Bilateral Contracting in Multi-agent Energy Markets with Demand Response

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Abstract. In competitive energy markets (EMs), customers can freely choose their energy suppliers. The electricity trade can be done in organized markets or using forward bilateral contracts. Currently, there are several simulation tools based on multi-agent techniques that allow modeling, partially or globally, competitive EMs. The existing tools allow simulating negotiation prices and volumes through bilateral contracts, transactions in pool markets, etc. However, these tools have some limitations, mainly due to the complexity of the electric system. In this context, this article focuses on bilateral trading and presents the key features of software agents able to negotiate forward bilateral contracts. Special attention is devoted to demand response in bilateral contracting, notably utility functions and trading strategies for promoting demand response. The article also presents a case study on forward bilateral contracting with demand response: a retailer agent and an industrial customer agent negotiate a 24h-rate tariff.

Keywords: Energy markets, multi-agent systems, bilateral contracting, demand response, trading strategies, simulation.

1 Introduction

Traditionally, the organization of the electricity sector was based on vertically integrated electric power companies from production to sale of electricity, which produced, transported and distributed the energy without any competition. The deregulation process began in the earlier nineties and basically separated the functions of electrical generation and retail from the natural monopoly functions of transmission and distribution. This process led to the implementation of a wholesale market, where competing generators offer their energy to retailers, and a retail market, in which retailers ensure delivery to end customers. Customers are able to choose their supplier of electricity depending on the best offers.

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Due to the complexity and unpredictability of Energy Markets (EMs), decision making becomes increasingly difficult. Thus, the entities involved have been forced to rethink their behavior and market strategies. Recent changes in the electricity sector have come to prove that the demand side may also have a relevant influence on the whole process, especially regarding strategic decision making by end customers. In this new paradigm, customers and buyers of energy can play a much more active role in EMs and, through appropriate strategies, achieve their objectives. Several strategies are associated to consumption efficiency and represent the actions related to the concepts of conservation, management and rational use of energy. One of these actions, that are expected to grow in the scope of EMs, is Demand Response (DR). DR can be defined as the capacity to manage the electricity consumption of end customers and in response provide appropriate conditions, including reducing the price of electricity, improve system reliability and reduce price volatility.

However, the entities of EMs are heterogeneous and autonomous, and follow their own goals and strategies. Usually, the production companies seek to adopt strategies that maximize profit, while costumers adopt strategies that minimize electricity cost. Thus, strategies have as their main objective reaching favourable agreements between the players involved. Strategies can be applied to any type of EMs. Several major markets are often distinguished, notably pools and bilateral contracts [1]. A pool market is defined as a centralized marketplace that clears the market for sellers and buyers. Electric power sellers/buyers submit bids to the pool for the amounts of power that they are willing to trade in the market. The bids are submitted to a market operator, whose function is to coordinate and manage the different transactions between the participants. Bilateral contracts are negotiable agreements on delivery and receipt of power between two traders. These contracts have the advantage of price predictability in comparison of uncertain pool prices.

Multi-agent systems (MAS) are essentially loosely coupled networks of software agents that interact to solve problems that are beyond the individual capabilities of each agent. MAS can deal with complex dynamic interactions and support both artificial intelligence techniques and numerical algorithms. Conceptually, a multi-agent approach is an ideal fit to the naturally distributed domain of a deregulated electricity market.

This article is devoted to demand response in forward bilateral contracting. It presents the key features of software agents able to negotiate forward bilateral contracts, paying special attention to demand response programs, including different utility functions and strategies for promoting DR. It also presents a case study on forward bilateral contracting involving DR management: a retailer agent (a seller) and an industrial customer agent (a buyer) negotiate a 24h-rate tariff. Furthermore, the work presented here refines and extends our previous work in the area of automated negotiation [2,3,4] and bilateral contracting with demand response [6,7]. As stated, it considers demand response into bilateral contracting, focusing on specific utility functions and DR management strategies, and describing a case study involving a 24h-rate tariff.

