ELECTRICITY MARKET AND RENEWABLE ENERGY INTEGRATION: AN AGENT-BASED CONCEPTUAL MODEL

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ABSTRACT

The emergence of electricity markets and the opportunities consequently created have radically modified the operation planning activities of Power Systems. As direct result, there is the need for developing new methods to meet in an efficient way the requirements of generation companies, so to respond adequately to new challenges such as market competition. Agent-based models have been proposed in the literature as surrogate to equilibrium models when the problem is too complex to be addressed within a traditional equilibrium framework. Driven by this trend, this paper discusses and proposes a conceptual model following the agent paradigm that deals with the inherent complexity of electricity markets. The devised model proved to be robust enough to represent key features of our study domain and is ready to be actually developed in a computational tool to help generation companies to build their short-medium term operation decisions in a more sounded and robust way.

Keywords: Electricity market, agent-based modeling, hydro-pumping generation

1. INTRODUCTION

The optimization of power generation systems is an area that was and still remains a continuous concern for electricity companies, as well as for researchers who are dedicated to this subject (Gomes 2007). However, the emergence of electricity markets in an industry as traditional as it is the electricity sector, and the business and production opportunities created by them, have radically modified the operation planning activities of Power Systems. As a direct result there is a need to develop simulation models to forecast efficiently the operation of electricity generation companies, so that they respond in an efficient way to the new market challenges.

Since the 80th of the last century, there was a large investment in renewable energy sources worldwide. Nevertheless, these sources due to their high volatility create several problems for the management of networks and power plants, as well as for the management of electricity markets. The use of renewable energies not only allows a slow rising or even a decline of CO2 emissions, but also allows a larger independence of mankind from fossil fuels such as oil and coal.

Having in mind these ideas, the main goal of this paper is to describe an agent-based conceptual model for the Portuguese/Spain Electricity Market (MIBEL) in order to study the operational short-medium decisions of the generation companies in the day-ahead markets with more information, in a competitive environment and with a large penetration of renewable energy sources. In this scope, the modeling of hydro power plants with pumping capability is one of the main objectives of this work.

The related literature has been growing rapidly in recent years, and many different modeling approaches, such as mathematical programming, game theory, and agent-based models have been investigated and used under a liberalized market environment (Li, Shi and Qu 2001). With the recent growing of renewable energy sources, especially in Europe, electricity markets are facing more complex problems and increased risks namely due to the connection of volatile renewable sources. The intermittence of some of these renewable sources motivates the players to optimize their bidding strategies by considering new challenges (Li, Shi and Qu 2001).

This paper is organized as follows. Section 2 presents a brief description of the power system market under study, and the motivation of the proposed work. Section 3 briefly overviews some works related with the simulation of electricity markets. Section 4 discusses the proposed conceptual agent based market model and Section 5 presents the final remarks.

2. ELECTRICITY MARKET DESCRIPTION

In the following subsections the electricity market structure and organization is presented and the new paradigms are discussed.

2.1. New Structures and the Unbundling Model

To allow a suitable implementation of the electricity sector liberalization, significant modifications are needed in the traditional system. In this context, electricity shall be regarded as a product whose sellers can be chosen by buyers, within certain rules. In this new framework, companies are seen as services providers and the grids correspond to the physical locations where electricity markets are established. On the other hand, in order to ensure that the whole system operates properly, independent entities, both at a technical and at a regulatory level) are required. The electricity sector restructuring originated the unbundling of the traditional vertically integrated companies and the creation of a disaggregated structure that involves multiple actors.

Figure 1 introduces the new model of the electricity sector (Saraiva, Silva and Leão 2002).

