Multi-agent Simulation of Electricity Markets
Economically-Motivated decision-making

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Abstract—The key motivation for this research is the perception that within a near future the electricity market will be composed of individuals that may simultaneously undertake the roles of consumers, producers and traders of electricity. Those individuals are economically motivated “prosumer” (producer-consumer) agents that not only consume, but can also produce, store and trade electricity. Therefore, as the prosumer agents follow their economically motivated goals (e.g., aiming for profit) they will also experience different forms of power (e.g., market power) and their social relations (e.g., dependencies) will mutually influence their decision-making processes. This paper describes the most relevant aspects of a simulation tool that provides (human and virtual) prosumer agents an interactive and real-time game-like environment where they can explore (long-term and short-term) strategic behaviour and experience the effects of power and social influence in their decision-making processes. The work on the quantitative description of power and influence concepts, is described and details are provided throughout an illustrative example.

Keywords—Electricity Market, Economic Interactive Simulation, Multi-agent Systems, Coalition Decision-Making, Power, Influence.

I. INTRODUCTION

The organizational structure of the electrical power industry has been completely altered over the two last decades. The traditional organization used to follow a heavily regulated perspective with a single nation-wide electric power company owning the whole infrastructure from generating stations to transmission and distribution facilities. Such monopolistic-market approach has been gradually deregulated and the modern organization is that of a liberalized market. A major economic rationale for the liberalization of the electricity industry was the vision of lower prices and more efficient power generation (and consumption) through market competition. A key assumption behind such rationale was that the power generation (after being separated from the power distribution) would endow competitive markets, rather than markets in which small numbers of firms exercise market power. The directives for an energy market where competition is to be achieved within a fair and transparent environment were settled by the current European Directive [1].

The behavior of markets depends on the participants’ economical motivation, but the electricity market is too complex for the analytical game-theoretic analysis. Therefore it is of utmost importance to develop simulation and prediction tools where the observations of all the agents’ plays are used to compute estimates for the utility of their strategies. This follows the “empirical game simulation” approach [2] where, despite the lack of an analytic game formulation, agents evolve within a strategic scenario, at a practical level of abstraction, such that the analysis is computationally feasible and the game-theoretic concepts can still be explored.

This paper describes a game-based simulator, named ITEM-game (“Investment and Trading in Electricity Markets”), where human and virtual agents can explore the investment and trading strategies for the electricity market. The ITEM-game was implemented as a derivation from the previous TEMMAS (“The Electricity Market Multi-agent Simulator”) simulator [3]. The main difference between both simulators (TEMMAS and ITEM-game) is that, while TEMMAS follows a machine (reinforcement) learning method to autonomously search for a (near optimal) competitive trading (pool bidding) strategy, the ITEM-game is designed for humans to explore investment and trading strategies. Thus, the ITEM-game is an interactive tool and has already been played several times in classroom competitions with (human) participants organized in teams, each representing a power company, that compete in a simulated market environment where investment and trading decisions are made interactively [4]. This paper also describes the initial ideas on extending the ITEM-game with the concepts of social power and inter-agent influence. The integration of quantitative metrics of social power and influence is provided for players to foster strategic coalitions.

II. THE ELECTRICITY MARKET ENVIRONMENT

The vision of a competitive energy market was initially driven by the availability of cheap energy derived from fossil fuels (originally coal, then oil, and more recently natural gas). However, the unlimited availability of cheap fossil fuels (mainly oil) cannot be taken for granted as its increasing demand may outstrip our ability to explore and produce such energy within manageable price increases (named “peak oil” effect) [5]. Additionally, the “fossil fuels assumption” has also been hindered by a growing consensus on the long term
impact of carbon emissions (from burning fossil fuels) which suggests that even if the “peak oil” is avoided, and energy security assured, a future based on fossil fuel will expose regions of the world to damaging climate changes that will turn the lives of the world’s poorest people even harder [6].

The future tendency for crude oil and other fossil fuel prices (gas, coal and fuel oil) to move quickly and follow one another will strengthen due to the substitutability of the four products in the heating and electricity markets. Moreover, gas increasingly serves as an oil substitute in the generation of electricity, and the amount of fuel-gas in the electricity market is approaching that of oil due to a stiffer competition from alternative technologies in the electricity market.