2 Demand Response in Competitive Energy Markets

Demand response involves changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [8]. The principle of DR aims to change the tendency of evolution of the energy consumption of the end customer in order to reduce the operating costs of the system, from the point of view of the producer or customer.

Customers participating in demand response options may adopt one (or more) of three basic load response strategies [9]. Each of these actions involves costs and measures taken by customers. The first option involves reducing the electricity usage by customers at times of high prices without changing the consumption pattern during other periods. For example, a residential customer might turn off lights during an event, or a commercial facility might turn off some office equipment. In both cases, this option results in a temporary loss of comfort. The second option involves rescheduling usage away from times of high prices. For example, a residential customer might put off running a dishwasher until later in the day, or an industrial facility might reschedule a batch production process to the evening hours or the next day. In the third option, customers may respond by using onsite generation to supply some or all of their electricity needs. However, the may experience little change in their electricity usage pattern.

Besides these options, there are different DR programs, such as Priced Based Programs (PBP) and Incentive-Based Programs (IBP). PBP programs refer to changes in usage by customers in response to changes in the prices they pay and include real-time pricing, critical-peak pricing, and time-of-use rates. IPB programs are established by utilities, load-serving entities, or a regional grid operator. These programs give customers load-reduction incentives that are separate from, or additional to, their retail electricity rate, which may be fixed (based on average costs) or time-varying (see, e.g., [8,9]).

The present situation of the DR in the world is presented in [10]. Several implementations of DR in the wholesale market are also occurring in Europe [11], China [12] and in other places around the world [13].

3 Bilateral Contracting with Demand Response

This section describes the process of forward bilateral contracting with demand response, involving a seller agent and a buyer agent. Negotiation includes the determination of prices and quantities of energy, and is executed on a long term, usually six months or more. Special attention is devoted to different utility functions and strategies for promoting demand response. As noted earlier, bilateral contracts are financially safer for market participants, due to the fact that they may guarantee protection against the volatility of high prices of energy markets in real time.

3.1 Pre-negotiation

The pre-negotiation process involves mainly the creation of a well-laid plan specifying the activities that negotiators should attend to before actually starting to negotiate. These activities include [4]:

- Identifying the issues to negotiate;
- Defining limits and priorities for the issues;
- Selecting an appropriate protocol;
- Defining preferences over outcomes.

Let a_s denote the seller agent and a_b the buyer agent. The agents define the negotiation issues, which in this case are the prices and volumes of energy. Let $\left[P^s_{k_{min}}, P^s_{k_{max}}\right]$ $(k = 1..n)$ denote the range of values for price that are acceptable to agent a_s. Also, let $\left[P^b_{k_{min}}, P^b_{k_{max}}\right]$ and $\left[V^b_{k_{min}}, V^b_{k_{max}}\right]$ $(i = k..n)$ denote the range of values for price and volumes that are acceptable to agent a_b. Priorities are set by ranking-order the issues, i.e., by defining the most important, the second most important, and so on.

A protocol is a set of rules that define how the negotiation process can progress, specifying what actions are allowed and when. We consider an alternating offers negotiation protocol [14]. This protocol models the iterative exchange of offers and counter-offers. At any given period of negotiation, an agent may accept an offer, send a counter-offer, or end the negotiation. If a counter-offer is submitted, the process is repeated until one of the agents accept or abandon the negotiation. Thus, the agents a_s and a_b bargain over the division of the surplus of $n \geq 2$ issues by alternately proposing offers at times in $T = \{1, 2, ...\}$. This means that one offer is made per time period $t \in T$, with an agent offering in odd periods and the other agent offering in even periods. As noted, the agents have the ability to unilaterally opt out of the negotiation when responding to a proposal.

Definition 1 (Proposal). *Let $\mathcal{A}$ be the set of negotiating agents and $\mathcal{I}$ the set of issues at stake in negotiation. Let $\mathcal{T}$ be the set of time periods. A proposal $p^t_{i \to j}$ submitted by an agent $a_i \in \mathcal{A}$ to an agent $a_j \in \mathcal{A}$ in period $t \in \mathcal{T}$ is a vector of issue values:*

$$p^t_{i \to j} = (v_1, \ldots, v_n)$$

where v_k, $k = 1, \ldots, n$, is a value of an issue $x_k \in \mathcal{I}$.

