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Intelligent trading agent for power trading through tariff market

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"Neka ti uvijek bude na umu da samo stvaralački rad stvara fizionomiju ličnosti". A.B.

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CONTENTS

ABREVIATIONS

AAAI	Association for the Advancement of Artificial Intelligence
ACE	Agent-based Computational Economics
AMI	Advanced Metering Infrastructure
CES	Constant Slasticity of Substitution
CNT	Center for Neighborhood Technology
CPP	Critical-peak Pricing
CPR	CPP with rebate
DAP	Day-ahead pricing
DLC	Direct Load Control
DSM	Demand Side Management
DU	Distribution Utility
ECS	Energy Consumption Scheduler
EEX	European Energy Exchange
EMCAS	Electricity Market Complex Adaptive Systems Model
ESPP	Energy-Smart Pricing Plan
EU	European Union
FIT	Feed-in tariff
GenCos	Generating Companies
IT	Information Technology

KPI	Key Performance Indicators
LRIC	Long-run incremental costs
LRMC	Long-run marginal costs
MAIS	Multi Agent Intelligent Simulator
MW	Megawatt
MWh	Megawatt Hour
NGO	Non-governmental Organisation
NIST	National Institute of Standards and Technology
OPF	Optimal Flow Model
PAR	Peak-to-average Ratio
PHEV	Plug-in hHybrid Electric Vehicle
PIM	Profitability Index Method
PTR	Peak Time Rebate
RE	Renewable Energy
REC	Renewable Energy Certificates
RES	Renewable Energy Sources
RTP	Real-time pricing
SRIC	Short-run Incremental Costs
SRMC	Short-run Marginal Costs
TAC	Trading Agent Competition
TADA	Trading Agent Design and Analysis
ToUP	Time-of-use Pricing
TSO	Transmission Systems Operator
U.S.	United States
UML	Unified Modeling Language

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INTRODUCTION

The existing electrical power systems are experiencing a change from the traditional grid to the advanced grid named the Smart Grid. The new and advanced grid offers more flexibility and stability to customers as well as for the producers of electrical energy. Additionally, new services arise from the incorporated ICT (Information and Communication Technology) layer situated between the power layer characterized with energy distribution and market layer for energy trading. In that sense, Smart Grid allows real time tracking and management of energy supply and demand thereby making the customer one of the essential roles in the whole power distribution system. To effectively deploy the Smart Grid and open widespread markets in wholesale and retail trading we need to develop stable market mechanisms and regulative that can be enforced. However, modeling markets may be a challenging task since there are numerous parameters and cases that need to be covered by simulations in order to produce reasonable and useful results.

This Master Thesis investigates on the issue of simulating power market, and focuses in the tariff market (also known as the retail market). The idea behind the work is to create an intelligent trading agent that acts as a mediator between the end customers and producers by buying and selling energy. The ultimate goal of the agent is of course to acquire profit, but in order to do that numerous mechanism and logic have to be implemented. In the thesis we focus on creating effective mechanisms and activities that are carried out throughout simulations. The most important part is the design and creation of different tariff models that are offered in the tariff market to customers. We create numerous types of tariffs and in the end perform statistical analysis of their success. Additionally, the intelligent agent is responsive to the current market state and activities therefore being a true competitive entity in the pool of other competitive intelligent agents during simulation procedures. In the end, the final implementation of the intelligent agent is a scalable and robust solution ready to be further developed and expanded.

The structure of the thesis is as follows. The first chapter introduces the idea of the Smart Grid concept and its implications for stable electricity supply and sustainability. The second chapter present a short overview of the various mechanisms for energy market modeling and pricing schemes that are applied. The third chapter presents all of the key features and principles of tariff designs are covered. The development of the agent relies on the working practices identified in the literature and that were documented in chapter three. The fourth chapter present the agent-based platform that was used for evaluation of the developed intelligent agent. The fifth chapter covers the design and implemented features of the trading agent developed for Master Thesis along with the software architecture. Lastly, the sixth chapter presents the results that we observed while simulation agent's behavior in the simulation platform. Last chapter is the conclusion of Master Thesis followed by the Appendix presenting key performance indicators that were tracked during evaluation.

1. Smart Grid concept

Traditionally, the term *grid* when used in the domain of electricity systems encompasses the meaning of all or at least one of the following action: i) generation of electrical energy, ii) transmission of electrical energy, iii) distribution of electrical energy, and iv) electricity control. The concept of the Smart Grid (SG), also called smart power grid, smart electrical grid, intelligrid, intragrid, intergrid, intelligent grid or future grid is no different from the traditional term but with certain enhancements that contain the integration of information systems into the electrical energy distribution grid. In general, the traditional power grids are used to transfer power from a few and centralized power generation facilities to a large number of potential customers over a vast geographical area. Opposite to that, the Smart Grid uses two-way flows of electricity **and information** to create a fully controllable, smart and distributed electrical energy network [23]. This chapter summarizes the history of electrical energy systems and implications for production and transmission of electricity while concerning the changes that are occurring. Smart Grid definitions and concept architecture is introduced as a solid backbone for understanding further chapters.

1.1. History of electrical energy systems

Energy has a vital role in shaping human life. Throughout history, people have utilized various types of energy to improve their life quality, finally discovering electrical energy. Today, life without electrical energy is almost unimaginable; therefore it is a highly significant form of energy [3]. However, the people have become unambiguously dependent on electrical energy increasing the overall consumption while the production capabilities do not follow the consumption trend. Even though we are still managing to fulfill the current needs, Agenda 21 [44] indicates that this path of development is not sustainable in the long-term. Reasons for this are not just related to the amount of energy being produced and the problem of its shortage but with the environmental effect as well. Production capacity is often enhanced with non nature-friendly facilities which as a byproduct have large amounts of carbon dioxide emissions (generally, greenhouse gas (GG) emissions) and pollute air, water and soil.

In order to eliminate adverse environmental effect and support the development and growth of electrical energy systems it is necessary to turn from fossil fuels (which are currently the main actuator of production facilities) to renewable energy sources such as bioenergy, wind energy, solar energy and water energy. As stated in [3] ([22][16]), the share of renewable source in the European Union countries (EU-27) in the total consumption/production capacity was only 12.4% in 2010. Strategic goals that are focused to achieve universal progress until 2020 are proposed in the Europe 2020 document: i) CO2 emission reduction by 20% compared to the emission level observed in the 1990; ii) increase renewable energy sources share to 20%; and iii) increase of energy efficiency by 20%. These goals are a challenge to the existing traditional power system deployed in most areas and therefore, improvement of existing technologies and reinforcement of the grid is inevitable.

Evolution from traditional power grids

Energy consumption and demand are exponentially increasing worldwide and the need for demand reduction and energy saving has increased dramatically. The mode of transmission and distribution of electricity to the end users and its supporting systems have continued to operate in the same way during many last decades [28], more exactly there were not changed significantly since their first design based on the idea of scientist Nikola Tesla in the year 1888 [3][56].

A simple architecture that describes the traditional power system may be seen in Figure 1.1. The main design points are the centralized production and one-way power transmission of electricity from production facilities to end consumers. Electricity is first transferred through high-voltage networks over long distances to distribution utilities where the energy is transformed to low-voltage form that is suitable for delivery and usage of end consumers. Additionally in the picture we see need of human activities for meter readings at consumer locations and no information infrastructure that would allow monitoring of the power grid. Traditional power grids are also facing high energy losses due to large transmission distances from production to consumption and low security for grid stability (i.e. often the production is centralized where a malfunction in the transmission process – electrical transformers or power transmission towers – from the production facilities may lead to a complete grid failure for vast geographical areas).

In order to respond to the issues of traditional power grid its is necessary to undertake certain changes in the electrical subsystem. One of the proposed solution is to transform the existing grid into a more advanced solution called the Smart Grid. The definition itself and the more in-depth characteristic of this new grid are more covered in the next sections, but it is useful to provide a short comparison overview between the most important characteristic of these two systems (Table 1.1).

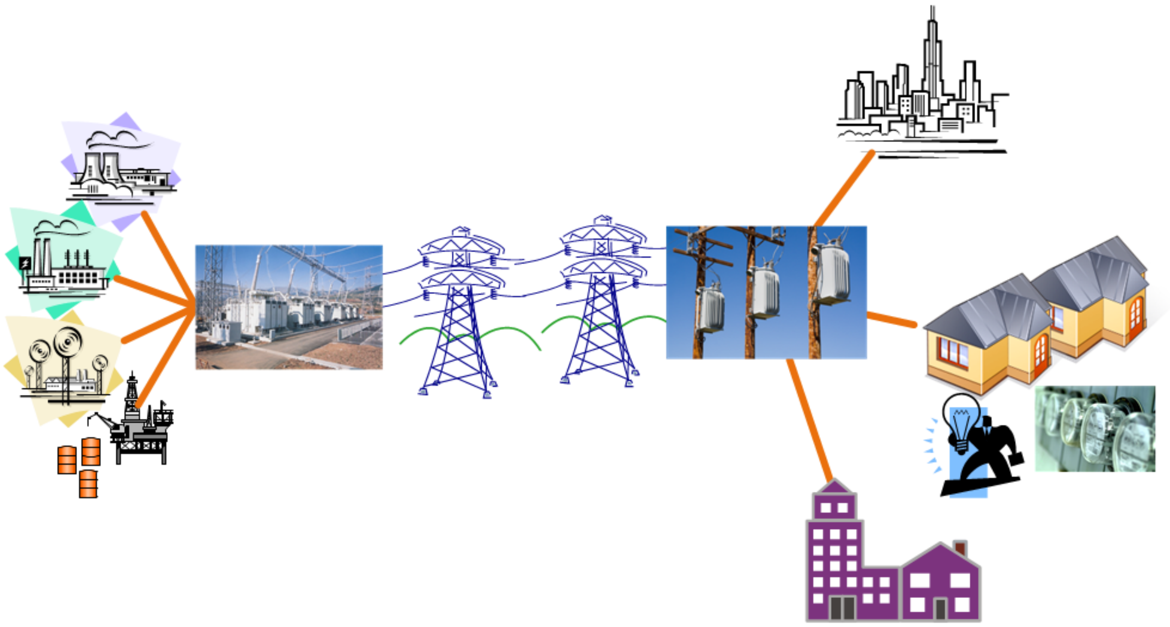

Figure 1.1: Simple architectural design of the traditional power grid

Table 1.1: Comparison of traditional power grid and Smart Grid ([24][15][23])

Characteristics	Traditional (existing) power grid	Smart Grid
Mechanics	Electromechanical	Digital
Communications	Non or one-way communication	Two way communication
Generation type	Centralized generation	Mostly distributed generation + centralized generation
Adaptability	Blackouts and failures	Adaptive and islanding
Sensor deployment	Few sensors	Monitors and sensors throughout
Monitoring	Manual monitoring (blindness)	Self-monitoring
Grid repair procedure	Manual restoration	Semi-automated restoration and self-healing
Security check	Check equipment manually	Monitor equipment remotely
Controlling capabilities	Limited control	Pervasive control
Power flow	One-way power flow	Two-way power flow
Portfolio diversity	Few customer choices	Many customer choices

1.2. What is a Smart Grid?

The first concept of the Smart Grid was based only on the idea of implementing an advanced metering infrastructure (AMI) that will provide the possibility to offer distinctive tariff to end customers thereby improving demand-side management, energy efficiency and overall costs related to electrical energy provisioning process. Additional aims were to improve the stability and security of the traditional grid since it was vulnerable to both natural disaster and on-purpose sabotage [51]. However, the development of the concept has led to the expansion of the initial perception of the Smart Grid bringing the new path of the electricity industry. The new expansion includes: i) considerations related to environmental issues (growth of renewable energy generation is eminent), demand response balancing, distributed generation; ii) the drive for better asset utilization while conserving a stable and reliable system operation; and iii) customer-important factors (tariff choices, incentives) [52].

During the evolution of the Smart Grid, the concept was defined in numerous different ways. The definition of the European Strategic deployment document states that a Smart Grid is a “an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies” [17]. Another definition that covers the entire spectrum of the electrical energy provisioning process ranging from generation, distribution to end consumption state that "the SG can be regarded as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable[1]" [26][23].

The ultimate Smart Grid still remains a vision since the overall architecture of the grid is a loose integration of many different components, subsystems and functions which should be controlled by an fully automated, intelligent management system. Nevertheless, Smart Grid utilizes modern information and communication technologies not only to deliver the electrical energy to its end customers but to react to any unforeseeable conditions and events (which may occur anywhere on the grid thereby making them easy to identify and locate).

As we may observe from the past few paragraphs, the research about Smart Grids is a vast area of different visions experienced by different researchers since the focuses and perspectives may be extremely broad in some cases. A possible division on the research focus can be presented as two main perspectives: the *technical perspective* that concerns the architectural (infrastructural) system and the *environmental-economic perspective* that concerns the general operational process of the Smart Grid (market design, load reduction, emission reduction, cost effectiveness, etc.)

[1]As stated by the Brundtland Report, "Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: i) the concept of needs, in particular the essential needs of the world’s poor, to which overriding priority should be given; and ii) the idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet present and future needs" [21]

1.3. Key elements of a Smart Grid operation

The scope of the Smart Grid operation is expanding rapidly from its first version based on the advanced metering infrastructure since the requirements and demands on the traditional grid are increasing. This drove the electricity industries, research organization and governments to rethink about the defined scope of Smart Grids. The U.S. Energy Independence and Security Act of 2007 directed the National Institute of Standards and Technology (NIST) to coordinate the research and development of a framework to achieve interoperability of Smart Grid systems and devices. According to the report from NIST and to the [23], the anticipated benefits and requirements of Smart Grid are:

– Improving power reliability and quality,
– Optimizing utilization and averting construction of back-up (peak load) power plants,
– Enhancing capacity and efficiency of existing electric power networks,
– Improving resilience to disruption,
– Enabling predictive maintenance and self-healing responses to system disturbances,
– Facilitating expanded deployment of renewable energy sources,
– Accommodating distributed power sources,
– Automating maintenance and operation,
– Reducing GG emissions by enabling electric vehicles and new power sources,
– Reducing fossil fuel consumption by reducing the need for inefficient generation during peak usage periods,
– Presenting opportunities to improve grid security,
– Enabling transition to plug-in electric vehicles and new energy storage options,
– Increasing consumer choice, and
– Enabling new products, services, and markets;

As we can see from the above requirements, a complete architectural design and a new framework has to be developed. In Figure 1.2 a typical utility pyramid is shown with the baseline consisted of asset management. Utilities who are responsible for the Smart Grid deployment have to build the foundation of the future grid on this baseline through careful design of the IT (information technology), telecommunication and circuit (topology) infrastructure. The organic growth of this carefully designed layer of intelligence over utility assets enables the Smart Grid's fundamental applications to emerge [24]. It is interesting to emphasize that even though the foundation of the Smart Grid is built on the lateral integration of these basic components, true Smart Grid capabilities which will bring new benefits will be built on the vertical integration of the upper-layer applications (i.e. a critical capability like demand response may only be feasible with tight integration of smart metering technologies and home area networks).

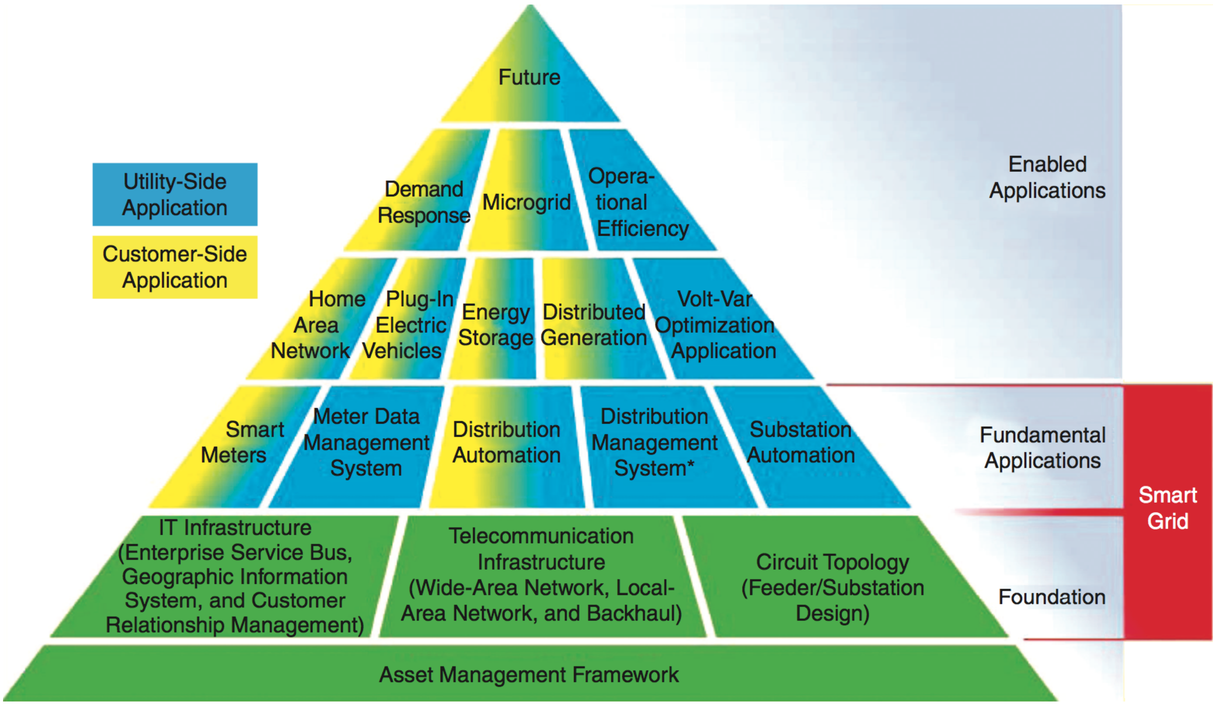

Figure 1.2: Smart Grid utility pyramid ([24] and BC Hydro)

If we take into consideration all of the factors mentioned above we can easily argue that given the amount and the value of utility assets, the development of the Smart Grid will more probably have an evolutionary trajectory than a distinguishable overhaul of the old traditional grid. Therefore, we may presume that the Smart Grid is going to materialize through strategic implants of distributed control and monitoring systems alongside the already existent electricity grid. Additionally, as the technologies develop, the functionality of specific Smart Grid components will start to grow allowing deployment of more intelligent and distributed systems across diverse geographies. Consequently, energy load would be shifted more and more from the old grid onto the new grid improving and enhancing the overall quality of services [24].

In Figure 1.3 a simple example of the advanced new grid is shown in high abstraction. The in-depth architecture is not taken into consideration (see the next section), but only the included entities and processes in the whole Smart Grid operational process which are:

- Retail customers,
- Transmission and distribution,
- Large (bulk) production,
- Markets,

– Operations and monitoring,

– Grid operator.

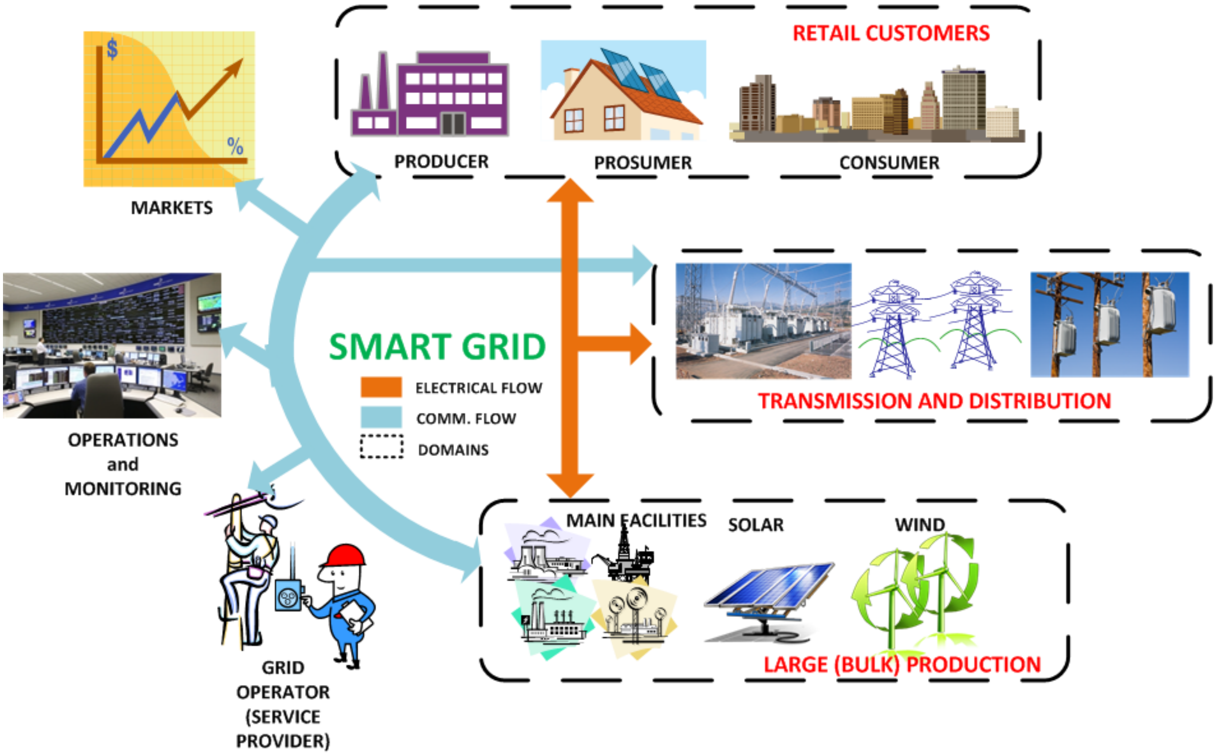

Figure 1.3: Smart Grid conceptual model

In the previously mentioned Figure we also see two different arrow types differentiated by color. The orange arrows denotes the two-way electricity flow that occurs between the retail customers and the production facilities with the transmission and distribution systems in between. The blue arrow denotes the two-way communication flow where all the information concerning the grid stability and usage are transferred between interested parties (e.g. smart meter reading, peak load notifications, network failures, etc.).

Retail customers are a common term for the following customer types:

– *consumers* (regular households, office buildings),

– *producers* (privately-owned wind turbine or solar panel that may be seen as small production facilities),

– *prosumers*[2] (households with, for example, solar panels on the roof top or electrical vehicles that offer storage capacities in peak demand periods) .

Transmission and distribution entails all the needed components for the end delivery of the electrical energy such as transformers to change voltage of the electricity as needed, redundant cabling and electrical towers that carry the energy flow and generally the distribution

[2]Prosumer is a portmanteau formed by contracting the word *producer* with the word *consumer* [3].

network. Large (bulk) producers are consisted of industrial power plants (like the ones in the traditional power grids) and new renewable energy sources (wind, solar, bio, hydro, ...).

Markets in the Smart Grid may be either *retail* or *wholesale* markets where the retail is more oriented to end customer while wholesale market is related to inner network trading between large utilities in the network (entities who buy in the wholesale and sell in the retail market). *Operations and monitoring* alongside the grid operator are responsible for the grid functionality and stability. These system present the core of the network with the intelligent components that allow the Smart Grid operation in a way that it is defined.

In the next subsection we discuss another point of view for the Smart Grid infrastructure where the entities are separated into cohesive units with different levels of abstraction.

1.4. Smart Grid multi-layered architecture

If we want to further separate the Smart Grid infrastructure into more levels of abstraction we may easily observe that there are three logical levels: i) Market layer, ii) Information and communication technology (ICT) layer, and iii) Energy layer [3]. Figure 1.4 shows the introduced multi-layer architecture along with its interconnections and covered functionalities. Correspondent flows for each layer are also shown in the Figure 1.4 which indicate the primary area on what the specific layer is based on. We briefly explain the scope of each layer in the next several paragraphs.

1.4.1. Market/Energy layer

These two layers are covered in the same subsection since the implications for the market design are given later on in a standalone chapter and the energy layer is a self-explanatory level of the multi-layered architecture. We may say that the energy layer is the backbone for all services that are provided and especially for the market layer which with the help of ICT layer gathers useful information from the energy layer and uses it to perform actions in the market.

The energy layer in the Smart Grid environment includes components needed for *production*, *transmission*, *distribution* and in the end *consumption* of electrical energy. These components are crucial for the functioning of the traditional power grid since the whole process is based on them. On the contrary, in a Smart Grid they just provide the foundation for the intelligent components which enable grid management and distinguish it from the old power grid.