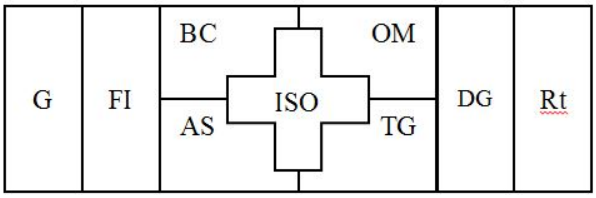

Figure 1: Desegregated Model of Electricity Sector (adapted from (Saraiva, Silva and Leão, 2002))

In this figure it is possible to identify some competitive activities: Generation (G), Financial Intermediation (FI) and Retailing (Rt). On the other hand, the Distribution Grid (DG) operates as a regulated monopoly because it is not economically feasible to duplicate distribution networks in the same geographical area. The central part of this scheme corresponds to a set of functions that were usually assigned to the transmission system. These activities include the Bilateral Contracts (BC), Organized Markets (OM), the System Operator (ISO), the Transmission Grid (TG) and the Ancillary Services (AS).

The Bilateral Contracts are characterized by the establishment of bilateral financial or physical relations between generation entities, on one side, and eligible customers or retailing agents on the other. These contracts involve several aspects as the price and energy to be supplied and consumed over a specified period of time.

Electricity markets (OM) typically correspond to a set of activities organized along time and usually starting the day before operation and continuing along the operation day. These activities are typically associated with the daily markets and the intraday markets. In case they coexist with bilateral contracts, there is what we can call a mixed model (Saraiva, Silva and Leão 2002).

Organized Markets receive bids to buy and sell electricity, typically for every hour or half hour for the next day (Day-Ahead Markets). These bids normally include power values and price (minimum amount to receive in the case of selling bids and maximum value to pay in the case of buying bids). These markets build aggregated demand and supply curves and their crossing point lead to the cleared quantity and the cleared price for each time step of the next day (Saraiva, Silva and Leão 2002). This also means that the Market Operator in charge of these day-ahead markets are responsible for obtaining a purely economic dispatch since network constraints are not yet considered until this point. There are also forward markets that include transactions of electricity blocks with subsequent delivery after day-ahead markets (futures), of physical liquidation or by differences. These markets are, in practice, derivative product markets in which the underlying asset is electricity and that can be used as a way to address the risk inherent to this short-term operation markets.

The Independent System Operator (ISO) is the entity in charge of the technical coordination functions to ensure the safe and reliable operation of the power system. For this purpose, the ISO should receive information on the economic dispatch built by the Market Operator, as well as information related to the Bilateral Contracts in terms of network nodes and powers involved. The ISO should therefore evaluate the technical feasibility of the dispatch for each time step of the next day taking considering the network constraints. If congestion occurs given the received dispatch information, the dispatch is not feasible and it is necessary to adopt a correction mechanism. If there are no limitations, the system operation is feasible from a technical point of view. In this case, the ISO sets the amounts of ancillary services and procures them given that some of them are typically mandatory while some other are contracted in specific markets. In some cases the ISO and the Transmission Grid (TG) are under the responsibility of the same entity. In this case, it takes the name of TSO (Transmission System Operator) as it happens in Portugal (REN) and in Spain (REE).

The Transmission Grid (TG) represents the entity that owns or has the concession of the assets of the transmission network and that, for economic reasons, operates in terms of a natural monopoly in the geographical area in which it is implemented. These companies, like the distribution network companies, are remunerated through network usage charges and the regulatory authorities regulate their activities.

For the safe and reliable operation of the power system it is necessary to contract several ancillary services (AS), e.g. primary, secondary and tertiary reserve and others. Ancillary Services can be mandatory or can be contracted in specific markets in which the System Operator determines the amount to be contracted and accepts bids for their provision.

This organization corresponds to the most disaggregated design with various activities associated with the generation, transmission, distribution and electricity trading. In many countries, several of these activities are grouped, as it is the case of the countries where the ISO and TG activities are merged in a TSO.

Taking into account the organization detailed above, markets can be classified according to the type of good/service that is traded and according to the temporal bases (Pereira 2004). In the context of this paper and regarding the traded goods, we can consider:

- Energy Markets: where electricity is traded between sellers and buyers, through a centralized mechanism, operating as a spot market, and/or through contracts directly established between buyers and sellers (Bilateral Contracts);
- Ancillary Services Markets: where some ancillary services are contracted, given that they are required for the secure operation of power systems with adequate standards of quality, safety and reliability. Such services include the frequency control, primary, secondary and tertiary reserves, reactive power/voltage control and black start. In some countries, some of these services are contracted by ISO's or TSO's in specific markets.