Definition 2 (Agreement, Possible Agreements). . *An agreement is a proposal accepted by all the negotiating agents in $\mathcal{A}$. The set of possible agreements is:*

$$\mathcal{S} = \{(v_1, \ldots, v_n) \in \mathbb{R}^n : \ v_k \in D_k, \ for\ k = 1, \ldots, n\}$$

where v_k is a value of an issue $x_k \in \mathcal{I}$.

Negotiators should express their own preferences to rate and compare incoming offers and counter-offers. Let $\mathcal{I}=\{x_1,\ldots,x_n\}$ be the agenda and $\mathcal{D}=\{D_1,\ldots,D_n\}$ the set of issue domains. We consider that each agent $a_i \in \mathcal{A}$ has a continuous utility function, denoted as U_i. Accordingly, when the utility for a_i from one outcome is greater than from another outcome, we assume that a_i prefers the first outcome over the second.

Now, the additive model is probably the most widely used in multi-issue negotiation: agents determine weights for the issues at stake, assign scores to the different levels on each issue, and take a weighted sum of them to get an entire offer evaluation (see, e.g., [15]). Typically, each agent a_i defines a partial (or marginal) utility function for each issue at stake in negotiation, *i.e.*, a function that gives the score a_i assigns to a value of an issue x_k. The utility of an offer is then computed by adding the weighted scores together. For convenience, scores are often kept in the interval [0,1].

Definition 3 (Additive Utility Function). *Let $\mathcal{A}$ be the set of negotiating agents and $\mathcal{I}$ the negotiating agenda. The utility function U_i of an agent $a_i \in \mathcal{A}$ to rate offers and counter-offers takes the form:*

$$U_i(x_1,\ldots,x_n) \;=\; \sum_{k=1}^{n} w_k\, V_k(x_k)$$

where:

(i) *w_k is the weight of a_i for an issue $x_k \in \mathcal{I}$;*
(ii) *$V_k(x_k)$ is the (marginal) utility function of a_i for x_k, i.e., the function that gives the score a_i assigns to a value of an issue x_k.*

The additive model is simple and intuitive, but it is not suitable for all circumstances. In particular, the model assumes two types of independence:

1. *additive independence*: the utility of an offer is simply the weighted sum of the scores for all issues at stake;
2. *utility independence*: issue x is utility independent of the other issues on the agenda, if the preference order for outcomes involving only changes in the level of x does not depend on the levels of the remaining issues, provided that these levels are fixed.

The additive independence assumption is usually not acceptable when there are specific interactions among issues. For instance, two or more issues may be complementary, leading to a combined utility for an offer that is greater than the weighted sum of the individual scores. Also, two or more issues may be substitutable, in the sense that they can be substitutes of one another. The multiplicative utility function is the most well-known function handling these types of interactions among issues (see, e.g., [16,17]). It accommodates interdependencies by considering a specific interaction constant and interaction terms involving the multiplication of the weighted scores together. However, for it to be valid, every pair of issues must be utility independent of the remaining issues.

Definition 4 (Multiplicative Utility Function). *Let $\mathcal{A}$ be the set of negotiating agents and $\mathcal{I}$ the negotiating agenda. The multiplicative utility function U_i of an agent $a_i \in \mathcal{A}$ to rate offers and counter-offers takes the form:*

$$U_i(x_1, \ldots, x_n) = \frac{\prod_{k=1}^{n} [1 + w w_k V_k(x_k)] - 1}{w}$$

where:

(i) *w_k is the weight of a_i for an issue $x_k \in \mathcal{I}$;*
(ii) *$V_k(x_k)$ is the (marginal) utility function of a_i for x_k, i.e., the function that gives the score a_i assigns to a value of an issue x_k.*

The question at this stage relates to the degree to which preferences may be sensitive to the use of an additive rather than a multiplicative function. The question has important practical implications, as additive functions are clearly easier to understand and to construct. Reading of the literature suggests that in practice the use of an additive function is likely to be adequate in the vast majority of settings. Also, in practice, there are often many issues under consideration, but only a few are interdependent. Certainly, in complex negotiation settings where the additive function may be considered inappropriate, agents should use the multiplicative function. This seems to be the case of the present work, since agents negotiate prices and volumes of energy, variables that are interdependent.