The market layer is conceptually divided into two different units: i) *retail market* and ii) *wholesale market*. The wholesale market allows involved utilities and mediators to buy

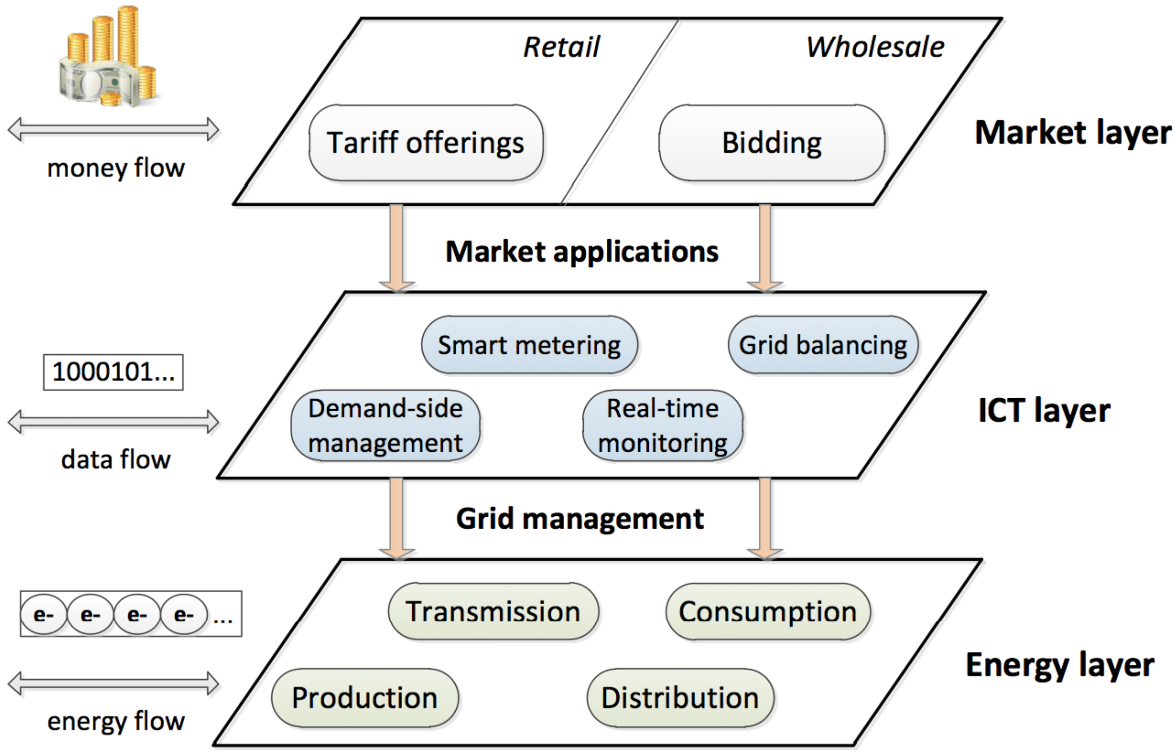

Figure 1.4: Smart Grid multi-layer functional infrastructure [3]

and sell available quantities of energy for future delivery to end customers. Typically, the energy is bought for time periods between 1 and 24 hours in the future and for that reason it often holds the name of the *day-ahead market* [3]. For these markets prices are cleared several times per day after concluding the bidding for the energy from all present stakeholders and by that the final price for certain quantities is established. All of the actions in the wholesale market serve as an input for the actions drawn in the retail market. Generally, the retail customer market includes creation of different pricing mechanism for customers (tariff offerings). Mediators use the available information about the consumer behavior related to energy consumption (i.e. time of day, consumption curves, quantities) and information from wholesale market related to current energy prices. Based on these, the mediator creates different tariff offerings for various customer types. It is up to the mediator to establish a cost-friendly tariff design that a certain customer will choose over the tariff offered by some other mediator. It is important to emphasize that all tariff and retail market actions are based on the ICT layer (more exactly smart network and metering components) which enables the creation of complex tariffs that will fit the needs of customers but also help to keep the overall stability of the grid.

1.4.2. Information and communication technology (ICT) layer

ICT layer provides the necessary infrastructure for the market layer (retail and wholesale markets) and thereby acts as a middleware between the energy and market layers [3]. The ICT layer itself may be easily divided into three major subsystems proposed in [23] (which perform actions related to smart metering, grid balancing, demand-side management and real-time monitoring): i) smart infrastructure, ii) smart management and iii) smart protection system. Even though the energy layer is separated in the proposed multi-layered architecture we consider that all the new and advanced features such as two-way power flow are based and therefore a part of the ICT layer.

The smart infrastructure system combines energy infrastructure with information and communication infrastructure underlying the intelligence of the Smart Grid. The key point is the support for both two-way information (communication) and two-way power flow, where by two-way information we consider smart meter readings, announcements, grid current state and by two-way power flow we consider that a particular household which has some elements of renewable energy production (e.g. solar) can either buy the energy (if in shortage regarding its own production) or sell energy to the grid (if surplus is achieved). This back flow of energy from the customers point of view is one of the most important features that a Smart Grid offers. An example of high utility of the feature is in the case of a microgrid[3] where a failure somewhere in the electrical systems (in the grid) causes the microgrid to disconnect and proceed on its own based on the local production (from household or small customer production facilities). Additionally the smart infrastructure system may be divided into three subsystems concerning the main functionality:

1. The *smart energy* subsystem is responsible for **advanced** (monitored and more secure) electricity generation, delivery and consumption,
2. The *smart information* subsystem is responsible for advanced information metering, monitoring and management in the context of the Smart Grid, and
3. The *smart communication* subsystem is responsible for communication connectivity and information transmission among systems, devices and applications.

The smart management system performs advanced management and control services and functionalities to support the Smart Grid process. The main reason why the Smart Grid is revolutionizing the old traditional grid is in the numerous expanded functionalities that it offers. The management system and its new applications and services may leverage the

[3]A microgrid is a localized grouping of electricity generations, energy storages, and loads. Microgrids may be *islanded* when there is a single point of coupling with the macrogrid (full Smart Grid) that can be disconnected upon a need promoting the microgrid to work autonomously

technology and capability upgrades enabled by the complete infrastructure for to grid to become more intelligent. Therefore, the smart management system takes all the advantages of the smart infrastructure system to fulfill various advanced management objectives related to energy efficiency improvement, supply and demand balance, emission control, operation cost reduction and utility maximization.

The last subsystem of the Smart Grid is the smart protection system which provides failure protection, security and privacy protection services and advanced grid reliability analysis. The smart protection system also takes all the advantages of the smart infrastructure system has to assure grid stability and protection from all unexpected, malicious and privacy issues that may occur at any time.

The previously explained division does not explain the connection between layers in the multi-layer infrastructure presented in Figure 1.4. The ICT layer may basically be explained as a mediator and enabler for grid management activities and as a information source for the market layer. The energy layer focuses on the delivery of electrical energy, while the ICT layer performs monitoring and metering techniques to acquire data and bill the customers. Additionally, the data is used for balancing purposes to reduce the outages of the grid. Lastly, market applications and the market layer use all that data to run the wholesale and retail market of electrical energy.

With this section we conclude the basic and simple introduction of the Smart Grid environment which is needed to understand the future discussions in this thesis. We continue with the market design implications and economical aspects of the Smart Grid while emphasizing more on the retail market (tariff offerings) where the intelligent agent will perform its analysis and offer new contracts (tariffs) to end customers.

2. Energy market modeling in a Smart Grid environment

2.1. Decentralization of energy provisioning process

Historically, the provision of electrical energy was characterized by centralized systems with production capacities reaching more than needed by the overall consumption. Even now most of the electrical energy systems across the globe are still centralized. Several recent major black-outs that occurred in the western world have caused the increased attention to the security of electrical supply in the energy distribution systems. The liberalization of electricity markets brings reduction to the overcapacity since the producers rationalize their production to fit the current market fluctuations. That reduction was well accepted by the generating companies and their production costs started to drop. However, the cost-efficiency has its price and it may be manifested through increased risk of the excess of electrical energy, again resulting in complete black-outs [40].

The key goal of the decentralized energy provisioning process is to address the non-stability of electricity supply by applying better mechanism of demand response. Also, by dividing the process into more entities that communicate/trade with each other we must address the already extensively researched and observed time-varying energy consumption. These characteristic did not pose a threat during past decades since the capacity was satisfactory, but the overall increase in energy demand is visible in short-term period raising the question of future sustainable development.

2.2. Implications of electricity market design

Electricity markets represent a special case of an energy commodity markets such as gas markets, oil markets, coal markets and other similar commodities. It is difficult to imagine how the new evolving electricity markets could achieve the depth, liquidity and regularity as of the markets for these other resources since they have a longer history and the commodity may be stored unlike the electrical energy.. The crucial difference that characterizes electricity is the lack of storage capacity which, if deployed and used, is extremely expensive and inefficient. Also, there are capacity constraints on the generation (production) facilities that cannot be breached in times when the demand for energy is high. Regarding the properties of electricity transmission, an imbalance between supply and demand at any place connected to the grid can cause stability issues and disrupt the process of energy exchange for producers and consumers on the grid. Additionally, the transmission can be congested over time (in extensive usage periods) and the prices can fluctuate dramatically in different locations and periods. Given the unusual characteristics of the electricity market it is important to enable flexibility on the supply side of the grid. By that, we imply that the fluctuating demand which occurs when consumers use the energy has to be controlled or at least closely monitored.

Nowadays, electricity metering equipment is widely available, due to the price reduction of components, for all energy consumers, from large entities to household. However, most of the world's installed metering equipment consists of either one or two meters which track the energy usage in peak and off-peak times of the day (variant of critical peek pricing (CPP) network tariff structure). By dividing the day into only two periods we can capture only a small portion of a day-to-day variation. Thus, the energy price is more time-varying than that, and closer to a hour-to-hour based variations. Another constraint to the electricity market design is the difficulty to predict the demand and its root cause, (in)sensitivity of energy consumption regarding price fluctuations.

2.2.1. Short-term pricing mechanisms

In nearly all electricity markets producers are faced with the fact that energy prices (for selling) clear at a uniform distribution over short periods of time. This implies that all producers sell their energy for the same price regardless of their production costs. Therefore, a short-term pricing mechanism between the generating companies (producers) and regulated utilities (bounded and regulated by state laws) which buy the energy from wholesale markets and sell it with the regulated price to end customer may cause financial problems to both of the entities [7]. For example, if the demand for energy drops bellow a certain threshold the energy price on the wholesale market respectively drops. This implication forces the producers to enter cold operation where they produce little amounts of energy. Yet the production costs exceed the market price leading generating companies into financial problems. On the other hand, if the demand for energy grows above certain threshold (where the mentioned threshold gives a fair price for both production and retail utilities), retail utilities are forced to buy energy for large amounts of money and sell it on a regulated price (much lower that the wholesale equivalent) to the end consumers. This implies non-avoidable bankruptcy of the retail utilities bringing extensive imbalance and problems to the electrical energy provisioning process.

The lastly mentioned situation occurred during the summer of 2000 in California, commonly known as The California electricity crisis (Western U.S. Energy Crisis). In that period wholesale electricity prices were nearly 5 times higher than in the summers of the preceding years [34]. California began thinking about restructuring the electricity market at 1994 influenced partially by the high prices of energy regulated by the state for end consumers and partially by following the example of the electricity market deregulation that occurred in the United Kingdom. High energy prices were the consequence of wrong forecasts for building maintenance-expensive and costly nuclear power plants. Investor-owned retail utilities made bad investment decisions and they were also faced with the pressure of California Public Utilities Commission to sign long-term contracts with small generating companies which in the end forced them to buy energy at very high wholesale energy prices

2.2.2. Long-term pricing mechanisms

To mitigate the fundamental problems of established policies and regulations on the electricity market and avoid situations like the previously mentioned energy crisis in the United States, in [7], the authors proposes two adjustments: long-term pricing and contracts; and real-time pricing (RTP). Long-term contracts are historically one of the oldest models of electricity markets where the regulation concerns cover all the entities in the process. With long-term contracts price variations which led to financial problems are avoided since buyers are protected from extreme and fast price variations and sellers are protected from price busts where the costs overcome the acquired income. Additionally, RTP would indicate future energy prices to the customer on an hourly basis, allowing them to schedule their peak consumption needs to less expensive periods. However, the most effective solution is the combination of both long-term contracts (between producers and retailers) and RTP (between retailers and end consumers). By introducing variable prices and RTP mechanism the cost of energy can vary extensively, but with the long-term contracts the final monthly electricity bills can still be stable enough. Furthermore, RTP will reduce the amounts of energy during the peak consumption periods and by that reduce the total production costs of generating companies [47]. Consequently, those generating companies would substantially offer lower prices to retailers since their production costs are reduced therefore lowering overall costs generated by long-term contracts. The end result would be seen in lower overall energy consumption, more regular market behavior and lastly environmentally more acceptable process.

2.3. Identifying opportunities and perspectives of future Smart Grid markets

In order to identify opportunities and perspectives of future Smart Grid markets as well as their limitations and problems we need to establish simulation platforms (and environments) that will provide sufficient and substantial implications for deploying real-world markets. In [3], the author shortly summarizes several methods used to model electricity markets: i) equilibrium models, ii) game theory, and iii) human-subject research. All of the observed models focus on different aspects and therefore do not provide a unified solution without shortcomings.

Equilibrium models use assumption about the available information that all participants have in the market environment. More precisely, it is considered that participants have all the relevant information about characteristic and behavioral patterns of other participants in the trading process while new information that could have been acquired while performing the trading is not taken into consideration. Thus, the learning process was ignored and the solution for the market design is more or less static (based on the input arguments). On the contrary, game theory models are often constrained to specific market situation that can provide only limited capabilities regarding the influential factors of the market. Additionally, the behavior of included participants may be unrealistic. The latter problem of unrealistic behaviors is also connected with human-subject research but related to the electricity generators where it is very difficult and takes great efforts to describe and combine human research with electricity production predictions.

One of the possible solutions to overcome all of the shortcoming of previous mentioned models is to use market modeling based on intelligent software agent. A software agent is a computer program that acts for a user or other program in a relationship of agency, which derives from the Latin *agere* (to do): an agreement to act on one's behalf. Such "action on behalf of" implies the authority to decide which, if any, action is appropriate [46]. While the term software agent is used in computer science, in artificial intelligence the definition goes as: an intelligent agent (IA) is an autonomous entity which observes through sensors and acts upon an environment using actuators (i.e., it is an agent) and directs its activity towards achieving goals (i.e., it is rational). Intelligent agents may also learn or use knowledge to achieve their goals ranging from simple to very complex implementations [53]. As a matter of fact, the final scope of this thesis is to implement an intelligent software agent that is ready to participate in retail energy markets.

Next paragraph briefly summarizes some of the examples of market modeling using software agents and closely follows observations found in [3].

Market modeling based on software agents

As we previously mentioned, agent-based modeling has proven to solve some of the problems that we encountered with traditional models for energy markets and markets in general. Numerous electricity market simulators are covered in the literature and here we briefly summarize some of them and their characteristics (from [3]).

Agent-based Computational Economics (ACE) [**?**] represents a software model that allows arithmetic study of economic processes in numerous market types (not just energy markets). Thus the economic processes are modeled in dynamic systems with software agents which are presented as self-acting entities consisted of relevant information for trading (data) and computational behavior for the virtual arithmetically created world. Its capabilities are useful for understanding and evaluating new market types and designs, evaluating interaction between markets and mediators (agents), supporting human-subject research in decision-making and in the end proposing new business policies.

The next two models are based on the electricity markets and interactions of the involved entities. First, the Multi Agent Intelligent Simulator (MAIS) [7] is a system developed to simulate the California electricity market in the times of energy crisis period that we described in previous section. The goal of the model is to use agents for analysis and understanding of the price changes in the wholesale electricity market in the period before, during and after the crisis. Different agent types are given various learning abilities and bidding strategies to provoke the same crisis that really happened so the causes could be discovered and identified - and all that so the similar crisis do no happen again. The second model is the Electricity Market Complex Adaptive Systems Model (EMCAS) [**?**]; an agent simulations of electricity markets. The model links the properties of producers and consumers behavior with the simulated activities of an electricity system and in the end calculates prices for electricity transmission per hour. These energy prices are dependent on numerous factors such as demand-supply, transmission congestion, production costs and additional external factors that could affect the price in a real world situations. The overall result is provides information about economic consequences for different entities involved upon applying various strategies in the simulation.

In the thesis we develop a software agent to act, learn and trade in the simulated energy markets. This chapter is followed with the information about network tariff design principles which is continued on Chapter 5 that provides a medium-detailed description of the agent-based simulation platform and its implications that is used to evaluate the characteristics of our agent.

3. Network Tariff design principles

Electricity is a commodity that is non-storable economically (the storage for electricity is expensive and it cannot be saved for a long time) and the wholesale prices vary from a daily to an hourly basis and usually fluctuate by an order of magnitude between low-demand night-times to high-demand afternoon hours. However, in general, almost all retail consumers are currently charged some average price that does not reflect the actual wholesale price at the time of conumption. As a solution to this problem, various time-dependent pricing models have been proposed: real-time pricing (RTP), day-ahead pricing (DAP), time-of-use pricing (TOUP), critical-peak pricing (CPP), etc. All of the mentioned variations have two main ideas [43]: i) encourage users to shift their consumption from peak hours made by high-load devices (appliances) to the off-peak hours of the day – and as a consequence get reduction in the electricity cost but also to help the overall stability of the grid by reducing PAR of the maximum load; ii) allow retail prices of electricity to reflect the fluctuations that occur with the wholesale prices and making customers pay the real value of the energy consumed.

Network tariff design principles are mostly constrained by the regulations and state policies and by metering equipment embedded in households and end customers' locations. In the US most households have electricity meters based on old technology by Elihu Thomson from 1888. Thomson was an inventor who founded the preceding company of today's General Electric and he was also serving as the president of Massachusetts Institute of Technology [1]. Characteristics of his technology is based on plain recording of the total consumption of the electricity in one household (or even in some cases a group of households). Since the meter does not have the possibilities to measure electricity consumption in different times, end consumers can only be charged one fixed price per kWh where the change in that price is seldom (on a monthly or even yearly basis depending on the regulation utility and laws of the state). Some electric utilities (depending on the country) installed multiple of those meters, commonly two. For example, the current situation in Croatia is that most of the meters are multi-tariff meters which track consumption in two periods during the day [20]. These metering techniques provide some flexibility regardning the price for the consumers. Yet, they are costly and potentially error susceptible since the electric utility has no other option than sending a worker to observe the households' meter readings.

With the emerging development in Smart Grid metering and management technologies, growth of potential elasticity and reduced prices of advanced electricity meters (Smart meters) are enabled. These factors influenced the interest in residential real time pricing mechanism since the empirical calculations indicate possible positive effect on the overall net welfare of all included entities, especially households. However, real time pricing experiments were avoided by electric utilities until recently when the end customers were exposed to the continuous time and value variation of the wholesale market prices. Before that, electric utilities experimented with other various tariff structures such as block prices, time-of-use prices (ToUP), critical peek prices (CPP) and other various forms of residential dynamic pricing [59][1].
The overall challenge, regardless of the peculiarities of a specific tariff design, is to emphasize and utilize the importance of "communication" between the retailers (electric utilities) and households improving cost and energy effectiveness. The chapter is organized as follows: the first section discusses the key features of a Smart Grid tariff design and what factors should be considered. Next three subsections describe the three most commonly used tariff designs, time-of-use, real-time pricing and critical peek pricing. Lastly, the chapter contains a section about a tariff design specifically important in the area of renewable energy generation where we discuss the main goals and implications for expanding renewable energy production.

3.1. Key features of Smart Grid tariff design and structures

The term *tariff design* implies integration of all parameters and variables that influence the process of energy and money transactions that occur in retail electricity markets while the term *tariff structure* refers to the criteria on which the customers would be charged (i.e. based on consumed energy, demand charge, fixed prices, peak load or a combination of these) In the upcoming sections we focus on:

– the key factors that should be priced while buying electricity,
– major concept used for pricing,
– resource/cost allocation for various tariff settings,
– elements of the tariff structure and its formulation,
– lastly, the contributing entities in the transmission and distribution process;

These focus topics were introduced in [48] and then discussed in [55] where the authors lead us to all implications related to the arising questions.

3.1.1. Pricing factors in electricity trading

In the electrical energy provisioning process there are numerous components involved for the process to be operational, such as infrastructure and networks costs, operation and maintenance costs, auxiliary services and congestion management cost. All of these cost come on top of the fluctuating energy prices both on the wholesale and retail markets.

The question that needs to be solved and regulated concerns the paying entity for each of these additional components. Some of them can be transferred to the next entity in the distribution chain or they may be incorporated as part of the end structural components of tariffs for customers. However, some events like congestion do not arise on regular interval and the total cost cannot be easily estimated. The importance lies in the establishment of transaction connections between separate entities to form a closed financial circle which in the end should be regulated to avoid any dramatical imbalances.

Another important factor mentioned in [55] concerns the cost of connecting various, either generation or consumer facilities to the electrical grid. In some cases the costs are covered by the network company since by law the state in many countries has to provide connections to the electrical power grid. However in case of large generating facilities where the connection can be followed by necessary reinforcements of the grid (which is by far an expensive process), costs can fall upon either on the network company (reducing the costs of the facility itself) or on the generating facilities creating large expenditures.

3.1.2. Major pricing paradigms

The pricing paradigm structures were proposed in [39] where the author, by observing the current research body identified three different pricing paradigms for transmission of electrical energy which can be applicable also to the energy pricing paradigms. Respectively they are:

- Rolled-in pricing paradigm,
- Incremental pricing paradigm,
- Composite embedded/incremental paradigm.

Rolled-in pricing paradigm

In the *Rolled-in pricing paradigm* all costs of the transmission process are *rolled-in* (summed up) into a single number therefore making types of costs indistinguishable. Additionally, the calculated costs have to be divided (allocated) between the different users present in the system based on the scale of use that characterizes the particular user. Several methods are proposed for allocating total costs to system users [55][39]:

1. **Postage stamp pricing**: A postage stamp rate is calculated by summing all network costs and dividing them with system peak demand therefore producing a fixed price. The customer is then charged for transmission by multiplying the postage stamp rate with the peak demand characterized by that customer. Today the postage stamp pricing method is considered unstable thus providing incorrect economic calculations. The customers are always charged with a fixed price without taking the current network situation in consideration and possible bottlenecks of the network are not taken into account. Yet, the simplicity for calculation makes it popular among electric utilities.

2. **Contract path pricing**: A contract path method for cost allocation creates a virtual (fictitious) path between the point of electric energy injection and its delivery (i.e. production facility and end consumers). The costs of transmission are then assigned to the predefined specific paths where the grid operator (acting as a controlling entity) has to be able to acquire information of all bilateral contracts between producers and consumers. Opposite to the postage stamp pricing, contract path takes distances between production and consumption into consideration. However, since the contract path pricing is based on a fictitious path (not dependent by the real network situation), there is high probability that the economical calculation will be wrong.

3. **Distance-based MW-Mile pricing**: A distance based MW-Mile methodology calculates the transmission charges according to the air distance (in miles) between the point of electric energy injection and delivery and the amount of energy that is transmitted (in megawatts). These costs are then charged to the involved entities where the total cost can be payed by producers, consumers or split between them. Regarding the correctness of the method we see that all drawback of the previously mentioned methods still apply.

4. **Power flow based MW-Mile pricing**: A power flow based MW-Mile methodology present more sophisticated price calculation by taking into account the real condition state of the network. It uses power flow analysis, prediction of future loads and generation configuration to allocate the costs for customers based on the scale of use of each network facility. There are several sub-methods proposed in the literature, such as *MW-mile, Modulus Method and Zero-Counterflow-Method* [39].

5. **Relay-based pricing**: A relay based pricing method applies transmission charges by the principle of its own name. The transmission costs are consisted of power flow expenditures and annual costs of maintaining transmission facilities along the path of the energy transfer. The key difference that characterizes this pricing method is that the costs of transmission are passed from node to node, charging customers on the

way that utilized the network. Moreover, the method has the advantage on top of other methods in the fact that utility (system) operator does not have to possess any knowledge about contractual agreements between producers and consumers.

In general, rolled-in pricing methods are one of the most used pricing mechanism in distribution and transmission pricing. The main idea is to proportionally allocate total system costs to connected users by measuring their total usage of the network. However, these methods are only cost-based and therefore some shortcoming such as the lack of integrated pricing components for the grid reinforcement process exist [55].

Incremental pricing paradigm

Incremental pricing paradigm is a methodology based on incremental costs[1]. The customers are charged with additional transmission costs that a transaction may cause to the system. Yet, the paradigm does not include the embedded costs of energy transactions. For calculation of the incremental prices, the authors in [39] propose the following methods respectively:

1. **Short-run marginal cost pricing (SRMC)**: Short-run marginal pricing scheme is based on the idea of bringing charging activities to each node, therefore establishing nodal or spot prices. The scheme should reflect temporal and spatial variations of the energy price regarding the observed energy demand but with the fixed capacity. In general, the idea is to model electricity markets with its various economical and technical specifications and optimize the system for the social welfare. This methodology therefore entails that electricity does not only need to be generated but also delivered to the end nodes and that along the way transmission constraints and electrical losses occur [39]. Regarding the economies of scale, SRMC does not cover the fixed costs of networks even in theoretical situations implying the need for additional charges.

2. **Long-run marginal cost pricing (LRMC)**: Long-run marginal pricing scheme unlike SRMC includes the possibility of change for the transmission capacity. Long-run scheme implies that no costs are by definition fixed. All the factors characterizing production, transmission and consumption are to be variable therefore presenting an optimization problem which carries out calculations for the optimal cost transmission capacity. In general, long-run marginal costs are costs of changing the overall system capacity (previously mentioned reinforcement of the grid), often represented in unit

[1] "Incremental costs are revenue requirements needed to pay for any new facilities that are specifically attributed to the transmission service customers" [38].

form. Such costs are also dependent on the estimation of the future energy consumption and peak loads. Lastly, it is important to observe that for the optimal capacity long-term and short-term marginal costs should be close to equal.

3. **Short-run incremental cost pricing (SRIC)**: Short-run incremental pricing scheme is a different pricing scheme than the marginal methodologies since it differs in the terms of cost definition. While it may sound ambiguous, in incremental pricing methodology *incremental* transactions have to be evaluated unlike the computation of marginal costs in SRMC. All new expenses that may appear are incrementally added to the transactions that are established on the path of the energy transmission. A problem may occur in the compensation process of the real costs since revenues of this model cover only short-run costs assigned to specific transmission transactions. Authors also propose the usage of the optimal flow model (OPF) to determine all the constraints and stability issues for cost estimation.

4. **Long-run incremental cost pricing (LRIC)**: Long-run incremental pricing represent an extension to the SRIC but still holds the shortcomings of the short run model. Minor difference is that LRIC holds the costs of the reinforcement for the network on long-run view. Such costs are characterized as cost changes between current transaction charges and long-term transaction plans.

Composite embedded/incremental pricing paradigm

The composite pricing paradigm incorporates both existing system costs and the incremental costs of transmission transactions [39]. The method solves the common problems found in both of the previously described pricing methodologies by combining advantages into one comprehensive and integral solution.