Taking into account the temporal aspects, we can consider:

- Spot market: a market that operates on a daily basis and which aims at negotiating energy for each hour or half an hour of the next day (also known as Day-Ahead Market);
- Intraday markets – these type of markets are intended to eliminate the existing imbalances between supply and demand and can be used by market agents to contract (buy or sell) electricity, typically in smaller quantities than in the day ahead market;
- Derivatives/Forward Markets: they deal with future contracts and options, which in essence are financial instruments intended to minimize the risk associated with the volatility of the price of short-term markets;

Planning markets – usually used to trade electricity blocks with longer-term delivery periods.

2.2. Power System Organization in Iberia

The power systems in Portugal and Spain went through several changes in recent years. It started with a centralized model, with vertical companies that were responsible for generation, transmission and distribution of energy. However, in the last decades there has been a change on the priorities regarding policies concerned with environmental sustainability, competitiveness and security of energy supply, especially in Europe. For this reason, and in line with the European Electricity Directives, Portugal and Spain implemented the Iberian Electricity Market (MIBEL), which is fully operational since July 2007. Nowadays, it is possible to organize the Iberian power system in five key activities, developed independently, which are:

- Generation;
- Transmission and System Operation;
- Distribution;
- Retailing;
- Organized Markets.

Generation and Retailing activities are carried out under free competition by the assignment of a license and Transmission and Distribution activities correspond to public regulated concessions, assigned by the state to specific companies. There are also two regulatory agencies for the energy sector, one in Spain and another in Portugal.

2.3. MIBEL electricity market organization

As mentioned before, markets can be classified according to the type of traded goods/services and to the temporal bases on which they operate. As for goods/services we can classify them as Energy Markets, Ancillary Service Markets and Transmission Markets. Taking into account the temporal basis, they can be also classified as Spot market, Intra Day Markets, Derivatives/Forward Markets and Planning Market. These markets can be voluntary or mandatory. The MIBEL market model is a mixed one, given that it includes a pool based market plus bilateral contracts, and it comprises two distinct geographical areas from the operation point of view, Portugal and Spain, each one under the responsibility of the respective Transmission System Operator (TSO). Figure 2 illustrates the MIBEL market model. There are also two regulatory entities, ERSE is the Portuguese regulatory agency for the energy services and CNE is its Spanish counterpart.

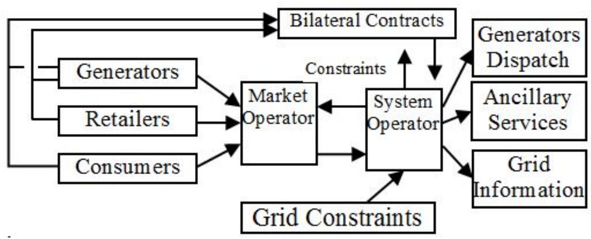

Figure 2: Mixed Model including Spot Market and Bilateral Contracts (adapted from (Li, Shi and Qu 2001))

2.4. The new paradigm and motivation

The emergence of electricity markets and the increase of renewable energy sources in an industry as traditional as it was the electricity sector, and the opportunities created by these markets have radically modified the operation planning activities of Power Systems. As a direct result, there is a need of developing new models and applications to meet in an efficient way the requirements of generation companies, so that they respond adequately to these new challenges, namely competition.

As for the electricity markets, it is necessary to understand the behavior of all its participants, and also the impacts coming from the increasing presence of renewable sources. Associated with this issue, hydro generators with pumping capability play an important role because of their storing capacity. Such generators have unique dynamic characteristics such as fast start-ups and fast response to load variations.