Therefore, there is a world-wide shift towards a low carbon economy where electric motors (free from internal fuel combustion) pervade the transportation industry (e.g., personal vehicles, high speed trains) and the increasing demand for renewable power generation calls for a huge amount of such generators, distributed across both the transmission and distribution networks. The current scenario of a grid where electricity flows one-way from producers to consumers is making the first moves towards a network of prosumer agents that both produce and consume electricity according to their individual profiles, thus giving rise to flows of electricity that continuously vary in magnitude and direction [7].

The combination of both the prosumer and the market perspectives opens a space for those companies and individuals that intend to make long-term investment decisions (acquire generation or storage capacity) and to explore short-term strategies on trading (selling or buying) the electricity asset. Hence, prosumers will be able to act (sell and buy) in the market not simply either as producer or a (close to price agnostic) consumer, but also aiming for the profit.

Therefore, each prosumer agent (or simply, agent) will need to be endowed with effective (long-term) investment and (short-term) trading strategies that can cope with the technical, economical and risk characteristics of the electricity market. A multitude of simultaneous strategies are applied at well-known decision epochs (e.g., daily spot market) and several economical and technical measures (e.g., market share, individual profit, capacity share, system reserve) form the observation space that feeds the next decision epoch.

The over-time repeated decision-making is well suited for the emergence of power and influence relations among agents.

The tendency towards some form of market-power gives a rationale for the formulation of power and influence relations among agents. The evidence of such relations can be used by agents to (re)evaluate their individual strategies. While some prosumers may try to settle local agreements, and resort to cooperative game-theoretic solutions, others will act directly in the market with a purely competitive (non-cooperative) approach. This raises the prospect that the investment and trading in electricity markets will become a daily decision-making process widely deployed in a huge number (possibly millions) of prosumer agents each reacting to prices, to individual preferences (e.g., demand profiles) and to economical, technical and power measures.

III. THE ITEM-GAME DESIGN

The ITEM-game explores the main features of liberalized electricity markets and the challenges faced by the agents in their long-term investment decisions and in their short-term trading strategies. Each ITEM-game player represents a generator company that pursues a profit maximization strategy. The investment and trading decisions are made interactively among players using a market simulator platform. The results of the game are based on the profit of each player, which results from the income of selling the electricity (produced by their generating units) in the power Pool and the costs associated with the generation, including variable costs (fuel, CO2 emissions) and fixed costs [8].

A. Investment

The ITEM-game supports long-term investment on generating units from a set of technologies, such as, nuclear, coal, and gas thermal power plants; hydro (not including pumping), wind and photovoltaic renewable power plants.

Each generating unit’s technology is described both by its price and its technical properties, such as, its total generation capacity, efficiency (ratio between energy production and fuel consumption) and CO2 specific emissions.

Each generating unit follows a 3-stage life cycle:

i. construction – the period (e.g., number of years) from investment to effective electricity production; this stage starts immediately after the agent’s decision to invest on this unit,

ii. operation – the period (e.g., number of years) of effective electricity production; this stage starts immediately after the ending of the previous (construction) stage,

iii. decommission - the date (e.g., year) from which the unit finishes producing electricity; this stage starts immediately after the ending of the previous (operation) stage.

Fig. 1 presents (in the top) a hydro generating unit with a total generation capacity of 100 MW, efficiency is 35%, the specific emissions is 0 ton CO2/MWh and the price is 50 M€. The Fig. 1 also depicts (in the middle) the hydro 3-stage life cycle; starting from investment decision we have 3 years (including the investment’s one) for construction, followed by 8 operational years and finally, at the 11th year after the investment decision, the unit is decommissioned.

An investment is a long-term decision, e.g., the hydro’s 11 years life cycle (cf., fig. 1). Its purchase price represents a fixed cost (amortized) during all the operation stage’s duration. Additionally, during the unit’s operation stage its generation capacity is available for trading.
Therefore, we have:

- power supply system comprises a set of GenCos,
- GenCo is an agent represented by a (human) player,
- GenCo contains its set of generating units, GenUnitGenCo,
- each GenUnitGenCo is described by a set of properties,
- each set of properties includes cost and capacity information,
- market operator, Pool, eval bids and settles market price.