3.1.3. Cost allocation in tariff structures

Electricity networks include large numbers of mutually interconnected object whereas an object present any facility included in the production, transmission and delivery of the electric energy. Therefore, it is difficult to provide assumptions on the magnitude of marginal costs that occur in each node of the energy transmission path. Moreover, it is even more challenging to allocate these costs in every possible time frame for every customer and for every location that is connected to the grid. If this information would be transparent to all entities included in the energy trading process we could establish an optimal market case where the participants adapt their operation (and by that their overall expenses) to maximize the social welfare and keep the stability of the grid at a secure level. To solve the problem there are multiple factors and criterion that may be included in the tariff structure to effectively respond such as geographical factors, time-of-use information and fixed and variable elements in the grid. These factors are complemented with some abstract information regarding customer types, payment liability and type of service provided. Figure 3.1 shows an graphical representation of the mentioned influential factors.

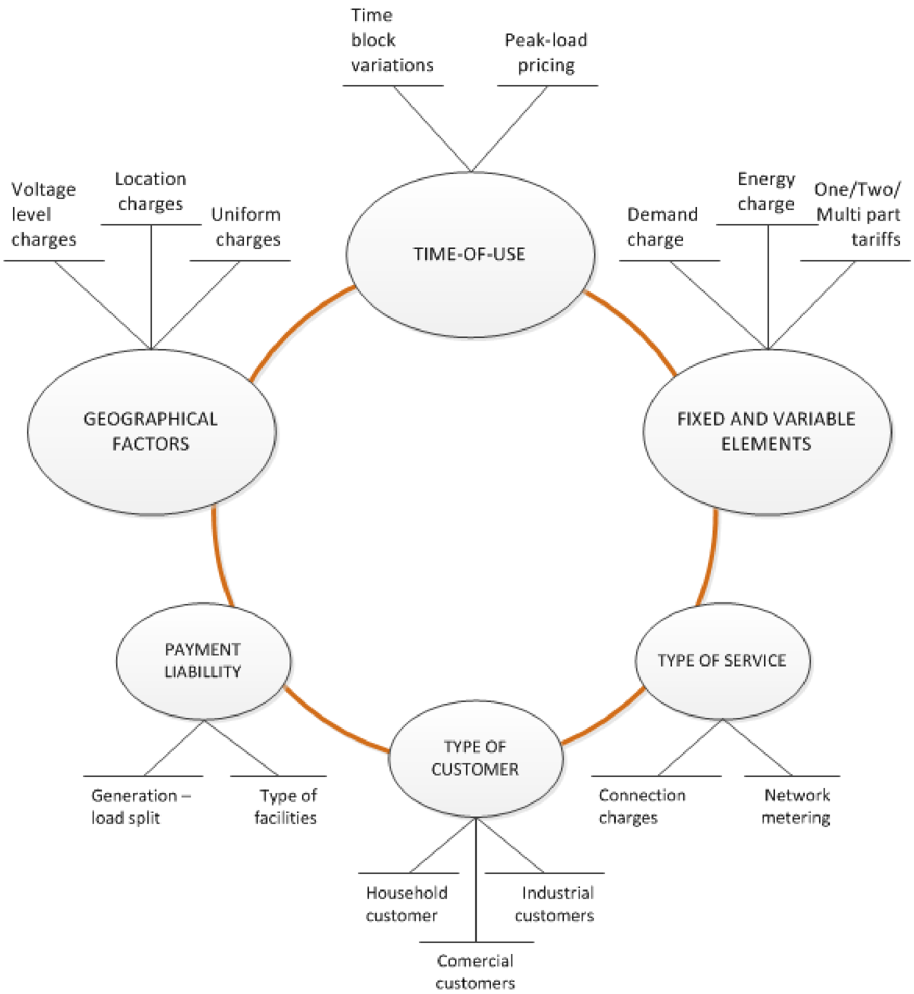

Figure 3.1: Influential factors for cost allocation and tariff creation

However, these factor form a basic tariff structure for entities involved in the grid. Electricity transmission and generally the whole provisioning process have highly nonlinear properties where the complexity grows if we take principles of planning of investments into consideration.

3.1.4. Tariff structure formulation

The goal of formulating a good tariff structure is to incorporate all important parameters that effect the overall energy provisioning process price. Parameters should be determined to fit the grid characteristic in the long run. The first and most important key factor that characterizes the tariff is its variability where we distinguish fixed tariffs and variable tariffs. The variable tariff structures formulations are gaining increased popularity over the old traditional fixed ones. Often when we apply the term variable tariff it implies that it is consisted of either dynamic pricing, differentiation of time or both.

Using differentiation by time in tariff design can result in truly dynamic tariffs [55]. However, not all of the components of a tariff need to be dynamic and time dependent. A good example is a tariff structure where the energy based components (price per kWh, load pricing, etc.) are calculated and charged on an hourly basis while some of the other components (connection fees, transmission fees, etc.) may have fixed charge on a monthly or even annual basis. This type of dynamic tariff design complements the features of Smart Grids where the development of new metering and load controlling technologies enables two-way communication between the production (as well as operators) and consumption entities connected to the grid. Why is real time communication important between an utility operator and a household consumer? The answer is simple; to increase the *smartness* of the electrical system and household appliances connected to the grid, therefore providing security, stability and more economic-friendly electricity transmission and distribution.

The second important characteristic of a tariff design is the basis on which the customers are charged regarding energy. Two different choices are available: i) charging energy regarding the extent of use (as price per MWh); and ii) charging based on capacity/load often called demand charge (expressed price per MW). In [48], the authors provide a brief comparison of the two mentioned pricing techniques. Table 3.1 shows the main difference in calculating prices as for the pros and cons.

Dynamic tariff structures may be divided into several important subgroups of time-varying characteristics. These subgroups include time-of-use (ToU) tariff, real-time pricing (RTP) tariffs and critical peak pricing (CPP) tariff. The subgroups are most commonly used in retail market structures where they represent the main means of charging end customers for the usage of electrical energy. Nevertheless, the structures provide flexibility in definition so they are also applicable for creation of transmission and distribution tariffs used in the backbone of the grid. Each of these would be examined in more detail in the further sections emphasizing the structures concerning retail market sales. Here we provide a brief high level description of the exact meaning and background behind the subgroup names.

ToU tariffs are based on the price variations for electrical energy under different blocks of time (e.g. morning, afternoon, night, etc.). Even though the prices are varying in time, ToU are often not classified as a dynamic tariff structure. Due to the fact that prices are often predetermined and fixed for the specific time blocks, ToU tariffs prices do not have to depend on the current state of the network leaving out all the unexpected costs that occur on an hourly basis (i.e. high load, network blackouts, etc.). On the contrary, RTP and CPP

Table 3.1: Comparison of different techniques for charging electrical energy

	Energy Charge	Demand Charge
Calculation	Revenue requir. / Energy transmitted	Revenue requir. / Relevant demand
Pros	- follows equity objectives	- reflects the network planing process (peak demand information for network design as well as causality between demand and cost)
	- considers the possibility of network usage in off peak periods	- compatible with peak load pricing (responsiveness to higher peak demand periods)
Cons	- allocation of sunk costs to energy quantities and distortions signals	- complete payment liability in a small number of time periods (often one)
	- possible negative effect on energy consumption and network usage	possible discouragement for network usage
	- can undermine causality principles	- network usage in off-peak hours
		- may lead to substantial differences in payments in case of different load profiles

provide real dynamic features to the tariff design. The prices vary in accordance to the prices on wholesale electricity market as of the current utilization of the grid (i.e. load). RTP has the highest degree of variations while the CPP is often combined with ToU tariff providing the operator the ability to call upon a critical peak load notification to the customers on a short notice (prices in these moment rise). Also, a modification of CPP tariff design is the peak time rebate (PTR) structure where opposite to the CPP, customers get a discount if their usage of electricity is below a certain threshold in certain critical hours.

3.1.5. Cost allocation on network consumers

In the previous sections we mainly focused on what should be priced in the transmission and distribution process and how it should be done effectively. Important factor that is missing is splitting costs of the electricity network onto connected entities. Particularly, when we talk about the retail electricity market and those tariff structures the question is if the end consumer takes all the burden and costs of the transmission process or does the generating utility participate with a certain level of contribution. As stated in [55], the author [49] discusses different possibilities of charging residual costs that are not incorporated in the tariff structure and may occur in different time periods. The proposition is to turn those cost in some sort of the tax that all of the end users connected on the grid share depending on the maximum peak load consumption. By end users we consider both consumers and producers, or more exactly the involved entities in energy trading. While distributing additional costs may be easy in the closed economy where all the participant are identifiable, the emerging electricity markets around the globe often combine more entities which make the overall picture unclear and often leads to non-optimal allocation. To conclude, it is important to address this issue in a more direct way in the future since the policies for charging additional cost vary from country to country. Moreover, costs should be allocated based on the extent of produced costs of every involved entity.

3.2. Time of use (ToU) tariff design

As we previously explained, time-of-use tariffs consider price variations during different time blocks. The analysis and discussion about this type of pricing mechanism date to the early 1950s where the pricing opportunities for electrical energy started to become interesting. In that time there were only theoretical considerations of applying time-of-use mechanism since the grid was starting to be more and more encumbered by the expanding set of newly connected users. The increasing problem of energy shortage and possibilities of new technologies made both producers and consumers to pay more attention to design and accept more effective pricing mechanism. These concerns have brought the noticeable attention to the ToU pricing mechanism as it is one of the several available solutions. With the ToU tariff the electricity price has two main allocations: higher price in the peak period and lower price in the off-peak period. Main goal of the tariff design is to stimulate customers having incentives to shift their consumption (of course, up to some extent) from the peak periods to the off-peak periods. It is clear that consumers do not have any incentives if their pricing tariffs are flat-rate (fixed pricing for electricity regardless of the time of usage) which leads to insecurity of electrical energy supply. It is also important to carefully design the tariff structure since only a win-win situation between producers and consumers will generate sustainable results. Customers are primarily concerned with the expenses and end monthly bills for their household while producers are concerned about the increasing generating costs which include building new generation units to provide the energy for peak periods (that most probably will not be used during off-peak periods). Recent finding show that deployed ToU tariffs provided up to 41% reduction of electricity usage during peak periods in the United States (Gulf Power Select Program in Florida) and up to 9% reduction in

Norway (a member of the Nord Pool Spot[2]) [25][60].

3.2.1. Historical experimentation

Some time after the theoretical propositions of the mechanism, residential electricity experiments became popular so the stakeholders in the electricity provisioning process could acquire empirical data about common user practices regarding energy consumption. In [12], the authors provide an econometric analysis of residential time-of-use pricing experiments conducted in the 1977 in Wisconsin (United States). While the analysis may sound outdated since it goes back to the year 1980, the authors provide significant results regarding elasticity estimation of energy usage in residential areas and consumer behavior. The experiment had to stages consisting of the elasticity estimation of energy usage in the first stage and affect of the allocation of total customer expenditures on that elasticity. For the first part the data yielded from the monitoring process of a control group with the size of about 600 people was reliable, while for the second part of the economical analysis the data was less reliable since other expenditure for different customers were hard to predict and allocate. To begin the static analysis they adopted the assumption that the elasticity of substitution of energy loads will be constant (e.g., constant elasticity of substitution, CES) and two high peak periods were determined. However, they proposed three different solution of the time frame (lenght) of the two peak periods: i) six hour peak; ii) nine hour peak; iii) twelve hour peak. An interesting fact is that regardless of the time used peak time periods, customers were charged with the same price of energy therefore not affecting their total bills. Results show that the estimated elasticity for the experimentally obtained data is very small, but statistically significant for the proposed different peak durations. This surely implies that the electrical energy consumption was able to be shifted[3]. Additionally, the second stage analysis showed that customers income did complement the extent of load shifting. However, these implications at that time did not provide any information about the costs and benefits of that type of shifting and the optimal tariff structure that could be used, but they did set steady grounds for today's research and application of the ToU mechanism.

[2]Nord Pool Spot runs the leading power market in Europe and offers both day-ahead and intraday markets to its customers. 370 companies from 20 countries trade on the market. In 2012 the group had a total turnover of 432 TWh, which includes the auction volume in the UK market N2EX [2]

[3]It is important to take into consideration the time of the analysis and the overall energy usage in 1970s. Number of everyday appliances was surely smaller than nowadays and the consumption of electrical energy was significantly lesser. This emphasizes that even in those specific cases it was possible to shift energy usage to off-peak periods.

3.2.2. Present application of ToU pricing

Unlike the historical experimentation, present application of ToU pricing patterns differ even in the most basic assumptions. While the previous analysis specify the constant elasticity demand functions for each hour, the authors in [13] promote the usage of monthly linear demand function. Additionally, analysis for cross-price elasticity between of pricing for different time blocks is considered. Combining these two assumptions with the fact that perfect competition condition cannot exists in reality and the fact that market has a large influence on the analysis we are moving towards stable grounds for further improvements.

An interesting proposition was made by the authors in [60] where a two-layer model for designing ToU tariffs is discussed. First they divided time into two periods naming them peak period and base period respectively. In the upper layer the producers analyze the current grid and consumption load and decide about the prices that will be applied in both time periods. On the other hand, the lower-layer concerns about the customer behavior, trying to parametrize and formulate their actions to fit the behavior model into the tariff design. As we mentioned before, consumers have the incentives to shift their load, but only if that is going to reduce their overall electricity costs. For example, customers who are subscribed to a ToU tariff will consider washing their clothes in the peak time periods if they can easily shift the action to an off-peak period. Yet, the customers on a flat-rate tariff will not do the same since there is no difference in the cumulative costs that can occur. They will plan the energy consumption to suit their everyday schedules and needs, without concerning about the total energy demand in the network.

Therefore the load shifting under ToU can reduce the total electricity charge, but there might be some additional *costs* that the consumers may experience as they have to arrange all the resources prepared for a change. These costs are not directly connected to the electricity price but more to the routine or activity shifting which can cause losings in other aspects. However, the extent of *the shifting costs* [60] depends on the amount of the energy that will be shifted. It is clear that the more energy a consumer shifts into off-peak hours the more of the shifting cost he has to withstand. In other words, a consumer can easily shift small loads while big loads will be difficult to shift. This fact implies that every user will consider shifting its energy consumption only when the total price difference is larger than the marginal costs that will occur. For extremely low off-peak prices, customers are likely to shift all of their consumption (or at least a high degree of max consumption) as it will bring profit to them. In situations where the difference between the peak and off-peak price is small we can presume that consumer will be more reluctant to do the change. The results concerning the conditions in which the ToU tariff is beneficial for all entities are showed in [60] as a comparison to flat-rate tariffs. By analytically deriving the optimal optimal tariff scheme under various costing environments the analysis points that a proper adoption of the time-of-use tariffs creates a win-win situation where producers increase their overall profit and consumer reduce their electricity costs.

3.3. Real-time pricing (RTP) tariff design

Research on the real-time pricing strategies for electrical energy has started in the early 1980s. Variable pricing achieved its popularity by introducing competitive electricity markets where the producers could adjust their generation levels based on the current prices of energy. In [5], the authors emphasize the importance of real-time pricing for active power as also for the reactive power. The term reactive power can be compared with power factor penalties that evolve from imbalances between production and consumption. Research body in that time focused on generating load management schemes to exchange existing rates with real-time prices and optimize investment conditions for revenue maximization.

If we look from the end customers point of view not all of them would be willing to switch from fixed price tariff designs to real-time pricing. Household enrolls and signs the contract with the new tariff design only if the expected utility is greater than the utility of the current subscription. It also depends on the customers possible responsiveness to the hourly price change where some customers do not need shifting of their loads because they already have low consumption in high peak periods of the day. A common complaint about the tariffs that change rates on an hourly basis (related to the wholesale price) and the reason why the customers are reluctant to transfer to these tariffs is that these dynamic pricing tariffs require customers to monitor hourly retail prices in order to decide whether to reduce demand for the specific time period on a specific day [58]. Additionally, these monitoring actions require further assessment from the customer since the decision that they make has to be profitable (i.e. price difference might not be so high so the shifting or reduction action will cause more *loss* than paying the full price for that period). The intention to transfer to a real dynamic pricing tariff may be more viable with the introduction of smart metering equipment that could control high consumption equipment (like heating and cooling systems) autonomously considering the price level.

3.3.1. RTP effects on households

In [1], the author presents results of an experimented conducted in the United States concerning the RTP responsiveness of household customers who accepted to participate in the analysis. The experiment was conducted in the are of the Chicago city where one of the non-governmental organizations (NGO) named Center for Neighborhood Technology (CNT) proposed the Energy-Smart Pricing Plan (ESPP) to test whether real time pricing could incentivize significant reductions in peak electricity demand and make customers use the energy more rationally.

The current situation on the electricity market at that time was strongly controlled by the state since the procuring events and crisis that occurred in California brought up the awareness and attention to the changes in the electricity trading process. To acquire households for the experiment extensive advertisement need to be done. Moreover, previously established channels, made by other environmental projects by the same organization were used to get to the customers. In the end, a group of 800 household applied for the analysis. Not all of them were offered new contracts since the process of enabling RTP required new installations in the metering system. Therefore, randomization algorithms were used to maximize the diversity of the controlled groups regarding the size of the households, their overload consumption and number of people involved. The experiment itself lasted for eight months.

The overall results show that above all the household customers are price and consumption elastic. Customers reacted to high price alerts available to them through the newly installed equipment and reduced the consumption during high price periods and respectively lowering their final bill. Another important fact that was observed is the overall net value of the consumed energy which was different than the expected. What can be concluded is that RTP causes household to significantly reduce the energy consumption during peak hours (afternoon and evening when most of the residents are at home an mainly all the appliances with the lightning works). However, the assumption that the reduction in peak hours would cause a major increase of the consumption in the night turned out to be false.

These finding about the net energy being conserved instead of shifted can be explained by the technologies available to households which do not enable customers to react appropriately to RTP [54]. To establish exact reasons why the net consumption was reduced, a small survey was conducted on the controlled groups that participated in the experiment. Results indicate that the major changes they made through the participation in the program were mostly visible by actions such as turning off the lights, using fans instead of high consumption air conditioners, turning down and replacing old air conditioners, and using household appliance (dish washing, washing clothes, etc) during low price hours. Only the last activity introduced shifting of the consumption from one hour to another while other activities are based only on energy conservation. There results also imply that the RTP positively influenced to reduce short-run air pollution emission from electricity generation as from the air conditioners operation [1]. Moreover, looking at the net value of consumption we can see that the capacity loads of both baseload (working all day) and peaker power plants (only during high peak consumption periods) were changed. The load that power plants are facing is more correctly distributed lowering the costs of the production [45]. It is important to emphasize that these result are bound to households whereas the generalization of the observed indication cannot be applied to, for example, industrial facilities which can respond to RTP changes through different schedules of their production processes.

In the near future we can expect this results to shift towards the opposite. Conservation of energy will reach its maximum and if the RTP is to be deployed in vast areas, shifting will become of greater importance. Additionally, new products that emerge in the electricity management field as for the new products like plug-in hybrid electric vehicle (PHEV) will enable automatic resource allocations through low peak hours leaving customers just to schedule (or even automatize the scheduling of) them according to the prices of future energy.

Aggregated affects on the complete market process

The main question is how would the real time pricing mechanism, such as ESPP, affect the market process if it were expanded to a larger group of end consumers? The observations show that it would influence the equilibrium prices of a restructured wholesale market through three different factors: i) the changes in demand would result in new equilibria along the existing aggregate supply curves; ii) increased short term price response would affect producers' profit-maximizing bid markups, inducing them to bid closer to marginal cost; iii) lastly, RTP would change incentives for entry and exit and affect the market institutions that govern total system capacity, the reserve margins and the capacity market [1][54].

3.3.2. Peak-load reduction using RTP

In [47], the authors propose a method to reduce peak electricity consumption in office building by applying model predictive control and real-time electricity pricing. More specifically, they propose a tariff design which will address the energy consumption in building climate control and therefore reflect the marginal costs of electrical provisioning process. To specify the tariff design and pricing algorithm it is important to incorporate price-optimal factors along with the energy-optimal factors which are often in contradiction. Furthermore, the tariff utilizes the information regarding spot market prices[4] and measured electricity transmission and distribution grid loading. The authors use the time series of previous spot market prices and load levels on the electric grid to acquire average values for both variables. These variable are then multiplied with relative weights calculated on previously based data. Additionally, the factor of mandatory city concession is added to the price. The time-series of spot market prices is acquired through European Energy Exchange (EEX) where the prices of fu-

[4]Spot markets are commodities or securities markets in which goods are sold for cash and delivered immediately. Contracts bought and sold on these markets are immediately effective. Spot markets are in contrast with futures markets in which delivery is due at a later date (forward physical market).

ture 36-hours horizon are announced at midday. Within their proposed tariff a grid-friendly behavior characterized as low consumption demand during peak consumption periods is rewarded with low prices of energy for the end consumer. Conducted analysis show that peak electricity demand in office building for climate control can be reduced by incorporating the proposed tariff design. However, the results show an increase in the overall price implying that the scaling of the tariff needs further adjustments for the customer to benefit from signing new contracts on that tariff.

3.3.3. RTP - ToU comparison

The section follows a brief summary made by the authors in [13]. In the past decade there has been numerous studies in the research body regarding the efficiency and social-economic effects of RTP in regards to single pricing (i.e. monthly, seasonal or yearly flat rates) and seasonal pricing achieved through seasonal and daily ToU mechanism (i.e. seasonal is referred to different prices during, for example, summer and winter, while daily is referred to multipart tariffs with two or more rates on a one day basis). The main focus of the studies was to perform experimental research of potential efficiency that could be gained by introducing RTP and to what extent would these mechanism sensibilize end users consumption. To be more precise, authors in [9] have focused on the long-run efficiency gains with consideration to the capacity investments (previously mentioned *reinforcement* of the grid) and long-term welfare transfers. The calculated gain ranges from 3-11% of the total energy consumption charge if the RTP pricing is adopted. While in the long-run we can see that the results are noticeable, authors in [31] inspected the short-run efficiency gains where the main focus is on short-run social welfare as of the marginal costs on the network. The results obtained show modest cost savings with the value of 0.24% and 2.5% of the total energy consumption charge if all connected customers transfer to RTP pricing. Comparing these results to the seasonal ToU, the author in [8] simulated that on the long-run, the ToU mechanism achieves only a quarter of the cost reduction obtained by the RTP. However, short-run efficiency gains show slightly better result ranging between the third and a quarter of the RTP cost reductions.

3.4. Critical peek pricing (CPP) tariff design

Critical peak pricing tariffs fall under the general group of dynamic pricing tariffs retaining its major challenge: to design a tariff that will deliver tangible benefits to the electricity consumer but without exposing them to high risk situations (customers are not keen on transferring to a dynamic tariff that just changes the prices on the basis of the wholesale market since the market events may not be stable and predictable) [29][58]. It is important to emphasize the difference between a CPP and ToU tariff design. Design of a ToU tariff follows common practices of setting different tariff rates for different times of the day (i.e. one price in the morning, second price in the afternoon/evening and third price during the night). Thus, a CPP tariff is often based on a fixed retail price during the whole time of the subscription but with the possibility to call upon a *CPP event*. A CPP event is an occurrence where the retail seller of the electrical energy pushes information to the customers informing them about a time period where the demand may be to large and impossible to satisfy so that they should reduce their loads (of course, the information also contains new prices for that specific period). With the possibility for the retailer to declare the *event*, a problem, generally called *the moral hazard problem* arises which we discuss in one of the following sections. Also, CPP may be introduced in some additional forms where one of them is the CPP with the rebate option. We focus mainly on this variation in the next section since it has distinguishable differences.

3.4.1. CPP tariffs with the rebate option (CPR)

A special type of a critical-peak pricing tariff is a CPP tariff with a rebate (CPR). The CPR sets the tariff rates and marginal prices approximately at the same level during the CPP event. The difference in the tariff design is that CPR offers customers a rebate which depends on the amount of electrical energy consumption during peak time periods [58]. For example, a critical peak pricing period is declared to be from 2 p.m. until 10 p.m. and the marginal price for electricity depends on the market price (or it can be set as a fixed retail price, but with a significantly higher price). If the customers consumption level is under the prespecified reference level, the price for the electricity has a certain amount of rebate. However, if the customer consumption goes over the threshold, the customer pays the full retail price of the energy. In contrast to that, a customer on a regular CPP tariff pays the higher price for his consumption regardless on the amount of energy consumed. Therefore, the CPR tariff is more user-friendly in a way that allows the customer a choice of either taking actions to reduce demand during a critical peak period or not, with the only consequence being that the customer will pay for the electricity at the standard and fixed price for that particular period. Even though the CPP tariff rates are roughly the same (but definitely always higher) as CPR tariff rates (taking into consideration the included rebate for the CPR tariff), the demand reduction during a CPP event is around 50% of the magnitude of the demand function that was achieved by the same type of customer, but on a CPR tariff [58]. This clearly shows that the rebate option is a good incentive for customers to level their consumption and reduce it on a larger scale during peak periods.

Although CPR tariffs addresses some potential disadvantages of the CPP tariff, some downsides still exist with the implementation and design of the tariff. Particularly, complications arise when calculating and setting the reference level for a specific household since the variability observed in the households' consumption curve can be enormous. The reference level, is of course, based on the consumption curve without the declared CPP event. The vast amount of historical data is needed to establish an accurate model (more precisely a model that compares similar situations in particular days and according to that produces a reasonable reference level). Thus, the historical data may not always be useful regarding the baseline inflation problem (customers different behavior on lower prices) [59].

