. Policy implications of the mathematical results

This research clearly delineates the policy implications resulting from the sensitivity analysis and literatures that are examined. By this means, the results may help DMs to develop correct policies as follows:

A) A retailer who is willing to earn more profit should decrease his overage and underage costs, excluding the decision made by suppliers/Gencos.
B) By increasing the overage and underage costs, suppliers/Gencos can increase their profits by raising prices, i.e. spot and futures markets prices.
C) The higher the overage and underage costs, the lower the order quantity. So, by increasing the overage and underage costs, suppliers/Gencos should reduce their power generation rate.
D) An increase in the amount of the overage cost increases the spot market share in the retailer's procurement plan.
E) An increase in the underage cost increases the need of the retailers to purchase from the spot market to bear lower penalty costs, hence the share of the spot market should be increased in retailers' procurement plan.
F) The discount given by a retailer reduces the sales price of retailers and spot and futures prices, while retailers' total order quantity remains almost constant.
G) In smaller amounts of α, for a more risk-averse DM, the effect of an increasing in the overage cost is greater. Because lower α allows retailers to move more quickly towards purchasing further power from the spot market even with the slightest increase in the overage cost.
H) An increase in discounts has a negligible but decreasing effect on the spot market share.

7. Conclusion and future research

Considering a liberalized and decentralized electricity market, this paper mathematically introduces an original ESC coordination framework through the single-period newsvendor inventory model to optimally design contracts aiming at maximizing retailers' profit and optimizing that of Gencos. The model is proposed basically from the retailers' point of view. Retailers decide on optimal trading with Gencos using bilateral contracts, optimal participation in pool market, and optimal contracts with consumers. Using a strong mathematical formulation, which leads to a global optimal solution, the framework is capable of optimally considering some inventory management characteristics and aspects such as overage and underage costs as well as the discount policy. The main contributions of the proposed model, which are verified by the numerical results, are as follows:

A) The research mathematically integrates separate studies on electricity markets, SC coordination, contract design, pricing and discounting policy making, inventory management, risk management, and linear optimization to develop an aggregated research schema. In the proposed aggregated framework, collaboration in the ESC is established based on the platform of a two-stage non-cooperative game between Gencos and retailers addressing the so-called general double marginalization problem. B) Overage and underage costs are addressed in the proposed model to cover the inventory and the shortage, respectively. This research is therefore a pioneer in considering battery usage in the ESC contract design. C) Linking retailers' attitude towards risk with the spot market share, this paper is the first to address retailers' risk-aversion level in the problem of contract design in a coordinated ESC. D) Using a strong, mathematically optimal formulation, this research is the first to simultaneously define contracts share and prices, i.e. futures and spot market prices, considering retailers attitude towards the risk arising from customers demand uncertainty. E) The framework is successful in using the well-known linear transportation model to obtain a global optimal solution through an original simulation-optimization solution approach. F) Some useful trade-offs are originally introduced, in this paper, among retailers' and Gencos profits, market share, overage and underage costs, and the all-unit discount given by retailers. G) An increasing, almost linear relationship is established between the spot market share and the underage cost. H) The retailer's sensitivity to overage cost is revealed to be much greater when the spot market share is very low. Therefore, the proposed model is practically suitable for a restructured, decentralized, and liberalized electricity market.

The proposed model in this paper can be developed in the future research as follows. A) On the generation side, renewable-energy based power plants can be modeled, which have the different behavior in comparison with traditional ones. B) The Microgrid aggregators can be modeled on the demand side to participate in both markets to purchase/sell the required/extra energy from/to markets. C) The transmission network constraints can be modeled to consider the congestion management problem in the proposed SC framework.

CRediT authorship contribution statement

Hêriş Golpîra: Conceptualization, Funding acquisition, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Conception and design of study, acquisition of data, analysis and/or interpretation of data, Drafting the manuscript, revising the manuscript critically for important intellectual content. **Heibatolah Sadeghi:** Funding acquisition, Data curation, Formal analysis, Writing - review & editing, acquisition of data, analysis and/or interpretation of data, revising the manuscript critically for important intellectual content. **Salah Bahramara:** Funding acquisition, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, acquisition of data, analysis and/or interpretation of data, Drafting the manuscript, revising the manuscript critically for important intellectual content.

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.

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