Due to their pumping capability, they have dual nature. They can participate in the market either as buyers, consuming electricity to pump and store water, or they can act like generators or sell electricity in the market. This propriety also gives them advantages regarding the participation in the ancillary services markets. It is in this framework that this work aims at contributing, namely modeling hydro power plants with pumping capability in the decision of bidding in energy and ancillary services markets.

3. ELECTRICITY MARKET SIMULATION OVERVIEW

3.1. Simulation Methods

A large number of research works have been dedicated to model liberalized electricity power systems. From an organization point of view and according to the literature review that was carried out, electricity market modeling can be classified in four main areas (Li, Shi, and Qu 2001):

- Optimization problems, addressing a single company;
- Equilibrium Models from Game-Theory-based economics, considering a larger number of competitors;
- Agent-Based Models that simulate the behavior of the companies and the interactions between autonomous agents;
- Hybrid solutions.

Optimization models are centered in profit maximization problems for a single firm competing in the market, often considered as a price taker, while Equilibrium Models represent the market behavior taking into consideration the competition between all participants. Agent-Based Models are increasingly an alternative to equilibrium models that becomes interesting when the problem is too complex to be addressed within a traditional equilibrium framework. Agent-based computational economics (ACE) is the computational study of dynamic economic systems modeled as virtual worlds of interacting agents (Yu and Yuan 2005).

3.2. Models using ABM

Agent-Based Modeling (ABM) is a recent and evolving research paradigm, based on agents that allow developing models to represent in more realistic way electricity markets, and overcomes some disadvantages of other approaches. In ABM, each agent can build its optimal bidding strategy taking into account past experiences obtained from the direct interaction with the environment and with other agents. In practice, these agents can learn from past decisions, improving their new decisions thus adapting their strategies. In ABM, the players usually have imperfect and local information.

In (Omicini, Ricci and Viroli 2008), the authors support the idea that agents in a multi-agent system (MAS) are surrounded objects (tools or instruments) and services that affect their policy selection by shaping their surrounding environment. For this reason they propose a unifying abstraction that can be used to model and engineer the world around agents of a MAS model. Based on such conceptual foundations they discussed a MAS-based meta-model that is characterized in terms of three basic abstractions:

- Agents, to represent pro-active components of the systems, encapsulating the autonomous execution of some kind of activities inside some sort of environment;
- Artifacts, to represent passive components of the systems such as resources and media that are intentionally constructed, shared, manipulated and used by agents to support their activities, either cooperatively or competitively;
- Workspaces, as conceptual containers of agents and artifacts, useful for defining the topology for the environment and providing a way to define a notion of locality.

There are some works addressing this issue. AMES (Agent-based Modeling of Electricity Systems) is open-source software developed by an interdisciplinary group of researchers at the Iowa State University. It allows developing strategic trading behaviors within restructured wholesale power markets operating over realistically rendered AC transmission grids (Li and Tesfatsion 2009). This software can be used to simulate the day-ahead market and the real-time market and considers the AC transmission grid and the system operator activities.

EMCAS (Electricity Market Complex Adaptive Systems) is commercial software developed by the Argone National Lab and is one of the most popular ABM for the simulation of Electricity Markets. It considers the physical structure of the market and it has the capability of taking decentralized decision-making along with learning and adaptation for agents. It uses the VALORAGUA model to include the hydro generation (Thimmapuram et al. 2008). Whereas EMCAS provides a framework to simulate deregulated markets with flexible regulatory structure along with bidding strategies for supply offers and demand bids, VALORAGUA provides longer-term operation plans by optimizing hydro and thermal power plant operation for the entire year. In addition, EMCAS uses the price forecasts and weekly hydro schedules from VALORAGUA to provide intra-week hydro plant optimization for hourly supply offers.

MASCEM (Vale et al. 2011) is another approach in which the authors developed a simulation platform based on a multi-agent framework. The MASCEM multi-agent model includes agents with strategies for bid definition, acting in forward, day-ahead, and balancing markets and considering both simple and complex bids. These characteristics turn the MASCEM both a short and a medium term simulation platform. This methodology uses learning algorithms to let agents recognize changes in the environment, thus helping them to react to the dynamic environment and to adapt their bids accordingly. A similar approach is used in (Conzelmann et al. 2009; Yu and Liu 2008; Rahimiyan and Mashhadi 2010; Wang et al. 2008). These multi-agent approaches have been used for analysis of gaming, learning, and decision support to market agents.