Another shortcoming of the CPR tariff (but not from the customers' point of view) is the *option-to-quit* action which considers that a customer does not reduce its demand in a CPP event. This is due to the fact that prices in a CPR tariff do not go higher if the load stays the same, thus they remain fixed and customer does not receive any rebate. The pure CPP customers do no have that option since the price for electricity gets very high during the CPP event. This leads to very different behaviors among some customers. Usage type that addresses this problems is clearly described in [58]. Let us presume that before a CPP event is called upon (in most cases its a one day ahead warning) there are two possibilities that may occur regarding the uncertainty about the customers intentions to reduce their demand. The first possibility entails that it is relatively low-cost to reduce the consumption under the fictive reference level, while the other one presents a extremely costly solution if the demand is reduced (with consideration that some small amounts may still be excluded). The externals that cause these two different possibilities are numerous (i.e. weather conditions) and are not important for this particular point. The customers who are facing the CPP pricing levels still have the incentive to reduce their demand, yet a CPR customer who predicts high cost for demand reduction will continue to use the power normally and thereby not reducing its consumption (since the price would not grow). By observing the realized consumption curves of both customer types we may observe the difference and that difference is the consequence of the *option-to-quit* possibility. Nevertheless, if designed carefully, a CPR tariff with some extensions (to eliminate the shortcoming and introduce more incentives for demand reduction) may be very profitable for all entities included.

In the end, CPR tariff has a similar variant named peak time rebate (PTR). The implications are the same with the difference that in some cases the PTR tariffs are considered mandatory since there is no downside for the customer. Each customer gets its own calculated baseline (or more exactly threshold) based on the average consumption of the household [57].

3.4.2. The moral hazard problem of the CPP method

A customer who is subscribed on a CPP tariff pre-commits to the possible periods of high tariff rates during a called CPP event. The disadvantage that a customer may perceive is related to the price level that a retailer can set during a CPP event thereby creating a moral hazard problem for the retailer. For example, a electricity retailer may charge substantially higher rates than the standard fixed rate during the CPP event that are also much greater then the costs for providing the energy to the customer [58]. Thus, a retailer earns enormous revenues both because of the large price but also for the reduced demand which in the end influences positively on the transmission and distribution prices. Additionally, by having insight in the demand load, retailer can predict the CPP event's degree of consumption reduction and use that information for trading energy in the day ahead market (specifically wholesale market). This brings stable conditions for the retailer to balance his retail obligations to customers with his activities concerning the purchase of electricity and therefore earning more profit.

A common solution (but still with some downsides) to address the moral hazard problem is to pre-commit the opposite side (the retailer) to a limited (small) number of CPP event that can be called during a specific time period. In this way the retailer is limited and if all the events are already used the retailer cannot call upon another one, even if the prices of the electricity in the wholesale market are substantially higher. However, the basic feature of the CPP tariff design related to transferring the whole burden of electricity trading (purchase) to the customer, remains. The retailer faces no risks upon declaring a CPP event, even if the wholesale prices are not higher than the regular average. Therefore, the customer may be charged with a much higher implicit wholesale price providing excess profits for the retailer. This fact does not motivate the retailer to reduce the number of declared events, but the bare opposite; the retailer will most likely declare the maximum number of CPP event that was declared and pre-specified in the contract [58].

To completely eradicate the moral hazard problem for retailers the previously described CPR is used. As mentioned, on a CPR every household (or a specific customer) has a reference level for energy consumption which if not crossed entails the application of a rebate to the overall costs of electricity. The CPP with rebate addresses the moral hazard problem for retails with the consideration to the CPP pricing because retailers are now faced with a revenue risk when declaring a CPP event [59][58]. The CPP retailer is obligated to pay the rebate if the households do not go over the specified reference level. Moreover, if the customers extensively reduce their consumption during the event a retailer faces substantial losses (considering that the event might be called when the wholesale prices are not to much higher). This way of price calculation and rate application provides a stable and strong motivation to the retailer not to declare CPP events if the rebate payments that have to be paid to the customers would not be covered by the cost savings on the wholesale market. Therefore, customers are relieved of the perception for disadvantages of a CPP tariff scheme. The risk is now shared between the customers and the retailer providing a win-win situation for both of them if the characteristics and opportunities that a CPP tariff holds are utilized to the utmost extent.

3.4.3. CPP effects on potential customers

Numerous analysis are being carried out to test the effect of the CPP tariffs and to analyze their efficiency. Several factors are important when comparing and rating the result such as the degree of load reduction that a particular CPP tariffs achieves, the price multiplication for the CPP event, aggressiveness of the tariff design (i.e. maximum number of declared CPP events in a closed time period).

In [30], the authors discuss the results of the exploratory analysis of California residential customer response to critical peak pricing. In the experiment participating customer received up to 15 high price signal (CPP events) from the local electricity distributing utility during one year period. The total amount of time where the CPP effects were analyzed was 15 months where the data about the consumers load was collected on an hourly basis. In some households of the involved customer smart metering and control technologies were installed (more specifically, air conditioning control system which is responsive to the current price received through price signals). Finally, the price of the electrical energy in peak periods was roughly three times bigger than in the off-peak periods where a regular time-of-use tariff was applied. The results show a significant load reduction for households with and without the smart controlling technologies. During 5 hour CPP events a reduction of 13% is observed for customers without the controlling technology. Participant with those communicating thermostats show even more load reduction ranging from 25% for a 5 hour CPP event up to 41% for a 2 hour CPP event. The authors concluded that the residential sector may provide substantial contribution to balance the retail demand response thereby increasing stability of the wholesale market system and the security of the whole grid.

Another experiment that supports the findings concerning load reduction is discussed in [58] where the author presents the results of the PowerCentsDC[5] Program experiment. The

[5]PowerCentsDC™ is a "smart" meter pilot program for approximately 800 to 900 customers of Pepco DC. Participants – who will continue to be customers of Pepco – received a smart meter, a smart thermostat (if desired and the residence qualified), and new energy price plans that allow savings for customers who reduce

analysis was carried out on a specified number of voluntary customers who were divided into subgroups based on their electricity usage activities and modes (i.e. regular households, household with only electric heating, etc). This experiment also incorporates the usage of CPR tariffs as an addition to the regular CPP tariffs. The results show that the dynamic pricing program provides stable predictable and sizeable demand reduction for all customers involved. Additionally, by observing human behavior they concluded that the problem with CPP tariffs regarding the need to take actions to reduce consumption (which is costly to the customers) does not appear to be economically significant so all consumers should be able to manage their actions without losses. In the end, CPR tariffs provided isolated cases where the reduction was not accomplished due to the previously mentioned *option-to-quit* case. Nevertheless, once more the result confirm the significant load reduction with the CPP tariffs are confirmed.

3.5. Feed-in tariff (FIT) design/policy

A feed-in tariff (FIT) is an energy supply policy mainly focused on supporting the development of new renewable energy (RE) projects by offering long-term purchase agreements for the sale of RE electricity [32][19][6]. Regarding the terminology and the market policies in the U.S. where the agreements are based on renewable energy certificates (REC) it is hard to exactly define FIT since it can be observed as the sale of electricity or as the sale of the electricity and renewable energy certificates. These purchase agreements are often offered as long-term contracts to encourage different entities to participate. The payments and charges vary due to different technology types used, project sizes and locations and quality of resource to fit the actual costs of the investment (project). Policies such as FIT are present in the market for over twenty years, but their deployment and practices differ from country to country. To additionally encourage the adoption of FITs and to boost the investments, some countries introduce policies that include fast administrative procedures to shorten the overall time for approvement, reduce bureaucratic overhead, minimize project costs and accelerate the pace of renewable energy development. Moreover, eligibility for FITs is not bounded to any specific customer/consumer group but on the contrary even extended to anyone with the intention and possibility to invest (i.e. household, companies, government/state projects, pri-

consumption during hours when wholesale electricity prices are high. It is sponsored by the Smart Meter Pilot Program Inc., a non-profit organization comprised of the Consumer Utility Board, the District of Columbia Office of the People's Counsel, the District of Columbia Public Service Commission, the International Brotherhood of Electrical Workers and Pepco.

[6]NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

vate investors, various profit/non-profit organization)[7][42]. Thus the successful FIT policy contains three key features: i) grid access is always guaranteed; ii) agreements are long-term (approximately 15 to 20 years) and purchases are stable; iii) payment levels are based on the costs of energy generation (therefore minimizing risks of costly investments).

History of FIT Terminology

Throughout the time since the FIT policies were launched numerous different names were used to describe them. Note that over the time, the change in names is a direct consequence of the increased evolution of the policy. The term as we now it today is coming from the Germany's Stromeinspeisungsgesetz that was literally translated to "Electricity feed-in law" in English. The concept entails that electricity is basically "fed-in" to the grid. Nevertheless, many other terms has emerged such as fixed-price policies, minimum price policies, standard offer contracts, feed/feed-in laws, advanced renewable tariffs and among the recent new names we have simplified names such as renewable energy payments or renewable energy dividends [33].

3.5.1. FIT policy goals in tariff development

In [19], the authors summarize three groups of goals of the FIT policy that are primarily intended for future policymakers as a guide to effectively target specifics of a FIT design. If the process of design and implementation is carried out carefully feed-in tariffs can be used to target precise goals of a specific policy maker. Note that the three groups of goals named respectively as primary, secondary and tertiary may be characterized differently depending on the jurisdictions where the policies are being applied. Contents of this section closely follows tables, figures and enumerated elements found in [19].

Primary RE policy goals

Primary goals include the most frequently named reasons for implementing policies to boost up the renewable energy development. Rapid renewable development (RRD) is the first goal which has to be met in order to attract many investors and high capital to develop renewable energy production rapidly. Investments may be additionally encouraged if a the technology offered is more wider since the opportunities for stakeholders with diverse goals

[7] In [42], the authors emphasize that not all renewable energy policies have to have these characteristics. The terminology problem arises once more and is still confusing what a FIT exactly constitutes. Nevertheless, to resolve the inconsistency we may differentiate types of FIT as cost based and consideration based (i.e., avoided costs, notion of value, etc.

are more likely to fit their needs. The goal implies undertaking of necessary actions regarding the approval process where the administrative burden and time-to-approval should be minimized. In the starting time of the policy, the attention of potential investors has to be drawn by pricing methodologies. A tariff price based on the RE project costs with the space for additional profit will certainly attract potential customers. Also, eligibility for subscribing to the FIT should be expanded to the utmost extent, allowing anybody with resources to participate. Thus, project size caps are not to be set (minimum or maximum) since they may lead to discouragement of large and very small interested parties.

Two other goals in this group are concerning jobs and economic development as well as greenhouse gas reduction. The emphasis is on creating a strong and stable (and rewarding) policy that will bring social and economical welfare to the local community. The tariffs should be differentiated by prices according to the size of the project and used technologies (more preferred/less preferred) and by that ensuring possibilities for more diverse projects but also for the wider technology sector where the project come from. Additionally, if introduced with reasonable incentives, the policy may create a favorable environment for green manufacturing. The transition to green manufacturing and usage or RE from various forms (concentrated solar thermal energy, wind energy, bioenergy) undoubtedly reduces high carbon emissions and slowly exchanges primer ways of generating base load electricity.

Secondary RE policy goals

While they are not the primary drivers for adopting FIT, secondary goals include the next most important reasons for FIT application and therefore include cost minimization and policy transparency. To minimize costs, the policy has to have long-term stability providing low capital cost and elimination of inflation adjustments (which are often inevitable). Transmission protocols (in cases of queues) must be effective to eliminate bottlenecks and minimize litigation while at the same time taking care of administrative action to be smooth and quick reducing the needed time and money. Additionally cost minimization can be achieved by constraining capacity caps on some of the newest (costly) technologies (this is thus opposite to the previous thesis that no caps should be set on the capacities, but note that a big disproportion of the actual capital investment and the income can result in a lose-lose situation for all entities included in the process if there is nobody to continuously finance the most probably very costly generation).

Another goal implies the need for policy transparency which directly influences the number of people who are wiling to participate and take advantage of the policy. A transparent policy may be characterized with stable tariff rates that are not discriminatory and are consulted with public opinion on their determination. Also, all FIT payment adjustments are on time announced to the stakeholders. Moreover, transparent policy is simple in design and based on clear protocols for tariffs that are very well documented publicly and updated regularly. In conclusion, higher policy transparency results in a lower risk which influences cost minimization.

Tertiary RE policy goals

Lastly, tertiary goals are related with additional goals that can be addresses to an already well-designed FIT. One of the most important goals is the displacement (replacement) of traditional base load technologies such as carbon coal and crude oil. By designing aggressive tariffs for renewable energy generation carbon emission can be reduced especially in the regions that depend heavily on the coal generation process. Due to the different structures and shares of generation processes in different locations, this goal might not be so important in areas where RE is already common (i.e. areas with vast amounts of hydro-electrical power plants). The repeatedly cited problem in this thesis regarding peak load has its place in the FIT design also. Incentives are given in a form of higher and more profitable tariffs are given for the usage of technologies that can modulate electric generation to complete the needs of peak period demands. Therefore, the RE generation in peak demands reduces costs to society significantly, maximizes the grid stability and security and as a consequence reduce intensive emission that characterize those periods.

To support and boost up local economic benefits, policymakers may offer higher tariff contracts for community based-project. The reasons are in the empirical facts that community projects have a greater job impact and overall economic outcomes than outsourced project funded by outside investors. Additionally, by differentiating tariffs and constraining the maximum share, that any individual may own, can promote partnerships and help RE developers to better scale their project for the optimal size of the grid. RE generators should also be encouraged to use high efficiency systems that reduce the release of any pollutants (waste management and exploitation is also considered as a contribution to the overall efficiency of a particular facility or community). In the end, policymakers in a particular jurisdiction may propose and introduce bonus payments for innovative projects that adopt new technologies (i.e. offshore power generation, usage of emerging technologies such as ocean, wave, thermal, storage, state-of-the-art grid integration technologies, etc.)

3.5.2. FIT pricing methodologies

FIT pricing methodologies are one of the most difficult challenges for a FIT policymaker since they are responsible for determining the actual tariff rates for project developers and investors in RE electricity generation [19]. Looking at the overall overview of available and used FIT pricing methodologies we may see that a variety of approaches are used to complement the policy goals discussed in the previous section. All of the approaches can be considered as a special case of establishing tariff rates and can be divided on the basis of establishing their calculation respectively as (also note that these approaches are generally cost-based because of the goals and policy imply cost coverage of RE generation):

1. **Market research and empirical analysis**: Using market research and empirical analysis of the current pricing flows regarding the renewable energy it is possible to determine tariff rates. Research provides security that the price levels will be adequate so the emerging projects are profitable to its investors. This approach is used by some European countries (Germany and Spain) and in the province of Ontario (Canada) [19]. It is important to emphasize that this is the most commonly used approach where the analysis itself is carried out by outside consultants or government agencies. Additionally, the market conditions are changing very often so the analysis has to be repeatedly exercised to ensure stability.

2. **Auction-based mechanism**: Auction-based mechanism is a cost-based approach that entails the market activities directly to establish tariff rates rather than observing market through analysis and consequently define prices. Auctions are completely separated from the FIT policies and are just used to inform policymakers of appropriate prices for projects carried out in different locations and time periods. This approach in its various forms is mentioned in several papers and online articles [35][27][50]. Information leads that the mechanism of this method is used in Spain, China and for various of technologies in India.

3. **Profitability index method (PIM)**: The PIM method is the last considered approach which basis the calculation of tariff rate on the targeted profitability of a specific renewable energy generation project. The method represents a comprehensive mechanism for calculating resource-adjusted FIT price levels which will ensure profitability and was used in France during deployment of wind generation facilities on the western coast [14].

As we already mentioned, these approaches are cost-based. A more general categorization of approaches may be done as follows:

- **Approaches based on real-world scaled costs of renewable energy generation** represent on of the most commonly used approaches used in Europe but also in the Americas. Its success lies in the ability for intense driving of renewable energy development across the globe.

- **Approaches based on the *value* of RE generation** that the society (e.g., greenhouse gases reduction – climate change mitigation, energy security, general health) or a specific utility (e.g., time and location when the energy is *fed-in* to the grid, utility costs) perceives. The approach can generally be found in terms of *avoided costs* and is more popular in the U.S. (more specifically California) and in British Columbia but it has found its place in Portugal too.

- **The simples of all approaches is presented as a fixed-price incentive** that offers a tariff rate with no consideration about the real costs of RE generation, avoided costs nor on the notion of value [18]. Approach is used by certain utilities (policymakers) in some areas of the U.S. but with bad results on encouraging significant development and deployment of the RE generation facilities.
- **The last approach based on the auction and bidding results** helps the price calculation by accessing market resources directly. The auction-based mechanism is one example of this approach and thus is used to apply different pricing to projects based on their market effect, project size and technology.

As the diverse approaches explained here indicate, the FIT policies are complex and their long evolution since the first implementation (1978 U.S. PURPA policy) adds to that. Such policies may sometimes be hard to establish and not all establishments are successful. Related to that the next subsection summarizes the advantages and disadvantages of the FIT policy that were discussed in [19].

3.5.3. Advantages/disadvantages of FIT policies

A brief comparison of pros and cons of FIT policies is given in the Table 3.2 :

Table 3.2: Advantages/disadvantages of FIT policies

	Advantages	Disadvantages
Economic	- offers a secure and stable market for investors - significant growth of local industry and job creation - only costs money if projects actually operate - provide lower transactions costs - may secure fixed-price benefits - distributes costs and development benefits equitably - settle uncertainties related to grid access and interconnection - enhances market access for all stakeholders	- near-term upward pressure on electricity prices - distortion of wholesale electricity market prices - does not directly address the high up-front costs of RE technologies - not market-oriented (must-take provisions) - may exclude lower-income individuals from participating - may be difficult to control overall policy costs - does not encourage direct price competition between project developers - challenging to incorporate within existing policy frameworks and regulatory environments
Other	- measurable impact on RE generation and capacity - encourages technologies at different stages of maturity - may be applied without linking avoided costs - high level of cost efficiency and effectiveness	- could lead to less-than-optimal project siting (due to guaranteed connection) - requires an up-front and continuous administrative commitment - needs for a long-term policy commitment - temptations to over-exercise the flexible nature of the FIT policy

4. Agent-based software platform for hosting intelligent trading agents

In Chapter 2 we discussed the implications for various electricity market designs and ways of modeling and simulating those markets. The models briefly described there are often useful to view many details about the activities on the market but also limited to incorporate different strategies and its effects of individual market participants [6][3]. Therefore the element of competition between different market participant in the simulation platform may help to purify the design of various markets. This competitive approach proved successful in the study of numerous innovations under the Trading Agent Competition (TAC) forum. TAC forum format was used for many competitive simulations such as TAC Classic (assembling and trading of travel packages), Supply Chain Management[1] (TAC SCM), Ad Auctions[2] (TAC AA – trading with keywords in sponsored advertising) and TAC Market Design (designing of market rules). A simulation platform that combines market agents and the element of competition in the electricity market simulation platform is Power Trading Agent Competition[3] (PowerTAC) [36].

4.1. Power Trading Agent Competition specification

"Power Trading Agent Competition (Power TAC) is a recently developed smart grid power market simulator that represents one competition scenario of the Trading Agent Competitions (TAC) international forum. According to the recent liberalization of power systems, the idea of Power TAC is the development of agent-based architectures which will provide realistic tests for the creation of future electric power markets" [41]. "The concept of the PowerTAC relies on the role of broker that serves as an aggregator of supply and demand for energy, which embodies software agent market at the level of program implementation" [3].

Thus, the formal definition of the competition is given in [36] as: "PowerTAC is a competitive simulation that models a “liberalized” retail electrical energy market, where compet-

[1] Official website of the TAC SCM game: http://www.escm.cs.cmu.edu/trading-agent-competition/
[2] Official website of the TAC AA game: http://aa.tradingagents.org/
[3] Official website of the PowerTAC game: http://www.powertac.org/

ing business entities or “brokers” offer energy services to customers through tariff contracts, and must then serve those customers by trading in a wholesale market". In this case the brokers are intelligent trading agents (as our implementation also is) who are challenged to maximize their profits by offering contracts and subscriptions to retail market and buying and selling energy in the wholesale market. However, the actions that brokers perform are a subject to fixed costs and constraints such as publication and withdrawal fees of tariffs, distribution fees for energy transmission and penalty costs upon imbalance between brokers’s total contracted energy supply and demand in a given time period. In the following sections we present the overview of the simulation platform, its implications and a use case for our intelligent trading agent which is going to be evaluated in this particular simulation platform.

4.2. Competition overview

The major elements of the PowerTAC scenario are shown in Figure 4.1. Participant of the competition have a task of constructing a competitive trading agent that act as a self-interested broker that aggregate energy supply and demand with the intention of earning a profit. The main competing factor in the simulation is offering attractive tariff contracts to a population of anonymous small customers (household, offices, villages) thereby building a portfolio of retail customers with a good-quality set of tariff subscriptions. The ideal portfolio implies profitability and the ability to be balanced over a range of environmental conditions. However, the consumption and production capacities in the broker’s portfolio often causes imbalance in energy supply and demand which then has negative impact on the grid stability and the broker’s cash balance (balancing fees are charged to brokers who are causing imbalance of the grid). Therefore, a self-interested broker which is also primarily profit-oriented has incentives to develop and use strategies that will contribute to lo energy imbalance. Such strategies for risk mitigated by acquiring uncorrelated sources and loads that may be expected to balance each other in real time, by acquiring flexible consumption and generation capacities (balancing capacity, interruptible consumption), by selling variable-price contracts and by trading future energy supply on the wholesale market. The last solution represent the second most important competitive task of the involved competition participants; developing strategies for the wholesale market (day ahead market) by placing bids and ask to acquire extra capacity (serve the retail customers and subscriptions) or sell the excess of electrical energy.

The PowerTAC simulation is carried out in discrete blocks or "time slots" where each time slot represents one hour in simulated time. The duration of each time slot is nominally 5 seconds of real time and the whole simulation lasts roughly about 1440 time slots or 60 simulated days which then recalculated in real time is approximately 2 hours. At every

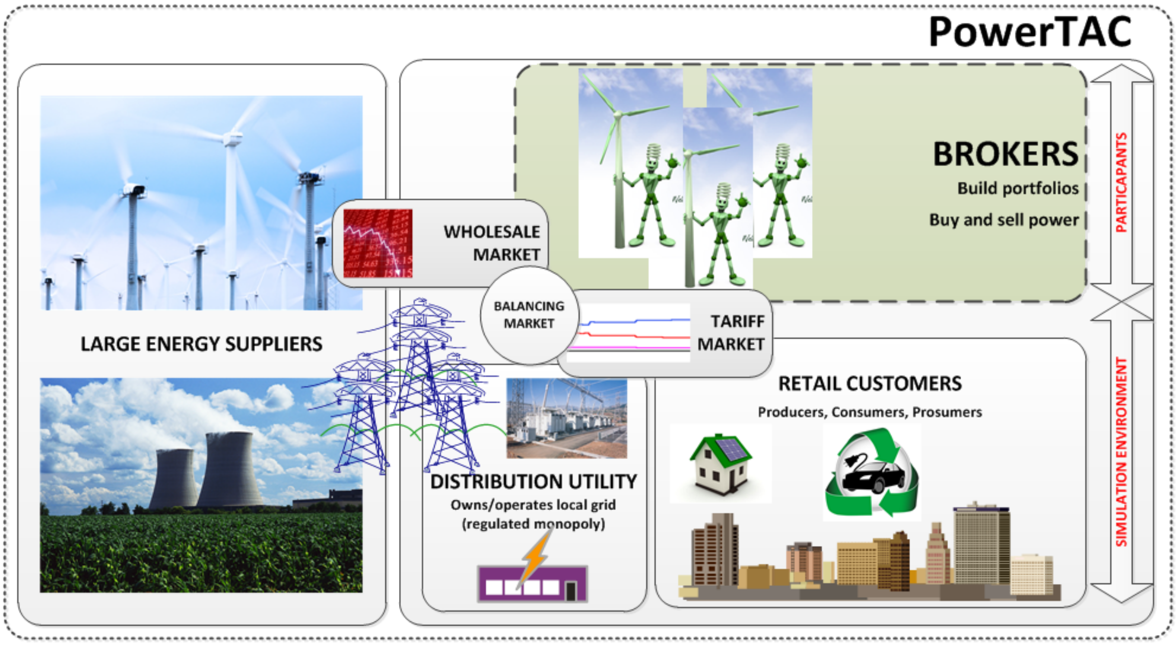

Figure 4.1: Major elements of the Power TAC scenario. We may see that the elements are consisted with the ones presented in Figure 1.3 with the difference that the broker is included as the powerful mediator and trader

time slot a broker is enabled to trade on the wholesale market for the future 24 time slots to accomplish the ultimate goal – balance between supply and demand for each future time slot.

The Customer (Tariff) Market is consisted of retail customers as the essential entities connected to the grid. The main types of retail customers are producers (e.g., solar panels, wind turbines), consumers (e.g., household, offices, villages, factories) and prosumers (e.g., electric vehicles, combined heat and power systems) which indirectly interact with the broker through tariff market. All of customer types choose a tariff subscription from a set of available tariffs offered by all brokers (managed by different participants of the competition). Some contract offers allow brokers to utilize the *balancing capacity* that a customer realizes. This capacity is then controlled (if broker wants) to the distribution utility for the balancing market in the grid balancing process. The Distribution Utility (DU) represents the regulated electric utility entity that owns and operates the distribution grid. Apart for the responsibility regarding grid balancing, the DU distributes power through the transmission grid to the customers and offers "default" tariff for energy consumption and production (which serve to establish a non-competitive regulated tariff market). All of these activities are accompanied with the wholesale market operations. The Wholesale Market allows brokers to buy and sell quantities of energy for future delivery, typically between 1 and 24 hours in the future. Therefore, it is often called "the day-ahead market". In PowerTAC specifically the market is developed as a periodic double auction while the clearing of the prices is performed once every simulated hour. Additionally to the brokers, the wholesale market participants include Generating Companies (GenCos) which provide bulk power to ensure liquidity to the market [36].

The overall competition settings also specify the number of competing brokers which vary from simulation to simulation (most often there are two or four brokers competing each other). The goal of specifying different group sizes is to observe brokers behavior in different market positions such as oligopolies (small number of sellers) or high-competition markets [3][36].