3.2 Actual Negotiation and Strategies for Promoting DR

The actual negotiation process involves basically an iterative exchange or offers and counter-offers. The negotiation protocol marks branching points at which agents have to make decisions according to their strategies. In this work, we consider strategies for promoting demand response. The two agents have similar structure, but opposite preferences. Thus, the seller agent is equipped with a strategic behaviour that maximizes its benefit, while the end customer (buyer) is equipped with a strategic behavior that allows to minimize its cost, through DR actions.

Seller Strategy: Price Management. This strategy aims to maximize the benefit of a_s. The objective problem includes the price (P_k^s) proposed by a_s, the volume (V_k^b) proposed by a_b, and the cost of production (C_k). The mathematical formulation of the objective problem is as follows:

$$Maximize\ B^s = \sum_{k=1}^{n} (P_k^s - C_k) \times V_k^b \tag{1}$$

Subject to

$$P_k^s \geq C_k \tag{2}$$

The constraint expressed by (2) has the main goal of guaranteeing that the cost of production does not exceed the price of energy of a_s.

Buyer Strategy: Volume Management. This strategy was developed with the aim of enabling the end users of energy having a more active involvement in EMs. Specifically, the "Volume Management" strategy has the main goal of minimizing the energy cost of customers through DR actions. Thus, through this type of actions, customers can manage their energy consumption in response to high prices for different periods of the day.

Generally speaking, DR actions refer to the end-user customers participation in the EM and are seen as a response, from them, to the price variations of electrical energy over time. We consider that customers can respond to the variations of retailers' prices by transferring volume quantities from the periods when the prices proposed by a retail agent are high to the remaining hours.

Thus, this strategy consists in determining the prices and volumes of a_b. The volumes are determined through an optimization problem that aims to minimize the cost of a_b, including the prices (P_k^s) proposed by a_s, and the volumes (V_k^b) proposed by a_b. The mathematical formulation of the objective problem is as follows:

$$Minimize\ C^b = \sum_{k=1}^{n} P_k^s \times V_k^b \tag{3}$$

Subject to

$$V_{k_{min}}^b \leq V_k^b \leq V_{k_{max}}^b \tag{4}$$

$$\sum_{k=1}^{n} V_k^b = V_{tot}^b \tag{5}$$

The constraint expressed by (4) has the main goal of guaranteeing that the quantity of volume offered by a_b is in the range of its acceptable values. Also, the constraint (5) guarantees that the total quantity of energy (V_{tot}^b) remains unchanged, or in a range close to the initial value.

The optimization problem is resolved through a linear programming method called simplex using lp_solve, a Mixed Integer Linear Programming (MILP) solver.[1] lp_solve is a free linear (integer) programming solver based on the revised simplex method and the Branch-and-bound method for the integers. lp_solve solves pure linear, (mixed) integer/binary, semi-continuous and special ordered sets (SOS) models. Via the Branch-and-bound algorithm, it can handle integer variables, semi-continuous variables and SOS.

Beyond the volumes of energy, the customer also negotiates prices. The prices offered in a new proposal are obtained by the following formula:

$$P_{k_{new}}^b = P_{k_{previous}}^b + Ct \times P_{k_{previous}}^b,\ k = 1..n \tag{6}$$

where $P_{k_{new}}^b$ is the new price to send by a_b, $P_{k_{previous}}^b$ is the previous price sent by a_b, and Ct is a constant.