The submission of bids (to Pool) conforms to the so-called “block bids” approach [9], where a block represents a quantity (MW) of energy being bid for a certain price (€/MWh). Also, there usually exists a regulatory price cap constraint (i.e., maximum allowed price), so that any bid price is always kept below a predefined cap value. Thus, a bid, b, is described by the vector,

\[ b = \langle \text{GenUnitGenCo}, \text{quantity}, \text{price} \rangle, \text{where price} \leq \text{cap}. \]

The fig. 2 shows the ITEM-game graphical interface that (human) players may use to submit their bids. The example shows two CCGT (Combined Cycle Gas Turbine) block bids (200 MW and 100 MW) and, possibly, a third bid (of 900 MW) being “prepared” to join the other two bids.

Each supplier (GenCo) submits bids to the Pool to sell electricity (cf. b vector above). The Pool aggregates the quantities (MW) of equal-price (€/MWh) bids and forms a non-decreasing incremental price curve. The market clears (accepts) the lowest price bids that are sufficient to satisfy the demand. The market price, mkP, corresponds to the highest price accepted in the market. All GenCo in the market (i.e., with cleared bids) will sell their energy at the mkP value.

### IV. DEPENDENCE METRICS AND COALITIONS

Given a marginal market price, mkP (i.e., the market price computed from marginal cost bids), a strict evaluation of the Lerner index [10] gives a positive value for bids below mkP and a zero value for the mkP bids. We take such strict evaluation to argument that mkP bids have a high motivation to increase the mkP value (and thus augment their market power). By doing so they will also increment the market power of the lower marginal cost bids, which calls for an equilibria analysis to be taken from each agent’s (bid aggregation) perspective. Nevertheless, we take the bid’s basic motivation (depart from zero Lerner index) as we intend to identify and develop the primary tools that will enable to achieve more sophisticated analysis.

Assuming that all agents, with at least one zero-valued Lerner index bid, have the goal to increase the mkP, they need to evaluate the possible coalitions that provide the power (quantity) required to achieve that goal. Given a set of zero-valued Lerner index bids and the common intention to augment the market price (thus, the market power) there are two possible power-of scenarios (that may coexist):

- at least one bid has power-of to increment the market price,
- at least one bid does not have such power-of.

The exhaustive construction of coalitions (given a set of bids, B, and a minimum quantity, q_{min}) enables to classify each bid (within each coalition) according to its power-of scenario.

The influence of a bid, b, is a measure of the dependence of all the other bids regarding b; i.e., the influence of b increases as more coalitions depend on b. Therefore, given a set of coalitions, SoC, a simple metric to express the influence of a bid, b, is its coalition frequency, cf(b, SoC), described as:
The influence of the 1-coalition bid, \( b \), is described as the inverse of the total number of such coalitions and corresponds to the special case, of \( c_f \), given by,

\[
c_f(b, \mathcal{S}oC) = \frac{\sum_{\mathcal{C} \in \mathcal{S}oC} I(b, \mathcal{C})}{|\mathcal{S}oC|}, \quad \text{where } I(b, \mathcal{C}) = 1 \text{ if } b \in \mathcal{C}, \ 0 \text{ otherwise.}
\]

Both the \( c_f \) and \( c_f_1 \) metrics are computed from each bid’s perspective. An agent aggregates several bids and therefore an agent’s, \( ag \), overall influence may be simply evaluated as the average of \( c_f \) (or \( c_f_1 \)) of the bids generated from the \( ag \)’s own portfolio. A portfolio distribution (among \( GenCo \) agents) implicitly defines an ordered (from lowest to highest) list of marginal cost bids. As an example, Fig. 3 shows the bidList generated after the ag1 and ag2 portfolios; e.g., the bidList lowest bid is a 3.0 €/MWh offered for the 25 MW from the generating unit u1 of generator company ag1.

To simplify the example we consider that there is no demand-side market bidding. Therefore, given a bidList and a demand value \( q \) the market price is the minimum price offer that satisfies the demand, described as,

\[
mkP = \min \left\{ p \in \mathcal{P}(\text{bidList}) \mid \left(\sum_{i \leq p} \sum_{q \in \text{quantity}_i} q \geq Q \right) \right\}
\]

where, \( \mathcal{P}(\text{bidList}) \) is a set that contains all the price offers in bidList and the quantity, \( q \), is a set with all the i-priced quantities in bidList. In Fig 3, for given bidList and a demand \( Q = 100 \) we have \( mkP = 6.0 \).