Despite of the development of these models, the hydro generation, specially pumping hydro stations, does not have the adequate characterization taking into account the new paradigms related to the renewable energies. Even in EMCAS, that uses VALORAGUA approach to deal with hydro generation, there is not an explicit and careful simulation of the hydro power plants, because EMCAS is very dependent on VALORAGUA performance.

Accordingly, our objective is to combine the hydro generation with a more detailed modeling, especially regarding hydro with pumping, and study their impact on systems having a large penetration of renewable sources, especially wind. We will include the possibility of selling the hydro energy in the energy market or the ancillary-services market. This kind of generation also has the possibility of buying energy in the electricity market and of storing it by pumping water to upstream. This possibility will allow a better coordination between renewable and hydro power plants.

4. ELECTRICITY MARKET CONCEPTUAL MODEL

As mentioned before, this work will focus on the electricity and ancillary-services markets. The main objective is to develop an integrated Agent-Based Simulation model to help instantiating agents to prepare their bidding strategies. In this model autonomous agents will interact in a competitive environment. It is also our objective to apply the proposed simulation tool to MIBEL. In the next sections we will briefly describe the work proposed in this paper. In order to simulate electricity markets in general, and MIBEL in particular, using an agent-based platform, it is necessary to define the structure of the model and the type of agents to be used. Having in view the application to MIBEL and given that each electricity market has its own peculiarities and rules, it is important to tune this definition considering MIBEL arrangements and the players that operate in this market. The propose model is shown in Figure 3.

The objective is to simulate two markets: the energy market and the ancillary services market. The main difference between them is due to the fact that on the secondary market only energy producers can participate. In the Energy Market, the inelastic consumers want to consume electricity. They represent residential, commercial or industrial consumers that cannot buy energy directly in market. They have to negotiate with the different Retailers that act as aggregators of individual demand and that then operate as market agents.

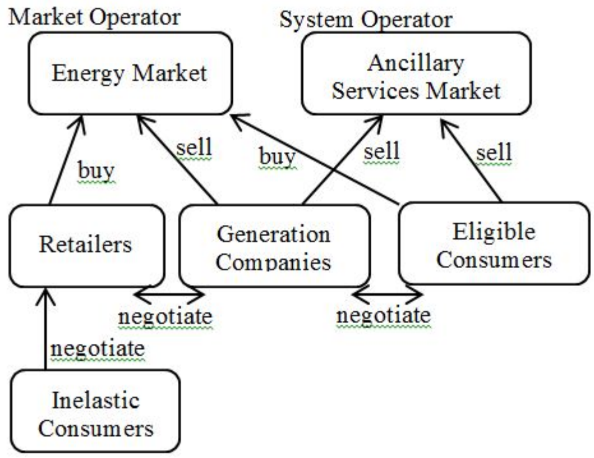

Figure 3: Structure of the Proposed Agent-based Model

Retailers are entities that buy energy in the market and negotiate with the consumers. They have to bid in the Energy Market to buy energy for the inelastic consumers. However, in the consumers group there are also consumers, typically large ones that have the possibility of buying energy directly in the Energy Market, because their demand is large these consumers will be termed as Eligible Consumers.

Generation Companies control power plants and offer their energy in the Energy Market, submitting-selling bids. They can also establish Bilateral Contracts with the Retailers or Eligible Consumers.

Regarding the Ancillary Services Market, the System Operator has the responsibility of operating the power system in a secure and reliable way. To ensure this safe operation, it contracts reserves with different time durations and activation periods. It receives offers from the Generation Companies for secondary and tertiary energy reserves and selects the least costly ones till a technical requirement is met.