[1] `lpsolve.sourceforge.net`

4 A Case Study on Bilateral Contracting with DR

David Colburn, representing N2K Power (a retailer or seller agent), and Tom Britton, representing SCO Corporation (a customer agent), negotiate a 24-rate tariff in a multi-agent electricity market. Table 4 shows the initial offers and the price limits for the two negotiating agents, and also the load profile of the customer agent. Some values were selected by looking up to real trading prices associated with a pool market in an attempt to approximate the case study to the real-world. In particular, market reference prices were obtained by analysing the Iberian Electricity Market.[2] The minimum seller prices, i.e. the limits, were then set to these reference prices. Also, some energy quantities were based on consumer load profiles provided by the New York State Electric & Gas.[3]

Negotiation involves an iterative exchange of offers and counter-offers. We consider the following:

- Priorities are (indirectly) set for the prices of a_s and the volumes of a_b (higher values mean greater importance);
- Preferences are specified by using the multiplicative model;
- The customer submits the load profile;
- After receiving the load profile, the retailer submits the first proposal;
- The agents are allowed to propose only strictly monotonically—the customer's offers increase monotonically and the retailer's offers decrease monotonically;
- The acceptability of a proposal is determined by a negotiation threshold—an agent $a_i \in \mathcal{A}$ accepts a proposal $p^{t-1}_{j \to i}$, submitted by $a_j \in \mathcal{A}$ at $t-1$, when the difference between the benefit provided by the proposal $p^{t}_{i \to j}$ that a_i is ready to send in the next time period t is lower than or equal to the negotiation threshold;
- The agents are allowed to exchange only a maximum number of proposals, denoted by max_p.

Figure 1 and tables 2 and 3 summarize the results obtained. The results show that the agents reach agreement before the maximum limit of proposals, namely after the seller and the buyer agents sending six proposals (three proposals each). During the course of negotiation, the buyer agent adjusts the load profile using the "Volume Management" strategy, in response to the prices submitted by the seller agent, and simultaneously defines new values for the prices. Also, the seller agent adjusts the prices using the "Price Management" strategy (and accepts the load profile proposed by the buyer). Figure 1 shows the variation of both prices and volumes, considering the first proposal submitted and the final proposal accepted. Table 2 shows the cost values of the received and ready to send proposals of the buyer agent. Table 3 shows the agreed prices and the final load profile.

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[2] www.mibel.com
[3] www.nyseg.com

Table 1. Initial offers and price limits for the negotiating parties

	Consumer			Retailer	
Hour	Price (€/MWh)	Limit (€/MWh)	Energy (MWh)	Price (€/MWh)	Limit (€/MWh)
1	45.26	49.69	16.77	51.18	43.23
2	34.85	39.52	13.56	40.45	34.72
3	33.49	37.76	7.65	39.61	32.20
4	33.45	38.70	5.96	39.55	32.15
5	33.15	37.32	5.89	39.15	32.82
6	33.45	38.70	6.02	39.55	32.15
7	40.36	44.64	25.63	46.90	40.87
8	47.51	53.89	55.92	55.57	48.86
9	45.52	50.32	77.20	53.88	45.64
10	47.51	52.89	66.08	55.57	47.86
11	49.44	55.39	82.68	58.18	50.02
12	46.51	52.89	74.30	55.57	47.86
13	46.56	52.96	44.03	55.64	47.92
14	46.51	52.89	76.91	55.57	47.86
15	44.54	49.06	74.00	51.56	44.55
16	43.65	48.90	53.88	50.35	43.55
17	36.31	41.41	17.20	42.43	36.35
18	34.47	49.02	15.41	40.93	35.29
19	32.08	37.23	15.44	38.06	33.74
20	36.00	41.00	16.21	42.00	35.00
21	44.26	49.69	16.34	51.18	43.23
22	46.22	52.52	16.50	55.18	47.54
23	46.31	52.63	16.66	55.30	48.64
24	44.03	50.68	16.49	52.21	45.09