\[
\text{Fig. 3. An example – the ag1 and ag2 bids.}
\]

\[
\text{bidList} = \begin{bmatrix}
3.0, 25, u1.ag1 \\
3.0, 15, u1.ag1 \\
3.0, 5, u1.ag2 \\
6.0, 40, u2.ag1 \\
6.0, 25, u2.ag1 \\
6.0, 5, u2.ag1 \\
6.0, 15, u2.ag2 \\
7.0, 10, u3.ag1 \\
7.0, 10, u3.ag2 \\
7.0, 15, u3.ag2 \\
8.5, 15, u4.ag2 \\
8.5, 5, u4.ag2 \\
9.0, 50, u5.ag1 \\
9.0, 20, u5.ag1 \\
\end{bmatrix}
\]

Fig. 4 (evaluation output), shows that \( Q = 100 \) MW implies a market price \( mkP = 6.0 \) €/MWh. The aggregate quantity of all the cleared bids is given by \( q_{agg} = 135 \) MW and so the minimum quantity that motivates a joint intention (to increase \( mkP \)) is given by \( q_{\text{min}} = q_{agg} - Q = 35 \) MW. Fig. 4 also shows the detail of all bids that will get involved in the coalition evaluation process; i.e., each bid, \( b \), such that price(\( b \)) = \( mkP \).

\[
\begin{align*}
Q &= 100 \ [\text{MW}] \\
\Rightarrow \quad mkP &= 6.0 \ [\text{€/MW}] \\
q_{agg} &= 135 \ [\text{MW}] \\
\Rightarrow \quad q_{\text{min}} &= 35 \ [\text{MW}]
\end{align*}
\]

\[
\begin{bmatrix}
6.0, 40, u2.ag1 \ \\
6.0, 25, u2.ag1 \ \\
6.0, 5, u2.ag1 \\
6.0, 5, u2.ag2 \\
6.0, 15, u2.ag2 \\
6.0, 40, u2.ag1 \\
6.0, 5, u2.ag2 \\
6.0, 15, u2.ag2 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
6.0, 5, u2.ag1 \\
6.0, 40, u2.ag1 \\
6.0, 5, u2.ag2 \\
6.0, 15, u2.ag2 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
6.0, 5, u2.ag1 \\
6.0, 40, u2.ag1 \\
6.0, 5, u2.ag2 \\
6.0, 15, u2.ag2 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
6.0, 5, u2.ag1 \\
6.0, 40, u2.ag1 \\
6.0, 5, u2.ag2 \\
6.0, 15, u2.ag2 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
6.0, 5, u2.ag1 \\
6.0, 40, u2.ag1 \\
\end{bmatrix}
\]

Fig. 5 show the set of coalitions, \( \mathcal{S}oC \), that are generated given the \( mkP \) bids and the \( q_{\text{min}} \) value (cf., Fig. 4); each coalition is (graphically) framed by an upper and a lower horizontal lines. For example, Fig. 5 the second coalition considers 25 MW from \( u2.ag1 \) and 15 MW from \( u2.ag2 \). There are 7 possible coalitions; the bid \( b = 6.0, 40, u2.ag1 \) is the only one with the power-of to increment the market price.

The Fig 6. shows the \( c_f \) and \( c_f_1 \) evaluation of the influence metrics. For example, the bid \( b = 6.0, 40, u2.ag1 \) has both the power-of to increment the market price and the highest influence value (i.e., \( c_f = 71.4% \)) regarding all the others’ bids perspective on possible coalitions. Also, the 15 MW bid is as influential as the lowest-quantity bids (5 MW).

\[
\begin{bmatrix}
6.0, 40, u2.ag1 \ \\
6.0, 25, u2.ag1 \ \\
6.0, 15, u2.ag2 \\
6.0, 5, u2.ag1 \\
6.0, 5, u2.ag2 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
6.0, 5, u2.ag1 \\
6.0, 40, u2.ag1 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
6.0, 5, u2.ag1 \\
6.0, 40, u2.ag1 \\
6.0, 5, u2.ag2 \\
6.0, 15, u2.ag2 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
6.0, 5, u2.ag1 \\
6.0, 40, u2.ag1 \\
6.0, 5, u2.ag2 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
6.0, 5, u2.ag1 \\
6.0, 40, u2.ag1 \\
\end{bmatrix}
\]

Fig. 6. The \( c_f \) and \( c_f_1 \) influence metrics (for the example).