As mentioned before, the main goal of this work is to develop an agent based model that also considers the hydro generation plants with pumping in the market model, accounting for a more detailed representation. This type of power plants has the possibility of buying energy and store water, which means they can be both seller and buyer. This fact gives them the possibility of getting larger profits, because they can buy at lower prices and sell at higher prices, not only on the energy market but also regarding the ancillary services provision. In fact, regarding ancillary services, the system operator typically contract upward and downward reserve energy and this type of hydro stations can provide energy in both ways.

Using traditional concepts of object-oriented development we can represent the following agent structure that groups similar agents into suitable classes of objects. Figure 4 presents the proposed model.

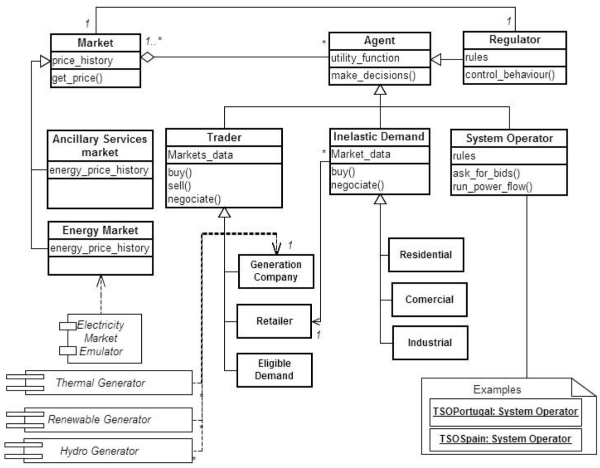

Figure 4: UML Conceptual Agent Model Diagram

This model uses 6 types of agents and 2 artifacts are defined as follows:

- Inelastic Demand Agent – it corresponds to the individual clients that can be residential, commercial or industrial consumers; they cannot buy energy in the market and have to negotiate with the Retailers Agents;
- Eligible Demand Agent – it corresponds to large consumers that can directly participate in markets. It can be either large factories or hydro pumping power stations. They can establish bilateral contracts with Generation Companies;
- Retailer Agent – it corresponds to an aggregator entity that has a portfolio of contracts with individual clients, that is, with Inelastic Demand Agents. This agent can buy electricity in the market or establish bilateral contracts with Generation Companies;
- Physical Generator Artifact – it is related to individual power plants and their characteristics; it will be an artifact agent because it does not take any decision and it has a passive role in the market with no goal or autonomous activity. It will be used by Generation Company Agents;

Generation Company Agent – it corresponds to the utilities that own a portfolio of generation assets, comprising different generation technologies, each one characterized by its generation operation and maintenance costs; These agents will have to decide whether they use their resources (hydro, gas, coal, wind) in the day-ahead market, in the ancillary services markets, or store some resources to be used in the future, when possible. It can also establish bilateral contracts with retailers. In some cases it is possible to adopt other utility functions, as for instance to increase the market share of the respective generation company. The formulation presented below shows, in a simple approach, the general problem faced by these agents:

$$\max \; X_{ct}\alpha_t + Y_{ct}\beta_t + Z_{ct}\,\varphi_t$$

$$\begin{aligned} s.t. \quad & X_{ct} + Y_{ct} + Z_{ct} \leq R_{ct} \\ & X_{c\,min} \leq X_{ct} \leq X_{c\,max} \\ & Y_{c\,min} \leq Y_{ct} \leq Y_{c\,max} \\ & Z_{c\,min} \leq Z_{ct} \leq Z_{c\,max} \\ & X_{ct}, Y_{ct}, Z_{ct} \geq 0 \end{aligned}$$

In this formulation Xct is the quantity to use in day-ahead market for power plant c, for hour t; Yct is the energy quantity to use for ancillary services for power plant c, for hour t; Zct is the energy quantity to be stored for power plant c, for hour t; αt is the value of the energy market, for hour t; βt is the value of the energy ancillary services, for hour t; φt is the future value of energy, for hour t; Rct is the quantity of resource availably for power plant c, for hour t. Hydro power plants with pumping capability can also work as Eligible Demand Agents to buy and store energy;