4.3. Brokers

Brokers, represented as mediator and energy traders, are the main entities in the competition. To understand all of the tasks of the broker in the competition it is useful to present an overview of the timeline and information exchange between the broker (distributed software agent) and the simulation environment (server). In Figure 4.2 we can see the three main activities which occur during one time slot: i) trading in the wholesale market, ii) portfolio development (tariff deployment), and iii) balancing of supply-demand. Note that the specific order of these activities is more flexible as long as all the messages sent by the broker arrive before the server needs them.

The main actions that a broker may initiate during any time slot are [36]:

- **Create new tariffs** (design of new tariffs for offering on the retail market),
- **Modify existing tariffs** (changing tariff terms by superseding tariffs),
- **Price adjustments** (adjust prices for existing tariffs if the terms allow it),
- **Contract negotiation** (participate in bilateral negotiation to define individual contracts (to be implemented in some of the future versions),
- **Balancing offer** (offer available controllable capacity to DU for real-time balancing),
- **Create asks and bids** (selling or procuring energy in the wholesale market);

The trading in the wholesale market begins upon the start of each time slot where the brokers collect information from weather reports, customer usage and production reports, balancing transactions, tariff subscription changes, transactions, and updates of the current market and cash positions. The broker then makes the final trading decisions and sends his messages to the server by placing bids and asks for the current time slot (n) and future time slots ($n+1$, $n+2$, ..., $n+24$). The wholesale market clears the price after the clock has changed to a new time slot thereby creating supply and demand curves. The clearing price is the price that maximizes turnover and is set at the intersection of demand and supply curves [3].

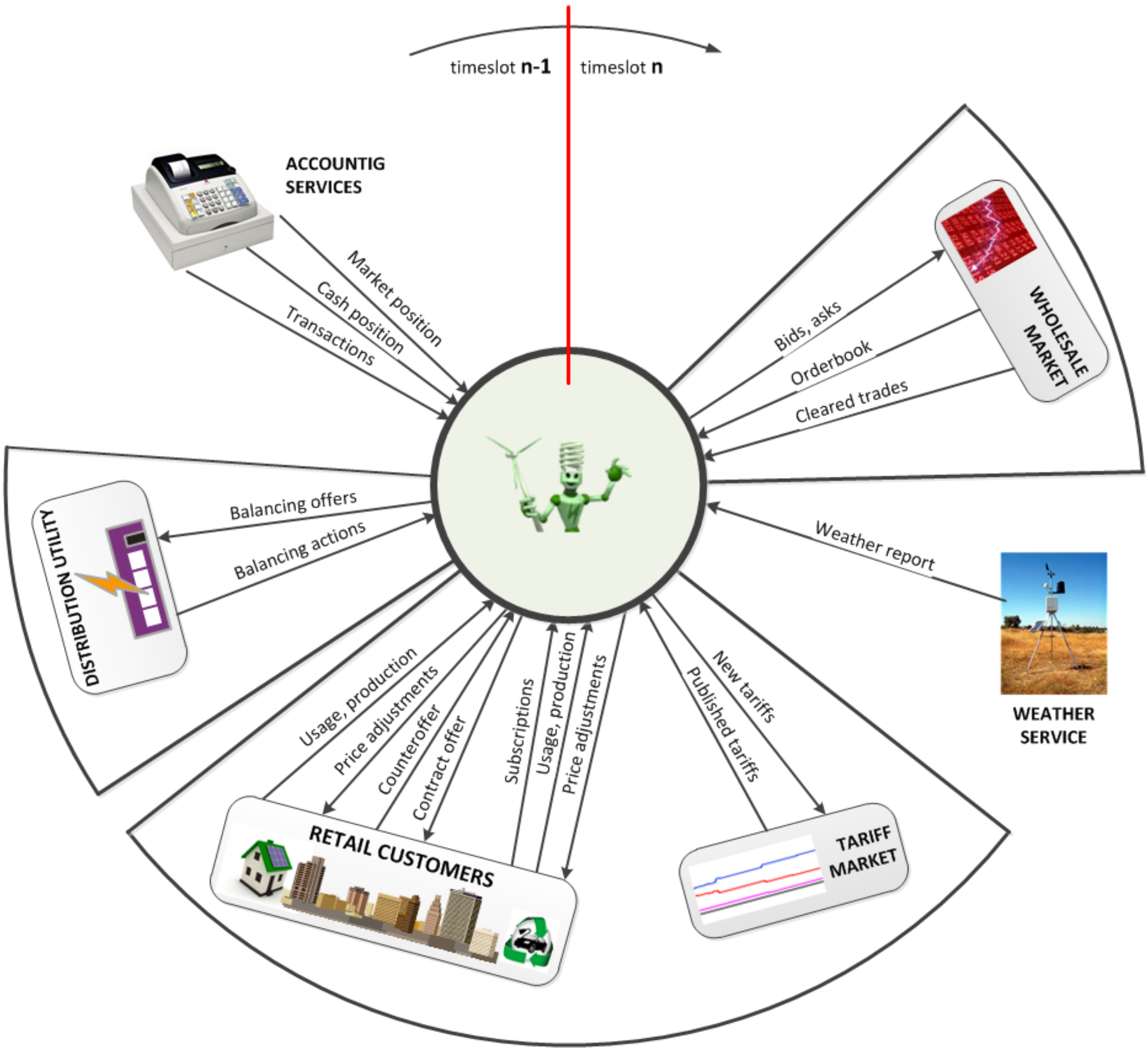

Figure 4.2: Power TAC broker's activities in each timeslot

"The primary goal of a broker is to publish tariffs and negotiate contracts for power sources and loads that result in a portfolio that is profitable and balanced, at least in expectation, over some period of upcoming execution activities and time slots" [36]. Therefore, a brokers goal is to carefully track the subscribed customers and their behavior, and all in favor of successfully predicting supply and demand. If the tariff market (customer market) state is well known, the broker may initialize a set of actions related to tariff offers and price adjustments to balance its portfolio. This results in major increase of brokers cash balance and a better position on the market.

Lastly, the broker sends balancing offers (for the energy capacity acquired from tariffs that have the interruptible consumption term in the contract) to the DU to further smooth its energy (demand-supply) balance. The incentive for these actions is of course related to avoiding the non-attractive penalties that are charged to the broker in proportion to the brokers contribution of the grid imbalance.

More on the development of the broker and its capabilities is covered in the next chapter where we present our solution for the PowerTAC competition in 2013.

5. CrocodileAgent 2013

The CrocodileAgent (in further text often referenced as the "Broker") is an intelligent agent developed by the team from University of Zagreb, Faculty of Electrical Engineering and Computing to participate in the PowerTAC competition which was mentioned already before. The development started in the year 2011 and currently it is still in progress. Previous version CrocodileAgent 2012 ([41][11]) was deployed on the PowerTAC 2012 competition and the current version that we named CrocodileAgent 2013 will participate in the PowerTAC 2013 competition in July 2013.

The **CrocodileAgent** has a modular design separating main activities that the Broker performs during his lifetime in one competition scenario. Independent modules interact with each other providing necessary information and valuable data for better performance. The CrocodileAgent is divided into two main modules that contain all the functionalities:

1. **Tariff Manager**,
2. **Market Manager**.

Each of these modules are divided into services that run the logic of the module, plain old Java objects that support the work of the services, a repository that tracks all changes during the game (e.g., important information about Broker's business development) and provides storage for relevant data that is used in the process of the Broker's decision making – to maximize the profit.

A high level overview of the CrocodileAgent's 2012 modules and their interactions between each other as well with the simulator components is shown in Figure 5.1. The difference in the overview between the 2012 and 2013 versions of the Broker are minimal where the Forecast Manager is now integrated with both *Tariff* and *Market Managers* providing functionalities needed directly by each of the Managers. From the Figure we may also see the information channels that the Broker has with the *wholesale* and the *customer market* where he gets the information about past clearing prices, energy usage and customer subscriptions. This data is of course used as an input to the Broker's main services that perform some actions based on the received values.

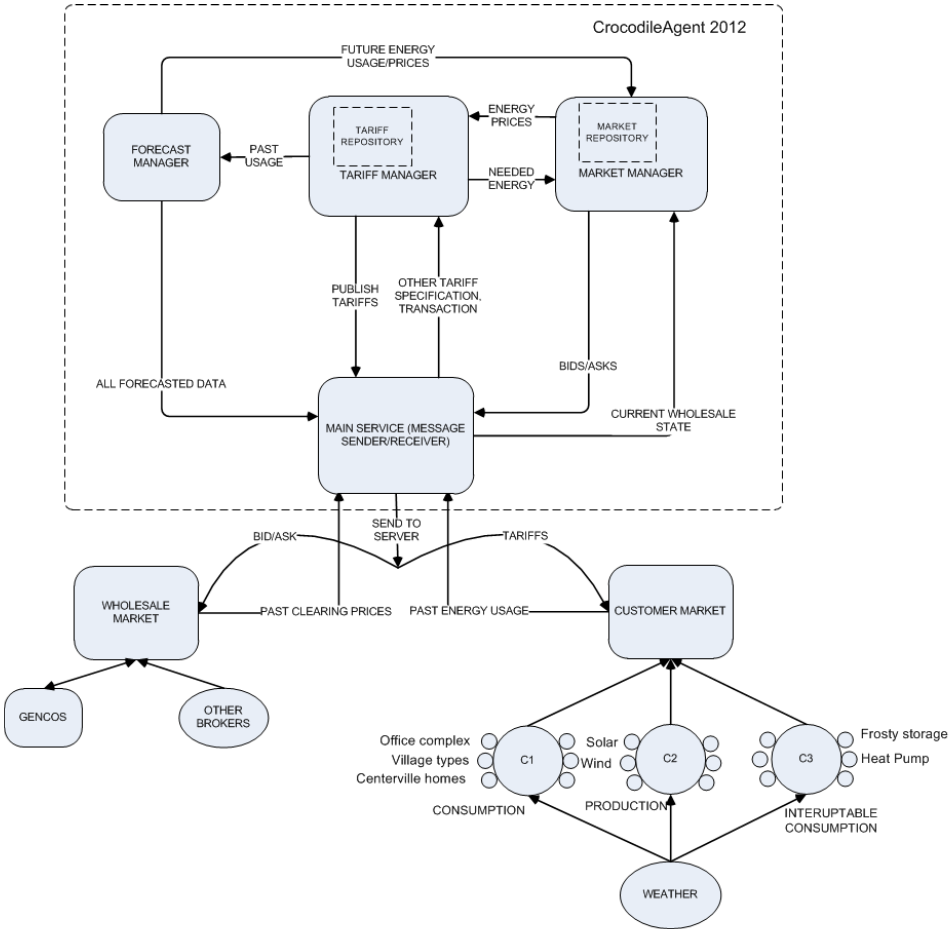

Figure 5.1: A high-level overview of CrocodileAgent's modules and their interactions with simulator components

An important aspect of the overall trading process is energy balance which greatly depends on the quality of the intra-communication between Broker's modules. Energy that is sold through the *tariff market* has to be in some way supplemented by the bidding strategies performed on the *wholesale market*. The Tariff Manager sends information about energy consumption of the Broker's current portfolio to the Market Manager in each timeslot so the Market services may buy enough energy for trading in the future timeslots. The Market Manager module is developed by another member of the development team and is presented in the separate Master thesis [10]. Key points that were emphasized in the development of the Market Manager were to establish reinforcement learning with the Erev-Roth algorithm to determine Broker's strategies with the prices and amounts of energy that is going to be traded in the wholesale market. In the rest of this thesis we solely focus on Tariff Manager while detailed information can be found in [10].

5.1. Tariff Manager activities

As already mentioned previously, Tariff Manager is responsible for managing Broker's customer portfolio, managing tariff specifications available in the customer market and providing responsiveness to different actions that occur in the customer market.

In the next several section we describe the main activities which the CrocodileAgent 2013 performs during a single PowerTAC game. These descriptions do not go in-detail with all of the characteristics but are more focused to the general idea of the activity with its implications in terms of PowerTAC brokers and their intelligent design.

5.1.1. Creation of Tariff Specifications

In the customer market broker offers tariffs which can then be subscribed by different customers. Profitable tariff design and specification are crucial for generating profit. Also, the process of tariff creation has to include customer tariff evaluation which is calculated as the expected cost (or gain) during the lifetime[1] of the contract with the customer. Customers choose tariffs depending on the rationality parameter λ, ranging from random selection (λ = 0) to the selection of tariff that best suits customer needs ($\lambda = \infty$).

Modeling customer behavior

Individual behaviour of different customer types can be described as a function of multiple variables presented as data available to the broker. The CrocodileAgent 2012 models energy usage for all customer types (i.e., C_1 – consumption, C_2 – production, C_3 – interruptible) as:

$$energyUsage(C_1) = f(\delta, \vartheta), \tag{5.1}$$

$$energyUsage(C_2) = f(\delta, \vartheta), \tag{5.2}$$

$$energyUsage(C_3) = f(\delta, \vartheta, \sigma); \tag{5.3}$$

where δ is the weather information, ϑ is the information about the current TAC hour and σ is the percentage of controllable capacity offered by particular customers. One example is shown in Figure 5.2 where we have the accumulated energy consumption of typical household customers (C_1,C_3) that are subscribed to one of the Broker's tariffs. Consumption is periodic on a one-day basis, ranging from low consumption during the night, medium consumption during the morning and high consumption in the late afternoon.

[1]Lifetime of the contract represents the time of duration for which the contract is signed (e.g., one day, one week, one month).

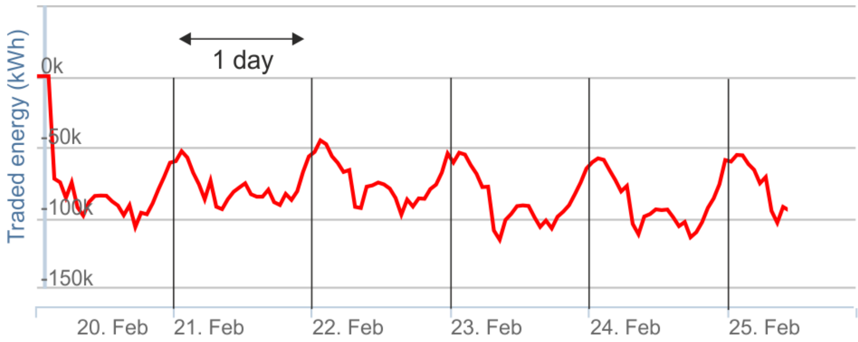

Figure 5.2: Consumption curve for the consumption customer types (C_1)

In the Tariff Manager we do not focus on modeling energy consumption per customer type, yet we emphasize the importance of modeling the overall consumption of the subscribed portfolio of customers since that information is crucial for predicting future energy usage, buying energy and creating appropriate tariff specifications. Even though some tariff specification types carry names of specific customer types, we intend to attract all the possible customers on each published tariff and therefore we model the energy based on the previous description.

Tariff Specification parameters

"Brokers design and offer tariffs, and may also modify existing tariffs by superseding them with a new ones, then revoking the original tariffs. Each tariff applies to a specific PowerType, such as general consumption, interruptible consumption, general production, solar production, electric vehicle, etc." [37].

In Figure 5.3 we may observe a detailed structure of the tariff offering. With the structure the brokers are able to support various number of different tariff specification that implement specific logic features. `TariffSpecification` specifies the basic structural elements that do not contain any charges (pricing) related to consumed or produces energy. `Rate` object on another hand specifies more detailed pricing and is primarily oriented on charging customers based on their energy consumption and production. Each tariff specification may have multiple rates that define pricing mechanism for different times of the week, different periods during one day, pricing after threshold amounts, etc. If a rate is variable then we have to specify a `HourlyCharge` object that will define the price for energy at a certain point in the future. In that case, we also have to take into consideration the minimum notice interval defined in the `Rate` object since we cannot define pricing for time periods earlier that the current time enlarged with the notice interval (counted in hours).

Each tariff specification has its own evolution path from the timeslot where it was created

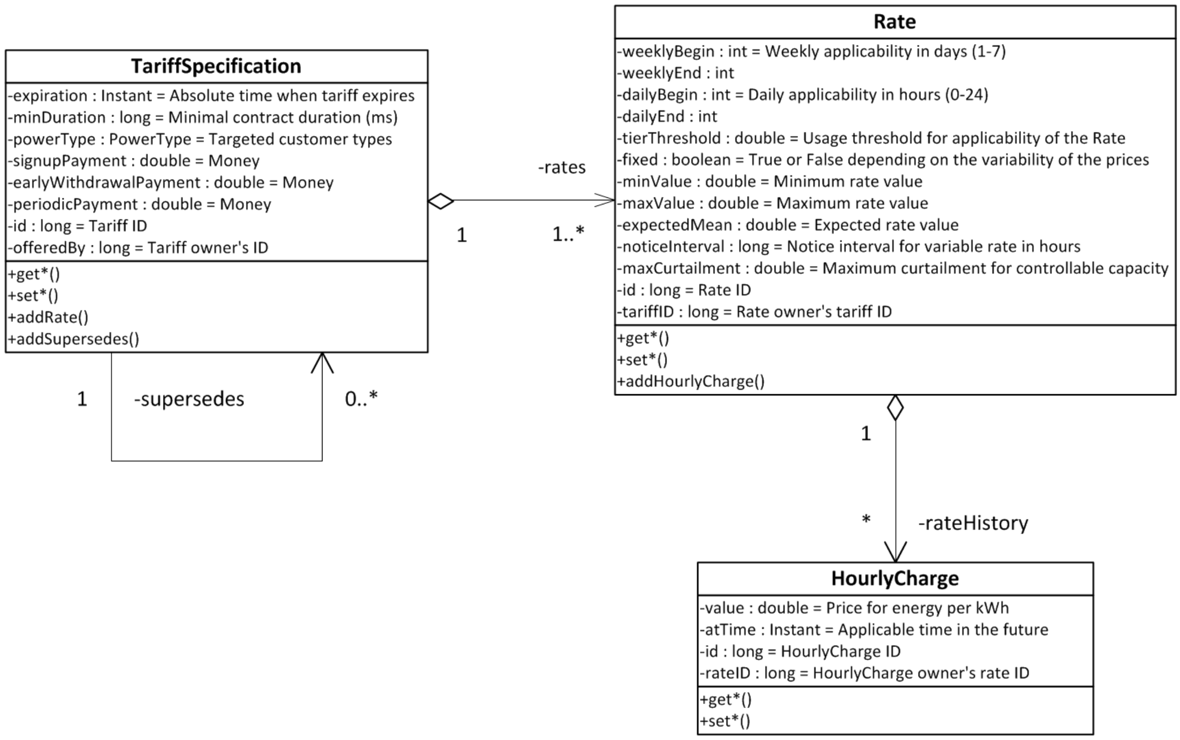

Figure 5.3: Tariff structure with applicable rates and its hourly charges

and sent to the server environment. Figure 5.4 shows the UML (Unified modeling language) state diagram which starts by tariff creation and sending a message consisted of the tariff specification details to the server. After the server receives the tariff specification the status of the tariff is *pending* since the new tariffs are not published to the market and customers in each timeslot, yet periodically after a certain time period (e.g., each sixth timeslot). Tariff specification is the *offered* on the market and various customer types may subscribe to the tariff after which the tariff becomes *active* or the tariff may be revoked by the issuing broker. An *active* tariff may also be revoked or its expiration date may pass after which all of the subscribers are unsubscribed and tariff becomes *inactive*.

Tariff specification that are designed by the CrocodileAgent 2013 will be presented in the next chapter that is related to the evaluation of the developed Broker's logic based on the competition scenarios played during the year 2013.

5.1.2. Superseding Tariff Specifications

"In addition to changing hourly prices on variable-rate tariffs, it is possible to “modify” a tariff by revoking it and superseding it with a replacement tariff. The superseding tariff must be received (but not necessarily published) before revoking the original tariff. All subscriptions to the original tariff will be moved to the superseding tariff during the next tariff-publication cycle" [37]. CrocodileAgent 2013 uses this PowerTAC functionality ex-

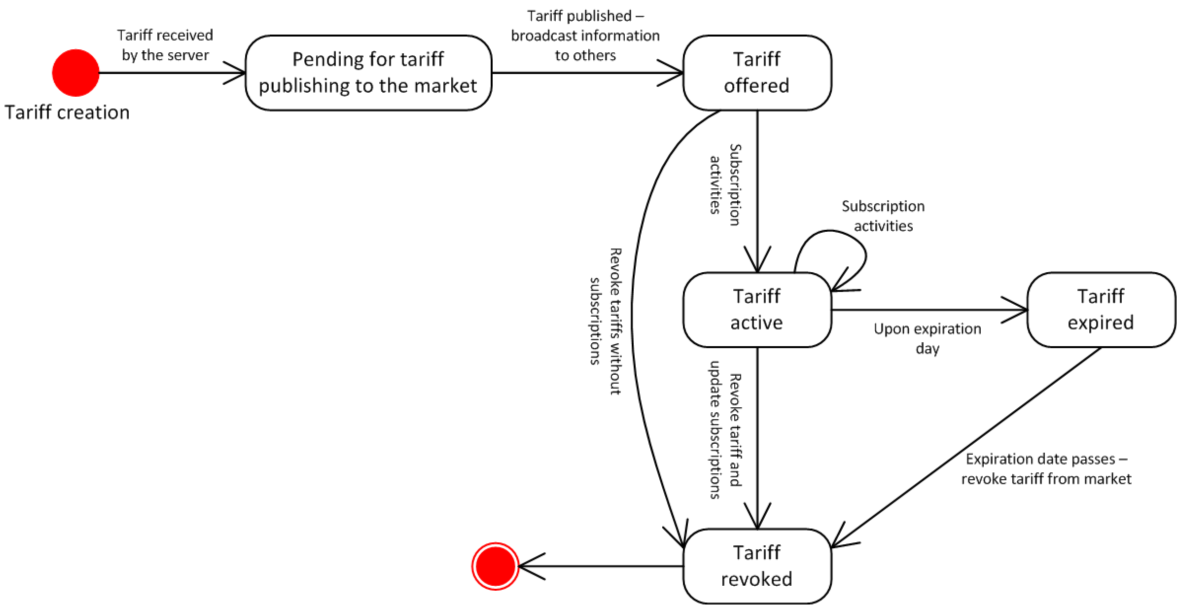

Figure 5.4: Tariff state transitions after creation until deprecated.

tensively in different time periods of the running game. The idea that our Broker implements is related to constantly tracking and evaluating tariff designs that are on the market. If some of the proposed and offered tariff specifications are not efficient (e.g. do not produce any revenues and have minimum subscribers) we supersed the tariff with a more appropriate one.

The superseding action may also easily be explainable by drawing analogies with Telecom operators and their tariff models (plans). If we take a closer look at the mobile plans market we may observe that tariff models are exchanged very often with new ones that suit the current market state and consumers (and operators of course) in a better way. In that manner we also use superseding actions periodically to eliminate all negative tariff specification cash flows and produce more suitable and competitive tariff specification that will have a greater impact on the customer market.

5.1.3. Handling server messages

Tariff Manager is responsible for handling several message types that are distributed from the server environment to the brokers that are in the current competition. More precisely, CrocodileAgent 2013 handles:

1. **CustomerBootstrapData** is received in the early stages of the game and contains information about customer behavior (e.g. energy consumption and available types of customers). CrocodileAgent handles the message by populating customer model corresponding to the given customer and power type. This gives the Broker a running start in the game,

2. **WeatherReports** are received through out the whole game and represent the weather information in the form of temperature, cloud coverage, wind speed and wind direction. This data is saved and may be used later as an input to the forecasting mechanism that may reveal energy usage in future timeslots which gives the Broker an opportunity to accordingly prepare for the consumption thresholds,

3. **TariffSpecifications** are received whenever a new tariff specification is received by the server from any of the competing brokers. Server then broadcasts the message to all the brokers and our CrocodileAgent saves the specifications based on the ownership; own tariffs are ignored since they are already stored upon creation while competing tariffs are sent for processing,

4. **TariffStatus** represents a message which gives a feedback in a form of a notification after the Broker has sent a tariff specification. More precisely, it gives information about the success of tariff publishing procedure to the customer market,

5. **TariffTransaction** is the most valuable and most important message that the Broker receives constantly and in large amounts during the competition. It holds information about specific transaction made by customers subscribed on one of the available tariff specification that the Broker has in its portfolio of tariffs. Information is then used for statistics purposes, evaluation and decision-making in the future timeslots.

5.1.4. Continuous tariff market tracking

Continuous tariff market tracking is by all means closely connected to handling server messages. The point is to extract all the available data that is offered by the server environment and put it into various context that will help in the decision-making process of the Broker.

Numerous *Hash Maps* are filled during the game and they contain information about tariff revenues, tariff specification, energy usage, different customer types, different tariff types, called strategies, number of subscribed customers, and many more. The key is to combine all this information to produce new finding and enable the knowledge evolution inside the Broker's logic. Therefore, all of the tracked information is often saved in an appropriate way so it may be compared and extracted for various purposes (timeslot present the most important key in almost every repository).

5.1.5. Calculation of energy prices

The CrocodileAgent 2013 uses the modified algorithm for price calculation that can be found in the CrocodileAgent 2012 version. The main idea behind the algorithm is to use cleared prices from the wholesale market and the amount of energy traded by these prices to get the minimum price of energy for tariff specification rates which will not cause and losses if applied to a certain rate. Basic arithmetic price may be calculated as:

$$arithmeticPrice = \sum_{i=1}^{360} \frac{\sum_j \phi_{ij} * \varphi_{ij}}{\sum_j \varphi_{ij}}; \tag{5.4}$$

where ϕ_{ij} is the executing price of the j^{th} cleared trading sequence in i^{th} timeslot and φ_{ij} is the amount of energy in MWh exchanged in the j^{th} cleared trading sequence of the i^{th} timeslot.

If the Broker does not have access to market clearings of the 360 previous timeslots (i.e., the current timeslot is not larger than 720 - since the game starts from 360) it reaches data received from bootstrap period (two weeks of pre-game data where the customers where subscribed to default tariffs and market was also cleared multiple times in each timeslot 1-359). The price given by the Equation 5.4 is then compared to a minimal threshold price with value ***30*** and if it smaller it is automatically set to the value given in the `properties` file of the Broker (loaded upon the start of each game). That price present the minimal energy price per MWh that the Broker will offer to its customers which is then subject to change by every tariff design procedure depending on various happening in the customer market. Additionally, the price is divided with 1000 because of the tariff specification parameters which receive prices for energy per kWh.