The Fig. 7 shows an overall perspective of each agent’s influence. An agent, \( ag \), aggregates a set of bids; hence, we take the subset of bids that belong to \( ag \) and consider such set’s \( c_f \) average as the estimated value for the \( ag \)’s influence. This overall influence metric gives a simple ranking criterion for agents to reason about possible coalitions and their position in the negotiation processes.

\[
\begin{align*}
ag1 &= 47.6\% \\
ag2 &= 28.6\%
\end{align*}
\]

Fig. 7. Influence (for the example).

This illustrative example details each step of our approach taking the electricity market motivation. The approach is not confined to the electricity market case study; for example, the “bid-quantity” value is an immediate extension point that can be generalized to any agent-specific quantitative evaluation function. Despite that, we intend to deepen our research (validate our assumptions) using this case study domain and to extend the ITEM-game platform to the inter-agent negotiation context prior to further generalization of the model.
V. RELATED WORK

The research on MABS for electricity markets can be grouped in three main categories: i) market design analysis, ii) modeling of the agents’ decision-making processes, and iii) a mixture of the two previous categories. The “market design analysis” describes a market by the behavioral correlations among agents. A pioneer work [11], simulates a uniform price market clearing model where generation companies are profit maximizers who assume that competitors bid the same supply function as in the previous day. The model is explored in a case study [12], to analyze whether two generation companies increase their profits by manipulating market prices above marginal cost; results showed that to profitably manipulate prices both companies would have to act together. Another work [13], distinguishes market power from situations where technical constraints might have raised prices. The “modeling of the agents’ decision-making processes” early research [14] describes the use of a genetic algorithm to optimize multiple bidding rounds for a one-time period of electricity deliveries. Another work [15], simulates buyers and sellers bidding on a double-auction market to analyze the impact of agent learning of market outcomes for bidding at marginal cost or revenue.

Research on both the “market design analysis” and the “modeling of the agents’ decision-making processes” are complementary to ours; they provide results and methods to explore and (possibly) extend and incorporate in the ITEM-game simulator. Approaches of both “market design analysis” and “modeling of the agents’ decision-making processes” are usually described as market simulation framework. The AMES (Agent-based Modeling of Electricity Systems) [16] is targeted to small and medium markets and uses learning agents (Variant Roth-Erev algorithm). The user can choose whether to use the learning agents but cannot choose (neither define) any bidding strategies. The AMES is implemented in Repast (Recursive Porous Agent Simulation Toolkit), which does not support distributed virtual agents with goals, communicative needs and behavioral capabilities. The most adopted simulator is the EMCAS (Electricity Market Complex Adaptive System) [17] that incorporates spot and bilateral markets and different levels of reserve for grid regulation. The consumer agents can switch their supplier or change their demand. The supply (power plants owners) decides on bidding strategies. Agents are maximizers of a multi-objective utility function that includes risk preferences, profit and market share; the goals are represented by a minimum and maximum expected value, and a risk preference. The EMCAS generates a price forecast based on data imported from external providers (electric system and historical prices); this information is used to calculate the expected utility of a given strategy. We remark that the commercial EMCAS system is being used by EDP (“Electricidade de Portugal”) to analyse the Iberian Electricity Market (MIBEL) [18]. The EMCAS is a commercial system and it is implemented in Repast, which is a stand-alone simulation environment (tailored to analyze the evolution of simulation parameters), where all agents reside in the same memory space. Hence, Repast is non-FIPA compliant as agent communication is based on memory sharing. Additionally, Repast is not suited for dynamically integrating human interaction during the simulation.

VI. CONCLUSIONS AND FUTURE WORK

This paper describes our work in the construction of a MABS framework to describe and explore the investment and trading dynamics of the electric power market. We used the proposed MABS framework to support the construction of the ITEM-game agent-based electricity market simulator.

The MABS framework was extended to include the social power concepts (ascribed as power-of and collective-power-of) along with a quantitative interpretation of such abstract concepts. Those concepts and the related quantitative metrics are the primary tools that agents can use to define (or re-evaluate) strategies for coalitions’ (re)formation. The market’s rational for a coalition is often related with the market power (or monopolistic-path) perspective. Hence, the combined integration of those elements (power, dependence, coalition) aims for a highly realistic game-like market simulator. This high-realism goal is a key guideline within our research effort and clearly distinguishes our proposal from the “would-be world” (or “toy-model”) approaches.

We intend to research new ways of augmenting the agent’s individual decision-making model with tools that foster everyone’s negotiation capabilities and thus disseminate the collective-intelligence perspective within electricity markets.

REFERENCES