- TSO Agent – it represents an entity that gathers the functions of an ISO with the ownership or the concession of a transmission network. It is also the ancillary services market operator and is responsible for the reserve energy agreement;
- Organized Market Artifact – it is a process that models the energy market operator as a central entity that receives selling and buying bids for each trading hour of the next day and organizes these bids to get generation/demand schedules; it is considered as an artifact because it presents neither internal goals nor any kind of autonomous activity;
- Regulatory Agent – this agent is in charge of evaluating the behavior of the agents according to market regulation.

In this work, models are introduced according to the concept of agent organizations. Organizations are centered on the perception of the AGR structure (Ferber, Gutknecht and Michel 2004): agent, group, and role.

These agents are the "main actors" of the model. They are the entities that produce, consume and trade on the markets of our models. Each agent assumes a role (i.e. sells, buys or regulates) according to the group it belongs to. The decisions that agents have to make are essentially associated with:

- The market type, energy or ancillary services;
- The player type, traders that operate in markets (such as generation companies, eligible consumers and retailers) or individual inelastic demand;
- All physical constraints, from grid and from generators.

Learning processes, such as q-learning and genetic learning, and also by decision-support models, will also support these decisions. For example, in the last case, to help taking decisions regarding the operation of hydro-pumping stations, we will use the model presented in (Sampaio, Saraiva, Sousa and Mendes 2013). Figure 5 depicts an overview of agent decisions as explained above.

This model will be implemented and tested in NetLogo (Wilensky 1999) agent-based modelling and simulation platform to rapidly prototype simple, yet realistic, "what-if" scenarios and analyze the market performance under different real set-ups. NetLogo is an open source multi-agent programmable modeling environment for simulating complex systems evolving over time. Modelers can give instructions to hundreds or thousands of "agents" all operating independently. This makes it possible to explore the connection between the micro-level behavior of individuals and the macro-level patterns that emerge from their interaction.

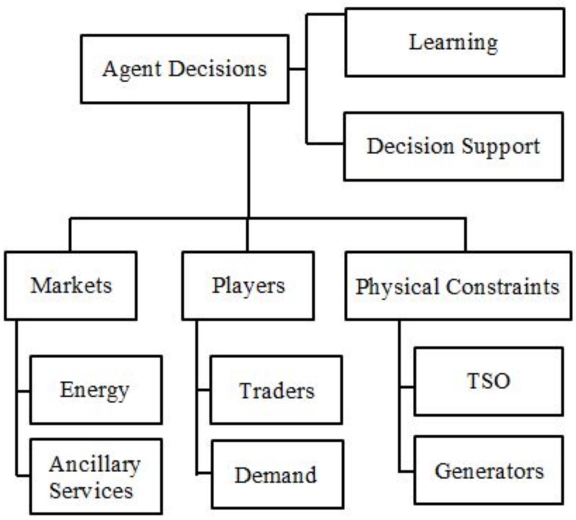

Figure 5: Agent Decision Framework

5. CONCLUSIONS

The studies on power system generation comprise a research area that was and still remains a continuous concern for electricity companies, as well as the scientific community. Electricity markets are complex frameworks that justify the development of computational models to simulate the interactions between all involved agents. In the last years, there was a large investment in renewable energy sources worldwide, and this fact brought more complexity to power systems. This paper describes an agent-based conceptual model to simulate the MIBEL electricity market and to study the behavior of involved agents, focusing on the representation of hydro power plants with pumping capability. The model is designed to be a viable tool to support planning and decision-making process in the energy market in presence of a dual nature actor that represents exactly the hydro-pumping generators.

In the near this model will be implemented using reinforcement learning algorithms, as for example q-learning (Watkins 1989) and SARSA (Rummery and Niranjan 1994), as well as communication protocols, such as Double Auction Protocols (Kant and Grosu 2005) for the negotiation among agents. The implementation design will be based on organizational concepts such as groups, roles and interactions (AGR).

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