5.1.6. Applying strategic behavioral patterns

Every broker that participates in the competition scenario should be able to adapt its behavior to the situation that occur in the customer market and in the competing environment in general. A broker without these functionalities present a static programming agent that only executes predefined actions in each game regardless of the number of opponents participating in a specific match and their in-game actions. CrocodileAgent 2012 was poorly responsive to other brokers actions in the customer market while it still used some basic info about customers received from the server.

The CrocodileAgent 2013 introduce a **completely new responsiveness mechanism** which reacts to all action made by the competing brokers in the competition environment. By closely tracking the tariff specifications published by other brokers and putting them into the time dimension, the Broker may observe and try to decipher intentions of the competing brokers to respond with appropriate actions. Based on its own observation the Broker can either call one of the specific and predefined strategies for responsiveness or react instantly with just several actions to overcome the negative effect on his subscription count that were identified as the consequence of competing tariffs in the customer market. The currently developed predefined strategies comprise the creation of tariff specification with cheap energy prices for various customer types, a general strategy that is modifiable for multiple purposes and a strategy specifically designed to overcome server's issues with evaluating tariffs that contain the parameter of periodic payment[2]. The last strategy mentioned creates several tariff specification with periodic payment and below minimum energy prices upon identifying competing tariffs with large periodic payments. By that, we eliminate the possibility of the competing broker to earn large amounts of money by stealing his customer subscription with our own tariff specifications.

Figure 5.5 represents a sequence diagram that clearly shows a part of the responsiveness activities (related to competing tariffs of other brokers) of the CrocodileAgent 2013 and the initiation factors that cause them.

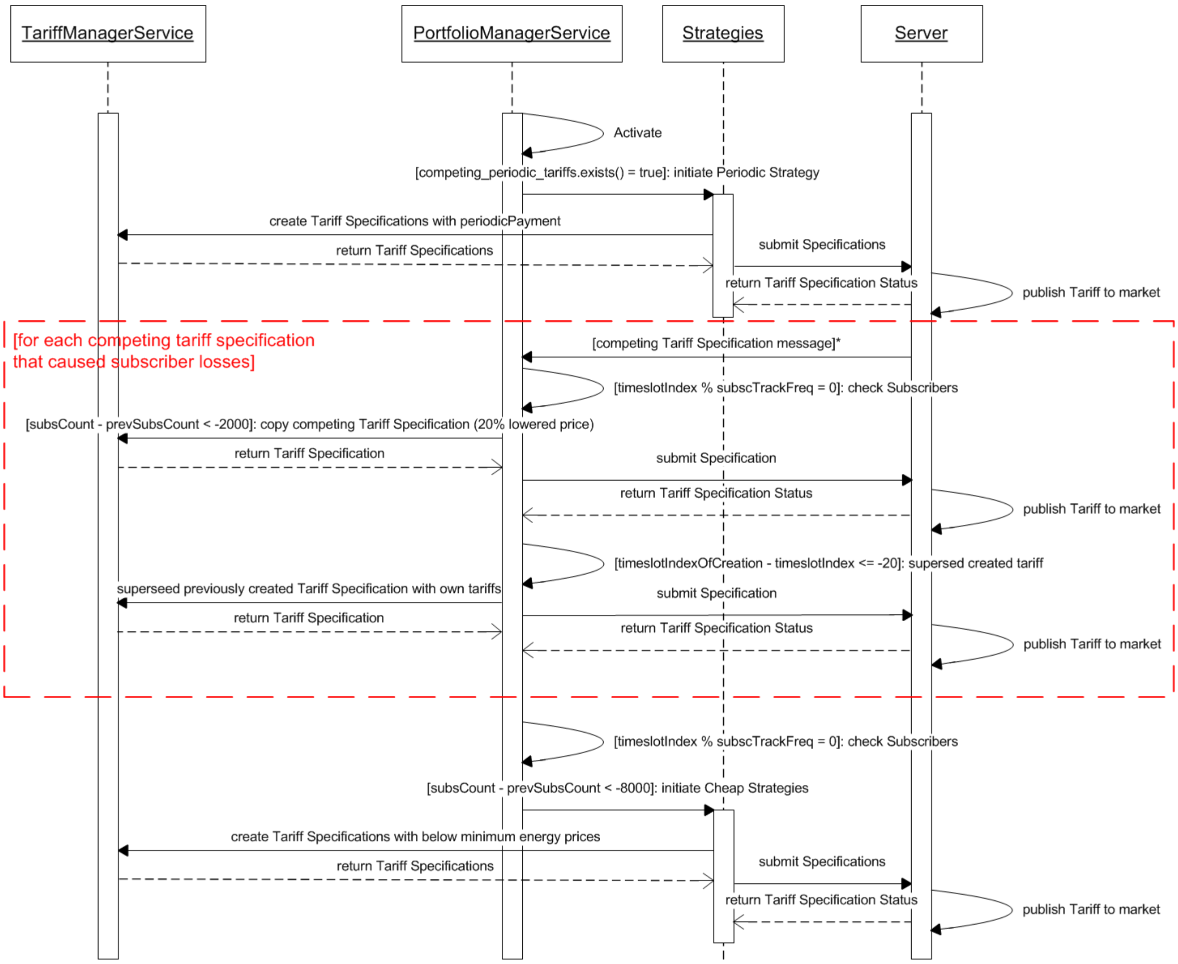

Figure 5.5: Sequence diagram for competing tariff related responsiveness activities.

[2]The server evaluated tariffs with high periodic payments as feasible while some other tariff designs were more appropriate regarding the overall price that has to be paid for consumed energy.

5.2. Technical description

This section provides detailed technical description about CrocodileAgent's design and implementation. We focus only on the Tariff Manager software architecture since the Market Manager is developed separately by different team members. The section is continued with the description of the available technical features that broker implements as well as the lifecycle operations that are performed in each timeslot of the competition scenario.

5.2.1. Software architecture

The CrocodileAgent along with all of the brokers developed for the PowerTAC are based on *agentware*. Agentware is the template software project used as a starting point for the further development process. The template is provided by the PowerTAC organizers in the form of a Maven[3] project called *sample-broker* project[4]. The sample-broker project is accompanied with the common project, which contains all domain classes common for all the Power TAC projects. "In order to free developers from implementing core functionalities (e.g., communication with server, maintenance of broker's internal clock and tournament login) and put more emphasis on the development of broker's intelligent behaviour, a standardized set of core services are incorporated within the agentware" [3].

Software architecture is shown in Figure 5.6 in a form of a UML class diagram. Here we can see all the interconnections between classes in the CrocodileAgent. Still, the main programming activities and outcomes may be divided as:

1. **Services**,
   (a) **Service Utilities**,
   (b) Enumerations,
2. **Repositories**, and
   (a) Report Generators,
3. **Strategies**;
   (a) Grading calculators

Each of these is described in the following subsection by presenting specific classes in the group and their description.

[3]Apache Maven is a software project management and comprehension tool (http://maven.apache.org/).
[4]Agentware is hosted on the Power TAC Github repository (https://github.com/powertac/sample-broker).

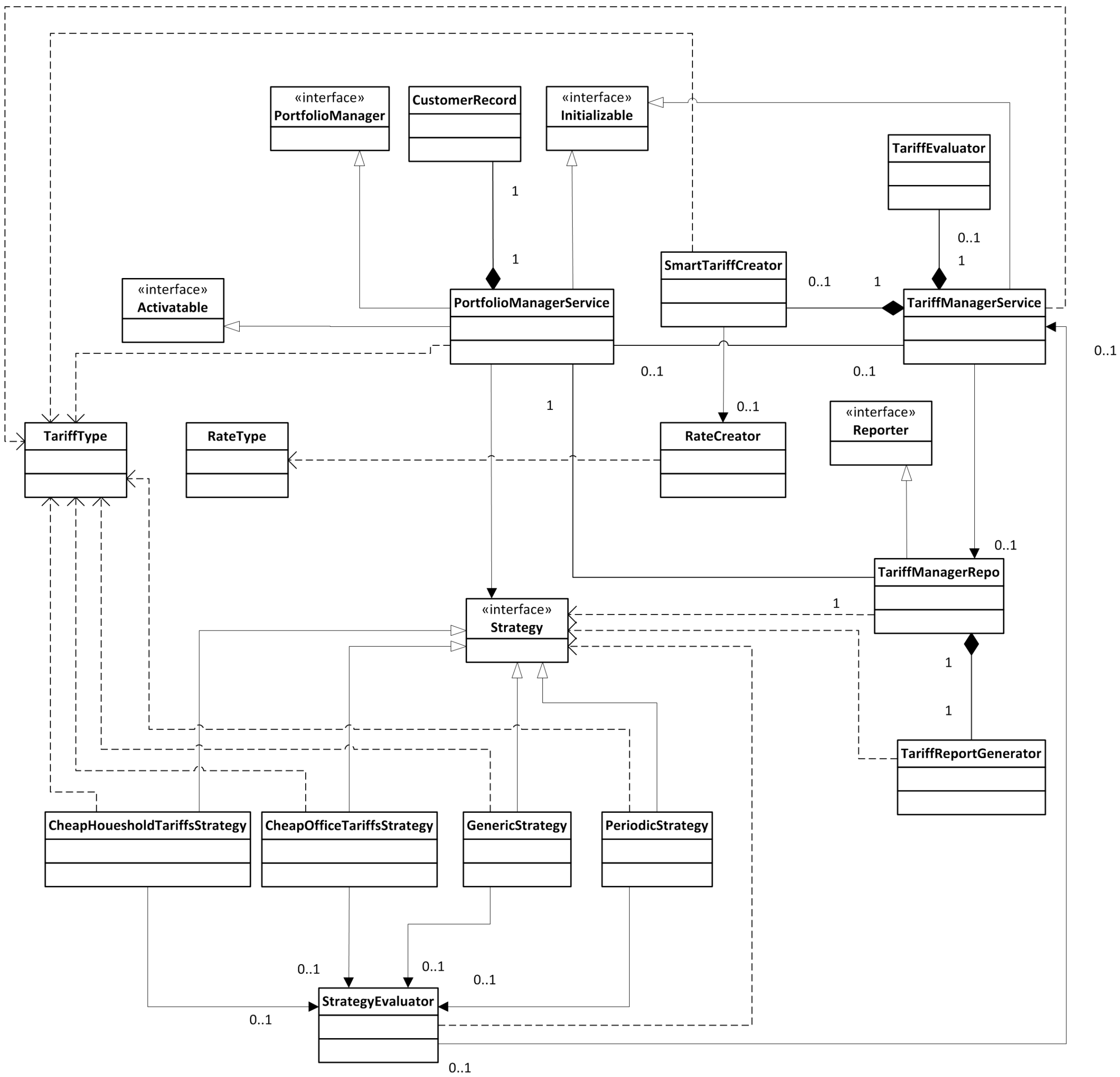

Figure 5.6: UML class diagram for representing the Tariff Manager architecture

Services

Services are implemented as Java classes annotated with `@Service` annotation provided by the Spring framework[5]. As the description of the Spring framework states, this features enables the establishment of programming artifacts in an automatic and simple way. The CrocodileAgent 2013 uses Services to carry out broker's logic in the competition scenario as well as the control of some underlying system logic (e.g. repository access, tracking decisions, management). The main functionality of the Tariff Manager module

[5]The Spring Framework provides a comprehensive programming and configuration model for modern Java-based enterprise applications - on any kind of deployment platform. A key element of Spring is infrastructural support at the application level: Spring focuses on the "plumbing" of enterprise applications so that teams can focus on application-level business logic, without unnecessary ties to specific deployment environments (http://www.springsource.org/spring-framework).

inside CrocodileAgent is divided into two services: `PortfolioManagerService` and `TariffManagerService`. The CrocodileAgent also uses some additional services that are not directly developed for the Tariff Manager and we address only a small part of them. The descriptions are as follows:

– **`PortfolioManagerService`** is a part of the `hr.fer.tel.powertac.crocodileagent.service` package and encapsulates broker's logic that deals with the portfolio management. The service is responsible for tracking information about specific Customers that are received from the server. Information such as subscription count, customer type and energy usage are stored inside predefined containers (often Hash maps). Also, the service is responsible of handling messages that are exchanged both ways. Firstly, the service has defined message handlers for historic bootstrap data, weather reports, new tariff specifications, tariff status updates and performed tariff transactions. After a specific message has been identified the service delegates message processing to other services and Java objects that are specifically responsible for the message type. Secondly, the service serves as a proxy to the `TariffManagerService` for sending (registering) new tariff specifications to the Customer market, updating Hourly charges, revoking tariffs and superseding tariff specifications. Additionally, the `PortfolioManagerService` manages the main broker activities during each timeslot. The task is to track the game progress and make decisions based on the current state of the competition and Broker's position on the Customer (Tariff) market. After a certain pattern has been identified, the service launches specific actions in other services to respond to the currently observed situation. These actions include tracking and reacting based on the: i) customer subscription count, ii) available competing tariffs published by other brokers involved in the competition, iii) per tariff specification revenue, and iv) time passed since the beginning of the simulation.

– **`TariffManagerService`** is a part of the `hr.fer.tel.powertac.crocodileagent.service` package and encapsulates broker's logic related to creating, sending and handling tariff specifications and their parameters. The service directly controls the actions of the tariff repositories (situated and controlled in `TariffManagerRepo`) such as adding and processing tariff specification (either its own or others'), tracking size of published tariffs, searching for potential tariffs for revoking and in the end superseding tariffs. The service uses *Service Utilities* for the creation of the tariff specifications. The main responsibility for the service is to handle and monitor the process of tariff creation. Through several defined methods, the service implements distinct activities related to tariff creations which are then called upon by the `PortfolioManagerService`. These activities include the creation of the initial batch of tariffs that are sent to the competition environment at the start of the simulation, creation of additional tariff batches during the early game development, creation of batches for mid and late game initiation to increase the overall share in the customer market. Additionally, the service is responsible for creating *response* tariffs that are initiated for fast and effective retrieval of lost subscribers. Furthermore, the complete supersed functionality for exchanging old and non-profitable tariffs is situated inside this service. Messages related to tariff publishing and revoking are also created here but are sent via `PortfolioManagerService` to separate the responsibility of communication handling to another service.

– **`PowerTacBroker`** is the top-level controller for the broker. It sets up other components, maintains the clock and terminates the broker when the SimEnd message is received. This service was initially taken from the `sample-broker` and extended with the `Handy` service to implement some useful methods for reporting and logging.

– **`LogService`** is used for setting up loggers for the agents. This service performs logging operations that are latter on used for identifying possible errors in the agent's implementation. Additionally, the service allows developers to log their own messages related to some broker action during the competition. All of these are used to evaluate the broker's behavior more accurately in the post-competition analysis.

– **`ReportService`** is used as a key enabler for setting up the environment used in generating reports as an *Excel* spreadsheet. The service is used by repositories which may contain data that needs to be stored in the end of the competition. The data is stored in the form of additional sheets inside the *Excel* document.

Service Utilities

Service Utilities are implemented as plain old Java object without using any Spring framework annotations. The purpose of these utilities is to support the work of the `TariffManagerService` service by providing price calculation, tariff specification and rate assemblies. These utilities are a part of the `hr.fer.tel.powertac.crocodileagent.utils` package and we take them as separate objects in the Broker's architecture. CrocodileAgent 2012 had all of the functionalities consisted in this package spread in the two main services mentioned before. This solution was not modular and very difficult to improve with additional functionalities. By dividing some of the action in different classes the CrocodileAgent's Tariff Manager presents a truly modular and extendable design. The description of the available classes in the package are as follows:

– **`TariffEvaluator`** is a Java object responsible for calculating prices used in the creation of tariff specification and their rates. The object uses information from the

Market Manager regarding the energy prices in the Wholesale market and calculates a scaled price vector consisted of different prices used in tariff creation actions. The calculation method also uses the amount of traded energy in the wholesale market to perform optimization on the end price.

– **`SmartTariffCreator`** is probably the most important Java object aside the implemented services. The object is consisted of several methods that are used for creating tariff specifications with the desired parameters and functionality. Based on the input parameters, SmartTariffCreator chooses and creates a tariff specification from a wide spectrum of available tariff models. All of the models are modular and have different configurable parameters that may be used to identify and set specific parameters which the Broker's considers as appropriate at the time when the tariff creation process is called upon. Some of the basic models are divided between general consumption and production tariffs, tariffs for household, tariffs for office, and a specific tariff group with periodic payments. The object also modifies the price by a giving parameter if needed depending on the Broker's decision and the state of the game (e.g. late game period, revenue issue periods, etc.). Additionally, the object delegates the functionality of creating tariff rates to another object and by that increases the modularity and extensibility factor on an even higher level.

– **`RateCreator`** is a Java object responsible for creation of different rates and their parameters that form a tariff specification. The object has a method which chooses the appropriate rate model (from six available models) based on the input parameters received from `SmartTariffCreator`. Furthermore, the object contains a separated method for creating ToU daily rates (with different periods in a single day). It is important to mention that this object only creates one specific tariff rate while a tariff specification may have multiple rates which results in performing the action of the object multiple times to accomplish the desired specification. Additionally, the object has configurable parameters which may define and change some rate parameters.

Enumerations

Enumerations are implemented as Java *enums* and are situated in the `hr.fer.tel.powertac.crocodileagent.enums` package. The idea behind these enumerations is to enable extensibility for future development of new tariff specification models and also new rate models but. Therefore, the package is consisted of two enums:

– **`TariffType`** enum defines different tariff specification types that CrocodileAgent can establish in a competition scenario. The total number of defined enumerations is twelve (`GENERAL_CONSUMPTION_HOUSEHOLD, HOURLYCHARGE_HOUSEHOLD,`

HOURLYCHARGE_INTERRUPTABLE_HOUSEHOLD, FIXED_TOU_DUAL_DAILY_HOUSEHOLD, PERIODIC_TOU_DAILY_HOUSEHOLD, HOURLYCHARGE_OFFICE, HOURLYCHARGE_INTERRUPTABLE_OFFICE, FIXED_TOU_DUAL_WEEKLY_OFFICE, PERIODIC_FIXED_SMALL, PERIODIC_FIXED_MEDIUM, PERIODIC_FIXED_BIG and PERIODIC_FIXED_EXTRA_BIG). Each of the models is implemented in the `SmartTariffCreator` and has its own parameters and functionalities.

- **`RateType`** enum defines different rate types that CrocodileAgent may apply to single or multi-rate tariff specification. The total number of defined enumerations is six (FIXED_WEEK, FIXED_WORKWEEK, FIXED_WEEKEND, VARIABLE_WEEK, VARIABLE_WORKWEEK, VARIABLE_WEEKEND). Each of the models explains two main characteristics of a rate type: i) is the rate pricing fixed or variable, and ii) is it applicable to workdays or weekends. Note that the rate creation for different ToU in a single day are not implemented with enumerations since there is no need to define those.

The defined enums do not contain any operations related to the implemented tariff and rate types. The operations are delegated to the two previously described Java object.

Repositories

"Similar to services, repositories are also implemented as Java classes. However, unlike services, repositories are annotated with @Repository annotation provided by the Spring framework. This feature provides exactly the same benefit as @Service annotation described in the Services section above" [3]. The main goal of the repositories implemented in the CrocodileAgent 2013 is to store data received from the server and agent-generated data created by inner Broker's operations. The data from both sources is used to serve two main purposes of the repositories: i) store/retrieve operations for usage during the competition, and ii) generation of reports after the competition scenario has ended for post-competition human analysis. Tariff Manager implements only one repository with extended functionalities from the CrocodileAgent 2012 version. The description of the repository is as follows:

- **`TariffManagerRepo`** is a part of the `hr.fer.tel.powertac.crocodileagent.service` package and encapsulates broker's store and retrieve actions as well as offers the functionality of a in-game data storage. This repository is, with the two main services, one of the biggest classes in the CrocodileAgent's implementation. Inside the repository numerous objects for storing specific types of data are created, often in the form of Hash maps and nested Hash maps since it is the fastest and easily understandable, coherent way of storing data that may have to be compared later on. Repository performs all operations invoked from the `TariffManagerService` with additional internal calculation such as adding, removing and counting of tariff specifications, their transaction per customer type and per timeslot. Big emphasis is on tracking different parameters of each tariff transaction such as revenue per tariff, revenue per customer, energy usage per tariff and per customer type. Also, the repository tracks and saves all competing tariffs where the exact data storage is extensively used by the `PortfolioManagerService` for defining responsive operations based on the customer market behavior. Additionally, the repository performs energy prediction activity using the Holt-Winters algorithm which may serve the Market Manager in evaluating the amount of energy that needs to be bought in future timeslots. In the end, the repository is responsible of invoking report generation activities by providing specific data storage per created report.

Report Generators

In the previous version of CrocodileAgent, report generators were incorporated in the `TariffManagerRepo`. Since its functionality slightly differs from the semantics of report generation, these actions related to reports were transferred to a separate Java object. Report generator is implemented as `TariffReportGenerator` class which is consisted of multiple methods that each generate specific report presented as a new sheet in the *Excel* spreadsheet. Basically, the object and its methods use data storage entities provided by the calling repository. Reportable features that we track and perform post-game human analysis on are presented in one of the following section with a small description for each of them.

Strategies

Strategies present a completely new feature in the Tariff Manager of the developed CrocodileAgent. The main idea behind strategies is to define different set of actions that could be performed in a certain time period as a responsiveness measure to the current customer market state. For example, if the Broker examines and concludes that he is losing customer subscription due to the high prices in comparison to other available tariffs on the market (by competing brokers), he is supposed to perform a set of actions that will regain all the lost customer subscriptions and secure future income to the Broker's cash balance. Each of the performed strategies needs to be evaluated on a certain level to provide useful information to the Broker if the similar situations, as the one that caused the strategy to be called in the beginning, occur. Currently, the Broker possess the ability to call upon four different strategies where two of them address the issue of customer subscription loss, one is responsible for responding to the identified periodic payments in the competing tariffs and the last one presents a general strategy that performs based on the given parameters. Each of the strategies is implemented as a Java object that implements the general interface. The description of the available classes in the package are as follows:

- **`Strategy`** is a Java interface that defines the generic methods that need to be implemented in each strategy. This makes the strategy models unified in the sense that each strategy is called, initiated and graded in the same way.
- **`CheapHouseholdTariffsStrategy`** performs operations of creating four tariff specifications with significantly lowered prices. Models used for creation of these tariff specification are already defined and executed in earlier stages of the game and may be characterized with enumerations that contain "HOUSEHOLD" string inside of them. The strategy lowers the price calculated by dividing it with factor 3. The factor is calculated after performing intra-development tests to find a price range that will not negatively effect on the Broker's revenue and cash balance (e.g. the price for selling the energy would not be lower than the price for which the energy was bought). The strategy aims to attract household customers back with the cheap tariff prices which may latter be changed (often to some higher prices to boost up the revenue model).
- **`CheapOfficeTariffsStrategy`** performs operations of creating three tariff specifications with significantly lower prices. The functional description is the same as for the `CheapHouseholdTariffsStrategy` strategy with the difference that here we address tariff models characterized by enumerations that contain the "OFFICE" string inside them.
- **`PeriodicTariffsStrategy`** was developed due to the observed problems in the server environment during qualifying rounds and trial competition of the PowerTAC international forum during 2013. The tariff specification parameter named *periodicPayment* was identified as a critical point in the evaluation process of the customer models inside the server environment. We have come to conclusions that customers switch to models with periodic payment regardless of its amount and size which bring distortion in the competition outcomes. CrocodileAgent did not use the parameter since the development team was aware of the problems and irregularities. Therefore, the strategy is to be executed if the Broker detects competing tariffs from other brokers that have this questionable parameter set to some value. Actions performed by the strategy consist of the creation of four tariff specification with different periodic payment amounts inversely proportional to the price per kWh of energy consumed. Inner test have also confirmed that this strategy eliminates the loss that the Broker would have suffered if some of the other brokers exploited the feature. Even though, the server development team announced fixes to this issue, the strategy stays

as a part of the main Broker functionalities since it was already used and may be helpful upon the existence of the same issue in the future.

– **`GenericTariffsStrategy`** represents a generic, modular and changeable strategy that depend on the parameter given during the initiation of the Java object. The instance receives a map of entries consisted of `TariffType` values as keys and a *check* parameter which defines the factor of the originally calculated price. For example, the may consist two tariff model types for household customers, one model for office and one for periodic tariff specifications. Each of these future tariff specification may have differently defined prices based on the featured parameter. Therefore, this strategy intends to suit multiple situations where the required responses on the tariff market may be defined appropriately. Emphasis is of providing the main Broker service with the highest degree of freedom for making decisions based on the identified and evaluated market state.

– **`StrategyEvaluator`** is a Java object used for grading of the previously mentioned strategies that are deployed during one competition scenario. The grade of each strategy applied to the retail market will give us the correct answer about its influence and profitability. The exact algorithm for grading a specific deployed strategy is carried out by calculating:

  - For each strategy we calculate the total cumulative number of acquired customers and divide it with the number of created tariffs,
  - For each strategy we calculate the total cumulative revenue that the tariffs created within the strategy produced and divide it with the number of created tariffs.

  These number are then used to calculate two ratios which have a 50:50 share in the final grading of the strategy. The ratios are calculated as:

  - **Ratio-1:** The number of subscribers per tariff (from the strategy) is divided by the average number of subscribers between all active tariffs,
  - **Ratio-2:** The amount that characterizes revenue per tariff (from the strategy) is divided by the average revenue per tariff from all active tariffs.