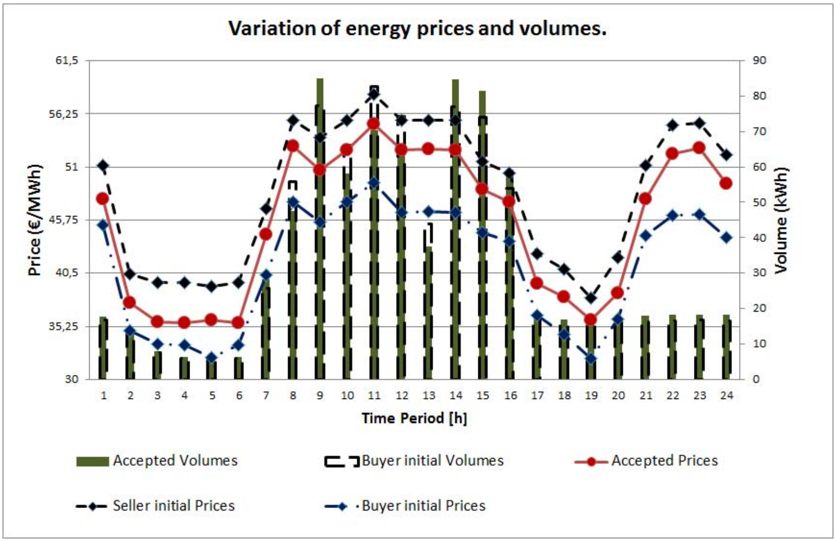

Fig. 1. Variation of energy prices and volumes

It is also important to mention, from the results, that the customer agent transferred quantities of energy from the market peak periods of greater importance, notably the periods 8, 10, 11, 12, and 13, to some periods for which the prices of the retailer agent are lower (see Figure 1). The cost of energy has proven to be minimal for the distribution of the volumes of the final proposal accepted. Furthermore, the retailer agent manages its prices by slightly reducing the price for the periods in which it has transferred a greater amount of energy. Accordingly to the results of the simulation, the negotiation ended when the retailer agent accepted the third proposal sent by customer, i.e. when the value of the buyers' Utility to send (U_{cmp}) showed to be greater than the value of the cost in the received proposal (U_{rcv}).

Table 2. Cost values of the received and new proposals of the customer

Cost (€)	1st Proposal	2nd Proposal	3rd Proposal
Received proposal	215,00	205,00	201,00
Ready to send proposal	179,00	195,00	200,00

Table 3. Case-Study final results

Hour	Price (€/MWh)	Energy (€/MWh)	Hour (MWh)	Price (€/MWh)	Energy (€/MWh)
1	47.87	17.61	13	52.72	37.43
2	37.61	14.24	14	52.65	84.6
3	35.65	8.03	15	48.75	81.40
4	35.60	6.26	16	47.57	59.27
5	35.85	6.18	17	39.48	18.92
6	35.60	6.32	18	38.13	16.95
7	44.28	28.19	19	35.86	16.98
8	53.08	28.19	20	35.86	16.98
9	50.64	84.92	21	47.87	17.97
10	52.65	58.05	22	52.29	18.15
11	55.20	70.28	23	52.83	18.33
12	52.65	63.15	24	49.36	18.14

5 Conclusion

This paper has presented several key features of agents with DR competence operating in a multi-agent electricity market. In particular, it has described a model for bilateral contracting with demand response, incorporating two negotiation strategies for DR management: a "Volume Management" strategy for a buyer agent and a "Price Management" for a seller or retailer agent. It has also presented the additive and multiplicative models for specifying the preferences of the agents over the negotiation outcomes. Furthermore, it has presented a case study on bilateral contracts involving a retailer and a customer of energy negotiating a 24h-rate tariff.

The simulation results, obtained with the new strategies and the multiplicative model, support the belief that the behavior of market participants is as expected in managing energy prices and volumes. They also confirm the belief that the simulation tool currently being developed can be important to help the decision process of the two parties during the negotiation of bilateral contracts in competitive EMs with demand response. In the future, we intend to perform a number of inter-related experiments to empirically evaluate the key components of the bilateral contracting model, notably the DR management strategies.

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