  After the ratios are calculated each of them receives a grade based on this criteria:

Algorithm 1 Grading of the calculated ratios

if $ratio > 2.5$ **then**
    $grade \leftarrow 5$
else if $ratio > 1.75 \wedge ratio \leq 2.5$ **then**
    $grade \leftarrow 4$
else if $ratio > 1.0 \wedge ratio \leq 1.75$ **then**
    $grade \leftarrow 3$
else if $ratio > 0.5 \wedge ratio \leq 1.0$ **then**
    $grade \leftarrow 2$
else
    $grade \leftarrow 1$
end if

The **final grade** of the strategy is given as the **average** of two calculated grades.

5.2.2. Technical features

The CrocodileAgent 2013 is characterized by two technical features that consist of configurable in-game parameters controlled from a properties file between different games in a competition and reportable features that generate *Excel* spreadsheets for post-game human analysis. This are made as a supplement to the broker's logic in the retail and wholesale market.

Configurable features of CrocodileAgent 2013

Configurable features of the Broker were made with the intention of emphasizing the automated behavior of the agent. Namely, the Broker is initiated by its owner and operates by itself and to introduce some fine-tuning mechanism we had to apply configurable parameters that may change the agent's behavior during a specific game. These parameters allow us to modify Broker's strategy without making any changes to the source code. The CrocodileAgent achieves this feature by using an input configuration file loaded by `CrocodileAgentProperties` service before the start of the competition. Additionally, the parameters that are intended to be changeable are annotated with `@Configurable` Spring annotation which gives indication to the loading procedure to overwrite the existing value that may have been predefined in the source code.

In Figure 5.7 we see an example of the configurable parameters that exist in the `TariffManagerService`, more exactly in the `SmartTariffCreator`. According to the presented parameters we see in the first section that the parameters will control the

```
crocodileagent.services.tariffManagerService.householdRTPMaxCurtailment = 0.3
crocodileagent.services.tariffManagerService.householdRTPMinDuration1 = 86400000
crocodileagent.services.tariffManagerService.householdRTPSignupPayment1 = 0.0
crocodileagent.services.tariffManagerService.householdRTPEarlyWithdrawPayment1 = 0.0
crocodileagent.services.tariffManagerService.householdRTPPeriodicPayment1 = -10.0
crocodileagent.services.tariffManagerService.householdRTPMargin1 = 0.5

multiplier = 40.0

crocodileagent.services.tariffManagerService.householdToUMaxCurtailment = 0.1
crocodileagent.services.tariffManagerService.householdToUMinDuration3 = 0
crocodileagent.services.tariffManagerService.householdToUSignupPayment3 = 0.0
crocodileagent.services.tariffManagerService.householdToUEarlyWithdrawPayment3 = 0.0
crocodileagent.services.tariffManagerService.householdToUPeriodicPayment3 = -10.0
crocodileagent.services.tariffManagerService.householdToUMargin3 = 0.5
```

Figure 5.7: A small representation of the configurable parameters situated in the properties file

available properties of a tariff specification and by the notation we see that RTP tariffs will be affected. The middle section has only one parameter which represents the multiplier for the price that is calculated for each tariff price. The last section affects ToU tariffs for household customers as it may be seen from the name of the variable parameters. The tariff parameters follow the modifiable parameters available when instancing a new `TariffSpecification` object from the `Common` project of the PowerTAC server.

Reportable features of CrocodileAgent 2013

Reportable features are an additional tracking mechanism for post-game analysis added to the standard logging system. After the competition ends (server sends an appropriate message) Broker's components that implement the `Reporter` interface will be called to initiate reporting by creating spreadsheets and filling them with information from various maps in the source code that were used during the specific competition scenario. Tariff Manager as one part of the complete CrocodileAgent 2013 generates 9 spreadsheets specific to the tariff design and evaluation. CrocodileAgent creates more spreadsheets related to the wholesale market activities and related to general game and pre-game information, but since these are not in the scope of our module we do not mention them here. The previously mentioned 9 reportable sheets are:

1. **CompetingMyTariffReportSheet** – counts and reports the number and type of the competing tariff specification created by other brokers,

2. **CustomerEnergyUsageSheet** – saves and reports the amount of energy that a specific customer type has used in each timeslot,

3. **PredictedCustomerEnergyUsageSheet** – starts reporting the energy usage of a specific customer type from a pre-game period where the data is generated by the server. The data is then used to predict future energy usage by the Holt Winters algorithm

which gives values that are easily comparable to the previous sheet to compare possible fluctuations from the real energy usage,

4. **ProductionEnergySheet** – saves and reports the amount of energy that was acquired by tariff specification intended for producers so we can compare the amount of energy used in total with the amount acquired from renewable energy sources,

5. **SubscrionTrackSheet** – tracks the subscription count of each tariff specification posted by the Broker in each timeslot. Additionaly, it tracks the total number of customer per timeslot with the oscillations from two adjacent timeslots,

6. **StrategiesSheet** – reports the timeslot in which a specific strategy was initiated by the Broker with the addition of the grade that the strategy acquired after evaluation,

7. **TariffRevenueReportSheet** – is probably the most important sheets that represents all the information about tariff specifications, such as its configurable parameter values, rate types and its values, timeslot of initiation, revenue from energy trading and revenue acquired from tariff transactions other than from energy trading,

8. **CompetingTariffReportSheet** – is similar to the previous sheet with the difference that it does not hold the information about tariff revenues since these are not available from the in-game communication activities (Broker only receive tariff transaction related to its own tariffs while it receives information about published tariffs from each other broker), and

9. **EnergyConsumptionTrackSheet** – tracks the amount of energy consumed by customers subscribed on a specific tariff specification per timeslot.

5.2.3. CrocodileAgent's 2013 lifecycle operations

To present all of the generic activities that the broker goes through within its lifecycle in a competition scenario we use the UML state diagram shown in Figure 5.8.

After the broker is ran from the development environment it switches its starting state with the *Idle* state where the broker's context has to be initialized from an XML configuration file. After the initialization is done, the broker initiates the *configuration* event which causes the state to transfer to *Configuring*. The previous event configures all of the broker's components that have some dependencies and may have been updated from the last initiation of the broker itself. The next step for the broker is to try to login to the competition with the credentials obtained from the properties file allocated in the source project package. After a successful login broker is situated in the *Waiting* state where he awaits the beginning of the game. Additionally, the broker can reinitiate the login procedure if some unexpected errors occur or it may quit the process if case of a timeout.

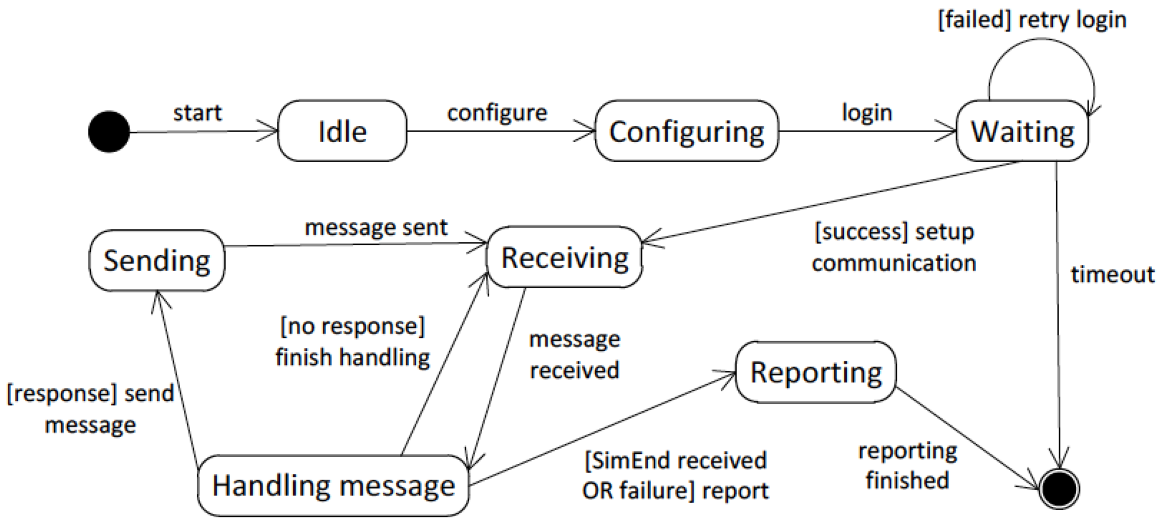

Figure 5.8: CrocodileAgent's 2013 lifecycle operations [4]

After the message for starting the simulation is received the broker changes the state to *Receiving* while setting up the communication channels and parameters. In this state the broker awaits messages from the server environment to arrive where upon arrival the state changes to *Handling message* state. From this state depending on the broker's intention (and need) to respond to the received message the state changes to either *Sending* if some messages are sent back to the server or to *Receiving* if we await for new messages. The *Sending* state handles the sending activities after which the state changes back to the *Receiving* state again. From this closed circle a broker may leave upon receiving the *SimEnd* message which when handled in the *Handling message* state switches the broker's state to the *Reporting*. This state performs the creation of post-game analysis spreadsheets mentioned in the previous section. In the end and upon completion, the broker goes to the end state and finishes its lifecycle.

5.3. Agent implementation

In this section we focus on the detailed description of the CrocodileAgent's 2013 implementation. Tariff Manager activities were already described on a higher level of abstraction in Section 5.1. In the next several subsection we describe implemented tariff types and timing operations and actions of the Broker.

5.3.1. Implementing various Tariff Specifications

Tariff Manager constantly tracks and analyses energy and cash flow and evaluates the received data to create Tariff Specifications. The Tariff Manager is very active when it comes to publishing new tariff specifications. Therefore it frequently sends tariff specifications to the customer market which it presumes will secure a reasonably good profit. Tariffs that are not profitable enough are being replaced (superseded) with tariffs that have better utility, in terms of CrocodileAgent 2013. Tariffs that show the worst or no utility (e.g. tariffs with the smallest revenue) over time are revoked completely from the game and saved in the repository so that the broker can repeatedly check and compare tariffs and create new, better ones [4]. Tariff utility can be presented as:

$$tariffUtility = f(cC, fPk, tR, profit) \tag{5.5}$$

where cC is the number of customers currently subscribed to the tariff, fPk is the fixed price per kWh, tR is the tariff revenue calculated by summarizing tariff transactions for the specific tariff received every hour in the game and finally $profit$ is the brokers profit margin. This utility helps the inner Broker logic to identify good or bad tariffs and make further decisions.

CrocodileAgent 2013 implement various tariff types that may be semantically separated based on the targeted customer types. Therefore, each tariff type is characterized by an Enumeration in Java for easier recognition and later post-game analysis. Figure 5.9 shows a graphical representation of various tariff types that the Broker designs during one competition. The main division of tariff types is based on the customer energy usage patterns: consumption, production or interruptible consumption (these tariff types allow the distribution utility (DU) to stop the delivery of electricity up to certain extent stated in the contract between the Broker and specific customer).

Another important division is made by separating 12 different tariff specification types for consumption purposes and 1 tariff specification type for production purposes. Since the production customers make only a small portion of the complete portfolio of customers in the competition, one tariff specification for them is more than enough which we prove later on in the evaluation chapter. Different tariff specification may have different rates applied for energy trading. We distinguish 6 different rate types where the 4 of them are for fixed pricing agreement and 2 of them are for variable pricing (real-time pricing). Arrows on the Figure tell us all of the possible combination between different `TariffSpecifications` and `Rates`.

Before we describe the implications of available tariff types it is important to explain the way how the prices for energy consumption/production are created. The next equation

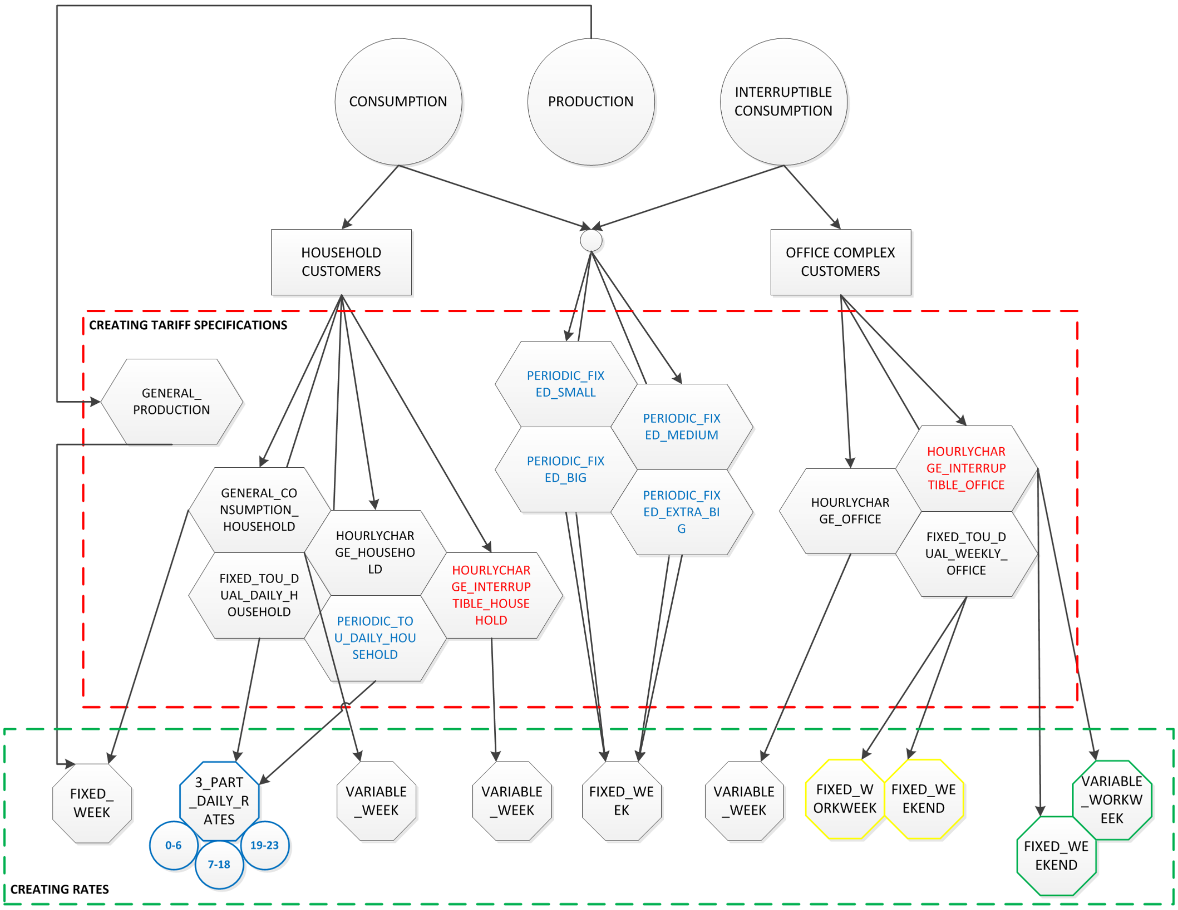

Figure 5.9: Taxonomy of available tariff models with different rate designs.

simplifies the formula for calculation and uses a parameter calculated in Equation 5.4:

$$price = (-1.0 * arithmeticPrice) * (1.0 + margin * marginMultiplier) \qquad (5.6)$$

where the $arithmeticPrice$ is calculated based on wholesale trading activities, $margin$ is a parameter characteristic to every type of tariff specification and $marginMultiplier$ is the modifier of original margins set by tariff specification parameter for a more fine-grained end price for electricity.

To improve understanding of all of the possible models it is best to first introduce and explain different rate types that are applied to the tariff specifications:

- *FIXED_WEEK* represents the most simple rate type that has a fixed price for energy regardless of the current time of the day and day of the week. The only difference in these rates is the *signed double* value of the variable for price where the positive price is set for production tariff and negative price for consumption tariffs,

- *FIXED_WORKWEEK* represent a rate type which starts its time of validity on Mondays and ends on Fridays. The price for energy is set a accordingly to the Equation 5.6 with the value of $marginMultiplier$ set to 2.5 (we want the price during weekdays to be higher than in the weekends).

– *FIXED_WEEKEND* is the opposite rate type to previous one and represents pricing for Saturdays and Sundays thereby complementing the FIXED_WORKWEEK rate type. The price for this tariff has a $marginMultiplier$ set to 1.

– *3_PART_DAILY_RATES* is a generic rate type that is consisted of three instances of the `Rate` class where each one of them represent one part of the day. CrocodileAgent 2013 specifies these times to be from 0-6, 7-18, and 19-23 hours with pricing value of $marginMultiplier$ as 1, 1.3, and 1 respectively (the price for energy should be the highest during daytime, and customers who are willing to shift it to off-peak periods are rewarded with lower energy prices).

– *VARIABLE_WEEK* represent the most simple variable rate type that changes the price following the true RTP mechanism. This rate type has the notice interval time set to 3 hours like all other variable rate types that the CrocodileAgent 2013 implements. Since variable rates have to specify minimum, maximum and expected price along with the Hourly Charges that control the current price we had to modify the Equation 5.6. For minimum price for electrical energy per kWh we have:

$$price = (-1.0 * arithmeticPrice) * (1.0 - margin * 3) \tag{5.7}$$

where the emphasis is on the exchanged sign before $margin$ and the margin multiplier value that is set to 3. For the maximum price the formula is the same as 5.6 with the value of margin multiplier set to 2.150 (the number was calculated based on successfulness of the rate in played competition scenarios). Finally, the expected mean price has the price calculated by having the multiplier set to 0 (expected price should always be in the middle without any margins to attract customers).

– *VARIABLE_WORKWEEK* shares the same design as the FIXED_WORKWEEK with the difference of variable pricing during the days of validity in a week. The minimum price is the same as in the case of VARIABLE_WEEK while the maximum price has the margin multiplier value set to 2.5 and the expected mean calculation has the multiplier ranging from 1.0 to 1.2 (in some cases unlike the previously mentioned one, we put the expected price a little bit higher – if the maximum and minimum price have a larger margin).

Tariff specification are on another hand grouped in three main groups based on the targeted customer type. Therefore, the first group intends to attract household customer types, the second one should attract office complex customers and the last, third one is generic for all customer types and is created to offer tariff specification with periodic payments while the energy prices in these tariff are very low (minimum base margins and margin multipliers). Each tariff specification is characterized by the set of basic parameters that an instantiated object has and a margin that will be forwarded to rate creation module upon applying specific rates to the created tariff specification. Table 5.1 shows the value of specific parameters for each of the tariff types:

- minimal duration if the signed contract,
- signup payment after subscribing which can be either made from Broker to customer (+ sign) or from customer to Broker (- sign),
- early withdrawal payment if the customer ends contract earlier than minimal duration,
- periodic payment that is charged on a daily basis (- sign when payment to the broker),
- maximum curtailment which indicates maximum percentage of controllable customer energy consumption by the Distribution Utility, and
- margin for price calculation.

Note that the variable names are different in the source code to suit in a more appropriate way for programming activities.

From the Table 5.1 we may observe that the CrocodileAgent 2013 did not focus on early withdrawal payments as incentives for securing minimal contract duration. Maximum curtailment is 10% in some applicable tariffs since the tests have proven that above that percentage customers are reluctant to subscribe to the tariffs. Signup payments are introduced in two ways: i) as an incentive for customers to subscribe to a specific tariff, or as a fee that allows privileged energy prices in that specific tariff specification.

5.3.2. Performing superseding actions

In the Subsection 5.3.1 we introduced the term of tariff utility. This model is used for supporting the decision making process of exchanging old and non-profitable tariff specification with more appropriate ones. The utility of every active tariff in the market is checked in timeslot that are dividable by 100 starting firstly from the timeslot 500 since the game starts at timeslot 360 so there is not enough time for the tariff to satisfy the factors of a good utility. Additionally, the superseding action depend on the oscillation of the total number of subscriber. This factor had to be added to the process since the superseding a tariff specification cost some money for the broker. Generally, server environment sets the publication fee of the tariff specification in the beginning of the game and every broker has to pay a certain amount of money for each tariff specification that it sents to the customer market.

Numerous and long lasting tests have proven that in later stages of the game our Broker has a large number of tariffs (above 30) where all of them are not profitable on an equal level. This may be caused by satisfied customer that subscribed to one particular tariff specification and do not have the need to switch to other available tariffs. Therefore, Broker may decide to

Table 5.1: Graphical representation of tariff parameters and their values for different tariff types

TariffSpecification Type	Min Duration	Signup Payment	E. With. Payment	Periodic Payment	Curtailment	Margin
GENERAL_CONSUMPTION_HOUSEHOLD	dynamic	dynamic	dynamic	dynamic	dynamic	dynamic
HOURLYCHARGE_HOUSEHOLD	86400000 * 100	-500	0	0	0	1.25
H.CHARGE._INTERR._HOUSEHOLD	0	0	0	0	10%	1.25
FIXED_TOU_DUAL_DAILY_HOUSEHOLD	0	0.5	0	0	0	1.2
PERIODIC_TOU_DAILY_HOUSEHOLD	86400000 * 100	10	0	-100	0	0.0
PERIODIC_FIXED_SMALL	0	0	0	-1	0	1.2
PERIODIC_FIXED_MEDIUM	0	0	0	-5	0	1.15
PERIODIC_FIXED_BIG	0	0	0	-10	0	1.1
PERIODIC_FIXED_EXTRA_BIG	0	0	0	-100	0	1.05
HOURLYCHARGE_OFFICE	0	0	0	0	10%	1.2
HOURLYCHARGE_INTERR. _ OFFICE	0	0	0	0	10%	1.2
FIXED_TOU_DUAL_WEEKLY_OFFICE	0	0	0	0	10%	1.2

supersed a large number of tariffs (arround 20) which then results in a significant charge from the server (arround 4000 euros per published tariff). To overcome the issue of superseding tariffs when the state of the market is satisfactory from the CrocodileAgent's point of view we limit the superseding when observed:

1. that the Broker holds the majority of the customer subscriptions available in the whole competition scenario,
2. that the Broker's customer subscription are not changing from the last superseding

action. This in particular means that the superseded tariffs from before were not good enough and customers are still subscribed to other brokers' tariffs due to extremely low prices for electrical energy (behavior was observed when other brokers give too low prices just to acquire customers even though the prices bring losses to the overall cash balance - CrocodileAgent then stop offering superseded tariffs and does not go on that price level)

When the superseding activities are initiated (after the decision has been made) each tariff specification currently active in the customer market is checked for its utility and revenue. If the tariff has under-performed it is superseded with the same type of tariff that was used to create it. Since the `TariffSpecification` object does not have any useful parameters that we could use to distinguish the exact type of the created tariff, a separate small processing module with its repository was added to track and connect tariff specification ID numbers with enums which characterized them upon creation.

5.3.3. Timing operations and activities during a timeslot

In Section 4.3 we described the generic structure of a PowerTAC competitor, more exactly a broker that participates in the game. Additionally, we presented the broker's activities in the Figure 4.2 by emphasizing all important activities that broker handles and performs in each timeslot. These activities include not only Tariff Manager activities, but also activities carried out by the Market Manager and some generic service of the broker. In this Section we focus only the activities of the Tariff Manager that occur in one (each) timeslot and Figure 5.10 is used for graphical presentation of performed activities.

These actions are of course accompanied by various tracking and data reporting mechanisms that allow complex processing and decision-making. Since the structure of these additional activities is complex and by all means deeply intertwined we disregard their description in this thesis. More in-depth information may be found in the source code and Java doc that can be generated. All of the activities are carefully explained and described so interested parties would not have any problems investigating more.

In the next chapter we present the results made by post-game analysis on the Broker's performance in PowerTAC competition. All of the implementation characteristics are evaluated and compared along with comments regarding general Broker's status in the played competitions.

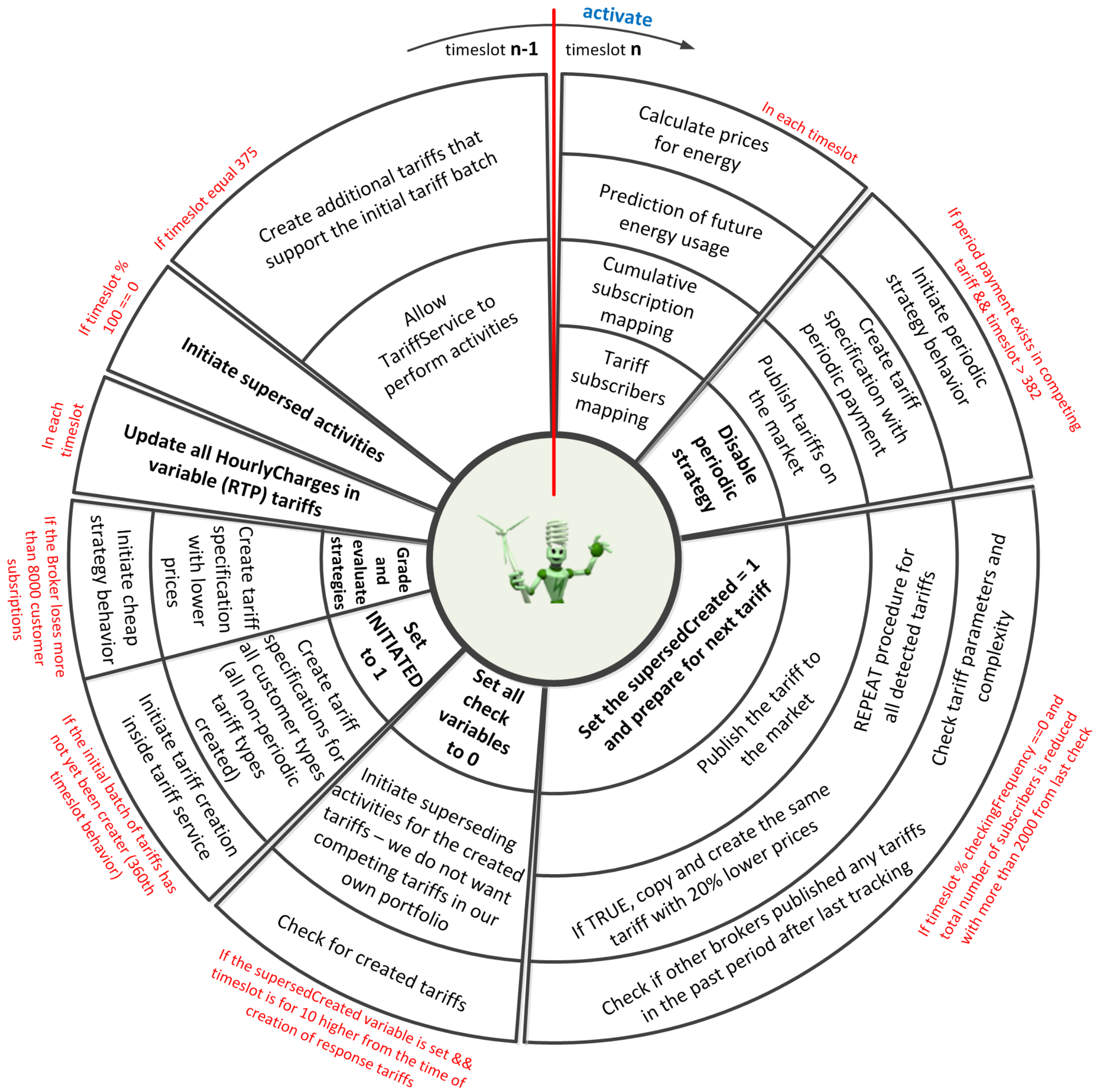

Figure 5.10: CrocodileAgent's 2013 activities inside the Tariff Manager in each timeslot

6. Evaluation mechanism and results of CrocodileAgent performance

6.1. General evaluation policy and data set description

The evaluation of the CrocodileAgent's 2013 performance is based on the PowerTAC qualifying competitions that were held three times during the year 2013, in March, April and May. There were eight competing teams (hereinafter brokers) participating in the March trial:

– our CrocodileAgent 2013(University of Zagreb, Croatia),
– AstonTAC (Aston University, UK),
– LARGEPower (Rotterdam School of Management, Netherlands),
– Mertacor (Aristotle University of Thessaloniki, Greece) (only in March),
– MLLBroker (University of Freiburg, Germany),
– cwiBroker (CWI Amsterdam),
– UTest (UT Austin), and
– INAOEBroker01 (INAOE);

In addition to competing brokers, each PowerTAC game contains the embedded agent called `default broker`, which serves in the role of default retailer for customers even before competing brokers join the game. Additionally, each competition holds two rounds: one qualifying round to test the brokers if they work properly and one final round that only has one winner.

The analysis that is performed is based on the outputs of chosen PowerTAC games and the *Excel* spreadsheets generated by CrocodileAgent. The PowerTAC output is a set of debugging logs and game exploration logs where the last one holds all the information about transaction and changes made in that specific game. The main key performance indicators are stated and described in the Appendix A that follows the schedule of presented results while their detailed and expanded explanations are in further sections and subsection concerning evaluation policies.

If we look in the overall results against other competing brokers, the CrocodileAgent performed very well in the first competition by winning it and acquiring the first place. The second competition experienced some server problems related to evaluation mechanism implemented by server components therefore making the competition results unusable. The last qualifying session was characterized with some problems in the Broker's behavior in the beginning where after modifications of some parameters was made stable. Additionally to the observed problems in the Broker's behavior, the server developers have observed multiple additional issues in the server environment which are being fixed at the same time as these paragraphs are being written.

The general policy for evaluation will be mostly based on the performance of specific Broker modules and behaviors in various competition scenarios (e.g., Broker plays around 50-100 games in one competition and each one of them ends with the previously mentioned logs ans *Excel* spreadsheet holds valuable post-game data and analysis) and not on the overall results against other brokers. The main part of the evaluation is related to success of various Tariff Specifications and strategic behavior that led to their creation. Next section explains in-detail the evaluation policy and key performance indicators (KPI) that were tracked and evaluated.

6.2. Tariff evaluation policy and key performance indicators

The first important division related to the tariff types that the CrocodileAgent publishes to the tariff market is dependent on the general customer type. In the previous sections we mentioned three possible options for a customer type: i) consumers, ii) producers, and iii) prosumers. Since the last type of customers is not yet available in the PowerTAC simulation, there were no tariffs structures developed by the CrocodileAgent that would suit these customers. Therefore, **we divide the evaluation of tariffs into two different parts**: i) consumption tariffs, and ii) production tariffs.

6.2.1. Evaluation of production tariffs

The PowerTAC competition is conceived in a way that it does not emphasize too much the importance of renewable production customers on the market. The number of different types and the amount of production customers represents a fraction of the overall customer count. More exactly from a overall customer count of around 50300 customers, the number of production customers is only 92 (90 customers characterized as WIND-PRODUCTION type, and 2 customers characterized as SOLAR-PRODUCTION).

Our main goal in the competition is to attract that small number of customers that act as producer to cut down the burden on the overall balancing of consumption and production which is maintained in the wholesale market. The price for the energy that the CrocodileAgent offers to the production customers will always be smaller than the price for the energy that could be obtained in the wholesale market. Reasoning for that lies in the main goal of the agent to obtain profit for its activities on the tariff market.

In the statistical data provided from competition and agent logs we focus on the **correctness of the price** that was established for our production tariffs and **the number of customers** obtained by these tariffs. Another important parameter is the retention factor of these customers. It is our goal by all means keep the production customers in the agents portfolio if the need for energy is present and the price that we can offer is lower than the mean cleared price for the energy in the wholesale market.

The production tariff evaluation mechanism starts upon publishing a production tariff, where the CrocodileAgent tracks the number of customers subscription on that specific tariff. If the tariff specification manages to obtain at least 50% of the available production customers (after it is available on the market – 6 timeslots for the server to publish it + 10 timeslots for the inertia of customer themselves) we consider tariff to have a successful publication. If the tariff specification does not acquire the specific share of customers we revise the tariff specification, label it as unacceptable and exchange it with the new tariff with modified pricing (modified pricing often means paying more credit to the producers per kWh until the wholesale price limit).

Additionally, **KPIs** regarding the evaluation of these tariffs are the amount of energy produced, price for energy offered by the broker and the percentage of consumed energy that was covered by the production customers. These parameters are taken and summarized from different *Excel* spreadsheets from each game that was played by the CrocodileAgent.

In the end we emphasize once more that the important matter related to production tariffs is to acquire energy at lower prices than they could be in the wholesale market to cut down the burden on the balancing that the wholesale market manager is experiencing.

6.2.2. Evaluation of consumption tariffs

Building on the foregoing characteristics of PowerTAC, we may observe that the consumption population presents the main profit generating element in the competition. Therefore the creation and design of competitive consumption tariffs is a great challenge and of utmost importance for the CrocodileAgent. In the previous chapter we explained all versions of the available tariff types on the customer market. The main division of consumption tariffs that we use in our evaluation can be presented as:

1. CONSUMPTION tariff specifications, and
2. INTERRUPTIBLE-CONSUMPTION tariff specifications;

Both of the tariff types may contain any of the previously mentioned in-depth characteristics of the tariff specifications (e.g. ToU, RTP and their combinations).

Additionally, the CrocodileAgents' tariff specifications are evaluated in two separate stages. **The first stage** evaluates all of the available tariff specifications in the same way concerning their overall success on the market. The overall success is characterized in four different directions:

1. obtained revenue during the lifetime of the tariff specification,
2. amount of energy traded during the lifetime of the tariff specification,
3. number of customers and customer fluctuations, and
4. responsiveness factor of the tariff specification;

The last parameter is considered only for tariffs that are published as a direct response to some of competitor's tariffs that managed to recapture our customer subscriptions. More precisely, the responsiveness factor of a tariff can have a maximum value of 1.0 where the value emphasizes that the tariff acquired all the lost customer subscription and recaptured them again. If the number of responsive tariffs published in one timeslot is greater then 1, the calculation of the responsiveness factor also depends on the successfulness of other published tariffs (i.e., if two tariffs are published as a response to two tariffs that recaptured some of our subscription and their responsiveness factors are 0.52 and 0.41 respectively, we may consider that both tariff acquired a shared success with a responsiveness factor of 0.93 - 93% of customers are recaptured again). The responsiveness factor calculation is based on the subscription count of both tariffs and the change of the cumulative subscription count where we look at the difference between the lost number of customer subscriptions and cumulative difference of acquired customer subscriptions.

The obtained profit of a tariff specification is measured regarding the share in the overall revenue obtained from the tariff market. This value is obviously dependent on the amount of customers subscribed to the tariff and energy that is traded to them. The tariff specification will be labeled as non-profitable, sustainable, and profitable where the non-profitable tariffs acquired small (less than 2000 euros) or no profit at all, sustainable tariffs kept at least a constant incline in the amount of profit, and lastly profitable tariffs are tariff specification with at least 10% of the overall profit acquired during the lifetime of the tariff. **This KPI is measured** based on the summarized results of tariff specification types in each game and not per tariff (since that number is extremely large).

The amount of energy traded is a direct indicator of subscribed customer characteristics and is closely connected to the obtained revenue for a specific tariff (a correlation factor of 0.938 where the oscillation is due to the periodic payment tariffs where revenue is acquired through periodic payments). The evaluation criteria is similar to the previously mentioned one where we consider the tariff to be successful if the cumulative traded energy is growing by each timeslot. It is important to emphasize that this factor may also mark a tariff specification as unsuccessful regardless of the fact that the tariff may acquired significant profit. This anomaly may be cause by tariffs with the periodic payment options where customers subscribed to those tariffs do not spend large amounts of energy but still pay the daily fee for being subscribed to the tariff. These cases are considered independently and are labeled accordingly.

The number of customer subscription is one of the most important factors of the tariff evaluation process. It is a direct indicator of the tariff specification popularity among the customer population of a specific instance of the PowerTAC competition. The number of customers subscribed to each tariff is closely tracked and observed during each timeslot. The first one is because of the quality evaluation of the tariff and the second reason concerns the responsiveness feature of the CrocodileAgent. Tariff specification that acquire more than 20% of the agents' customer population and over 30% of the overall customer population of the competition (reduced by the number of production customers) is considered extremely successful in this category. Note that some customer types (e.g., VillageType[1,2,3]) may consume a noticeable amount of energy and acquire distinctive profit for the agent but are not very well characterized by the customer number (since one village can contain numerous houses that use the energy, but are seen in the competition as one entity).

The combination of these four parameters and their success factors gives us a clear picture of the successfulness of the particular tariff published by CrocodileAgent in a specific competition instance.

The second stage of the tariff evaluation process concerns the evaluation of specific tariff types that were used in the competition (e.g., RTP, ToU, and their derivatives). The main goal of this stage is to evaluate the statements discussed in Chapter 4 (Network Tariff Design Principles). We either have to confirm are refute the successfulness of specific tariff types. Additionally, the concern is to evaluate which tariff types (primarily regarding fixed or variable pricing mechanism) are more popular among the customer types and which of them acquire more profit. This stage of evaluation also considers the identification of tariff types which were more suitable for customers (lowering their overall expenses for electrical energy) and how the customer inertia is affecting their choices during the competition. **KPIs in this stage are measured by summarizing the revenue from all games** made by different tariff specification types. The result gives us a clear view of the popularity and quality of each tariff type.

This stage uses information acquired from the first stage and groups tariff by the pricing type that they realize. All tariff specification may be grouped on the basis of their creation and labeled with the parameters of the `TariffType.java` enumeration class. The outcomes of the analysis contains the comparison for each of the available design structures specified by the CrocodileAgent. Parameters taken into concern range from the number of tariffs per each group, number of supersed that occurred for each group[1] and the overall revenue that they acquired.

Another part of the evaluation in the second stage addresses the comparison between the CONSUMPTION and INTERRUPTIBLE-CONSUMPTION tariff specification types and fixed/variable price tariff types. **KPIs in this evaluation are measured by summarizing revenue of each characteristic group of tariffs** and by calculating the percentage that they take from the overall profit obtained. **Additionally, we focus on the distribution of different transaction types** that the Broker performs during the game and their influence on the total cash balance.

It has been observed from the game logs that INTERRUPTIBLE-CONSUMPTION customer types are only available as those previously mentioned aggregated customer groups (e.g. VillageType). Therefore for the evaluation of the successfulness of these tariff types, in comparison to regular CONSUMPTION types, we use only the factors of energy usage and acquired profit during the time span of tariff availability.

6.3. Production tariff results and discussion

The situation regarding producers and *Tariff Specification* made by the Crocodile Agent 2013 is rather specific. During the three different competitions we have acquired different results related to the success of production tariff specifications. In the first (March) and second (April) competition the production tariffs made more or less equals results if we take into account the evaluation policies described earlier. In the third (May) competition CrocodileAgent 2013 did not acquire any of the production customers. These results are a direct consequence to the changes made in the price calculation mechanism for the production tariffs. Namely, by preparing the Broker and its internal parameters for the last competition

[1]superseds occur during the game for a tariff specification if its profit has not met the specific criteria - amount of profit obtained in a specified time span

we have observed that in the earlier stages of the Broker the price for buying electrical energy from Wind and Solar power plants were to high. Therefore the energy price used in the last competition was drastically reduced to fit the pricing scheme of energy consistent with the wholesale market prices. Reasons for that will be explained later on.

In Table 6.1 we may see the summarized results from chosen games played in the first and second competition. The first column represent the game-id if the reader wants to reference to complete logs to the game for further investigation (Trial March 2013 logs). The second column is consisted of the total number of tariff specification created for production tariffs in that game by the Broker, counting both new tariff specification and the ones that are created as the result of supersed operations. The third column represents the total amount of money payed from the Broker's account to the production customers and the fourth column gives us the average price between the available tariffs. The fifth and sixth column represent the amount of energy produced by these customers and the total amount of energy that was sold by the Broker to the consumption customers. Lastly, the seventh column shows the percentage of the total sold energy covered by the production customers.

Table 6.1: Representation of production tariff characteristics and results

GAME	No. of tariffs	Total debit [Euros]	Avg. price [Euros/kWh]	Energy produced [MWh]	Total energy consumed [MWh]	Percentage covered
10	2	-1534689.54	0.1586	9677.00	127696.36	7.58%
17	2	-1857697.28	0.1811	10255.22	85560.59	11.99%
30	2	-1640635.54	0.1584	10359.90	141568.45	7.32%
31	2	-1619170.25	0.1681	9632.33	9559.10	100.77%
37	4	-1650777.49	0.1601	10275.27	73300.43	14.02%
40	2	-1145877.15	0.1575	7274.96	95884.19	7.59%
43	4	-1437128.96	0.1441	8736.37	121748.03	7.18%
49	8	-1341378.57	0.1347	8562.67	128547.69	6.66%
	average	**-1528419.35**	**0.1578**	**9346.71**		**8.90%**

All of the tariffs in these games may be characterized as **successful** related to the evaluation policy since they have acquired all of the production customers available in every game. Additionally, the customers were retained until the end of each game. However, after closer inspection (stimulated by zero customers in the third competition) we have observed that the price for energy was to high and that it resulted in the overall loss in the Broker's cash balance. If we had completely discharged the production tariffs and bought this energy on the wholesale market the price for it would have been up to **5 times less** than this average of **0.1578** Euros/kWh.

As we mentioned earlier, in the last competition there were no subscribers on the published production tariff specifications. The reasons for that are the prices that were coordinated with the wholesale prices. This means that other brokers published tariffs with more suitable parameters (higher prices) and the available customer types have subscribed to them. Even though all of our tariffs are now considered as **unsuccessful** regarding the evaluation policy, the overall results of the Broker's performance are better.

To conclude, it seems so that the focus on production tariffs were not made by other research group that developed competing brokers in the competition. Most of them have only one or two tariffs for the production customers group thereby proving little interest in the analysis of production characteristics. As a way to overcome this issue, **Crocodile Agent's development team suggests a higher influential factor of the production customers on the game scenarios**. More precisely, if the number of customers that produce energy were to higher, the incentive to analyze and create production tariffs would be greater (e.g. the brokers could use those customers for balancing purposes or even perform strategies for selling the energy that they have already bought through subscriptions).

6.4. Consumption tariff results and discussion

As previously mentioned, consumption tariff are the main profit generator for the Broker and we have put a greater focus on them throughout the development of the Tariff Manager. The evaluation process started by acquiring game logs and *Excel* spreadsheets from the past three competitions. The total amount of isolated game scenarios for post-game analysis ranges from 20-25 games that were played (all of the competitions were not taken into account since anomalies in the game activities were observed – therefore reducing the influence of CrocodileAgent's actions which in the end results in bad evaluation of Broker's mechanisms). Also, we need to emphasize the fact that these competition were held in three different time periods and therefore the functionalities were upgraded over time based on frequent analysis. Therefore the acquired results are different and we combine all of them to present a complete picture about Broker's behavior in the customer market.

The first part of the evaluation process includes complex and thorough analysis of tariff specification applied in all three tournaments (March, April and May). Based on the evaluation policy mentioned in the previous Section, we tracked the number of customers, traded energy and the revenue for each tariff specification. Here we do not label each created tariff specification as non-profitable, sustainable or profitable since the number of created tariffs is extremely large. Rather than presenting individual result we focus on counting the frequency of tariff labels and thereby compare results between games and competitions. Results that were acquired are quite interesting and the conclusions may be made not only on the Broker's performance but also for the *Server* anomalies that are identified between different competitions.

Table 6.2 represents the cumulative count of various tariff specification labels for the first and third competition. The second competition was ruled out from the table since it showed large fluctuations that would not help in the analysis. Additionally, not all of the games were taken for analysis from competition one and three. The criteria for choosing the statistical data that is presented was that the observed games do not have any anomalies in the functioning of the server environment nor the unexpected errors (or anomalies) in the functioning of all brokers that participate in the game.

In the first column we may see the game-ID which may be useful for readers with the intention of further analysis of these competition scenarios, since all of the logs are publicly available. The second column states the total number of created `TariffSpecifications` by the CrocodileAgent. This is followed by the number of tariff specification that acquired no profit at all during their lifetime (e.g. zero revenue in the competition scenario where they were created). Finally, the last three column represent the frequency of tariff labels that were evaluated following the evaluation policy.

As it is obvious to notice, in the first competition there were no tariff specifications that had zero revenue. That means, although many of them were non-profitable at least they managed to acquire some subscriptions and provide small income to the Broker. If we then look at the third competition we see that there are numerous zero revenue tariffs, almost the same number as the non-profitable tariffs. Keep in mind that the zero revenue column is a sub-group of non-profitable tariffs where the revenue was 0 unlike the rest of the group where it was less than 2000 Euros but at least higher than 0.01 Euros. This means that customers do not even try out new tariff specification if their evaluation labels the tariff as unsuitable. Nevertheless, the number of non-profitable tariffs is high in both competitions and the reasons for that lie in the Broker's strategy to test out various different forms of tariffs and even the same forms with different price so it may decide later on in the game which of the tariff specification and the applied prices suits most of the subscribers.

The number of sustainable tariffs is rather small in compare to the total tariff number, and we consider those tariff as cross solution for the ultimate profit generating tariffs. Tariff specifications that make those tariffs may be the same as for the profitable tariffs but the prices are higher and therefore they do not suit a large number of customers. The last group of tariffs characterized as profitable generated distinguishable profit in the overall Broker's balance in the tariff market. An interesting fact is that in the first competition we had on average three times more profitable tariff specifications than in the third competition. By making in-depth

Table 6.2: Tabel representation of consumption tariff characteristics and results

GAME	Total no. of tariffs	zero revenue	***non-profitable***	***sustainable***	***profitable***
First competition					
15	74	0	54	6	14
17	73	0	42	11	20
21	74	0	50	6	18
30	73	0	43	10	18
37	76	0	45	9	22
43	75	0	40	8	27
49	79	0	40	9	30
53	69	0	44	9	16
average	**74.13**	**0**	**44.75**	**8.50**	**20.63**
Third competition					
48	9	6	7	0	2
49	34	14	19	7	8
54	36	15	22	7	7
57	34	14	22	5	7
59	50	27	35	6	9
64	36	23	26	3	7
69	63	39	48	10	5
101	37	24	28	4	5
49	31	15	20	4	7
73	30	16	23	2	5
average	**39**	**20.78**	**27**	**5.33**	**6.67**

analysis we have come to a conclusion that the server evaluation (i.e. customers evaluating tariffs) was different in the first competition and therefore customers agreed to much higher prices: to be more precise, on average three times higher price which in the end resulted in the high number of profitable tariffs since we used the same criteria (e.g. in a form of the boundaries where we decided what is profitable) for both competitions.

6.4.1. Evaluating responsiveness actions

Responsiveness actions may be characterized as the set of activities that the Broker performs to overcome customer loss owing to other brokers competing tariffs. The performed action for responsiveness starts when the Broker identifies loss of more than 2000 customers. After it has been detected, the Brokers searches the tariff log to see if any of the other brokers published tariffs in the last 20 timeslots. If there are published tariffs, the Broker takes the same tariff specification, creates the same tariff as that competing one but with the 20% lower price than the one on the market. With that we intend to regain back all the customers that transferred from our portfolio to one of those tariffs. Lastly, 10 timeslots after the creation of those tariffs Broker supersed the created tariff specification with one of its own tariff designs with the intention to keep the customers regained back but on its own tariff specification type.

Figure 6.1 shows one of these actions. We may see that from the timeslot 500 the Broker starts losing customers. At the time of the timeslot 520 the Broker identified serious loses and competing tariffs that caused them on the market. The response tariff is initiated immediately. As a consequence we can see that the Broker starts acquiring customers back. in the timeslot 530 the previously mentioned supersed action is performed which causes an immediate loss of customers. The reasons for that are in the server environment behavior where the supersed was configured wrongly thereby not transferring the customers from the superseded tariff to the newly created one immediately after revoking the old one. Nevertheless, we see the improvement already in the next period where we regain customers back. Additionally, many new customers are attracted to the tariff since the price suits them. The easiest way to see the fluctuations is to follow the red line which signifies the total amount of customers. We first see the decrease, then the short increase followed by a one time loss (remember the supersed issue) and continues on with the stable increase of the customer population.

Regarding the results of responsiveness action throughout the third competition (not implemented in the first one yet) we observed that **all** action were performed successfully (the **responsiveness factor was even larger that 1.0** - which means that even more customers than the lost ones were acquired) in the same manner as the previously explained case. The conclusion is obvious: the strategy to respond to competing tariffs have proven to be of utmost value to the Broker's performance.

6.4.2. CrocodileAgents market share and tariff market profit

To visualize and explain the performance of the CrocodileAgent 2013 we have chosen 2 games from the third competition which were extensively tracked throughout the whole

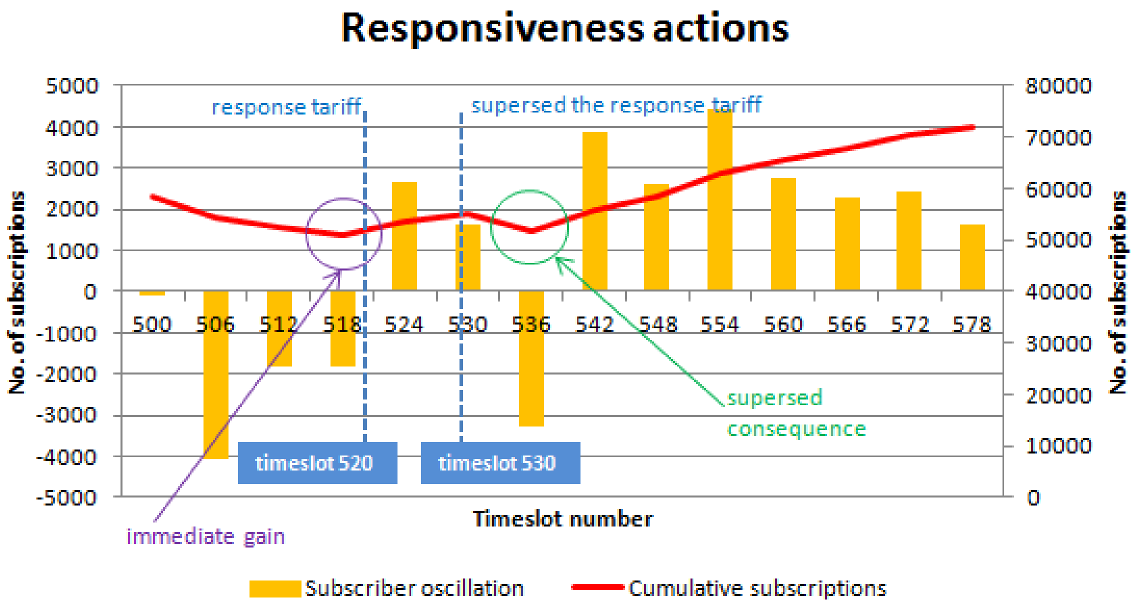

Figure 6.1: Graphical representation of the responsiveness actions performed by the CrocodileAgent upon identifying subscription loss

duration. In these two games the CrocodileAgent is the winning broker. The Broker did not only win in those two games but in many more as it has also lost many games. It is important to emphasize that the lost games were caused by serious errors that occurred either on the server side or in our own Broker development and by this time we have not yet completely confirmed the cause of these errors. The problem is that they occur in some games and in some them they do not (the implementation of the Broker was the same in every game).

Figures 6.2 and 6.3 represent the game results in a form of graphs created by the server Visualizer platform. These graphs were only slightly polished to fit the Figures and for combining useful graphical presentations that are available. In Figure 6.2 on the left side we see the total financial graph that summarizes all the transaction made by the balancing market (rewards or penalties for good balance or imbalance), wholesale market and the tariff retail market. The picture clearly shows the high income increase that the CrocodileAgent has. The direct consequence for that may be observed in the top right part of the picture where we see the cumulative income only received from the tariff market.

If we compare the numbers that represent the total cash balance and the generated profit we may observe that the Broker acquired almost 2 million Euros with transaction through tariff market, but the total cash balance is little over 500 thousand Euros. Reasons for that are of course in the fact that the energy sold to the customers has to be bought somewhere (in this case in the wholesale market) prior to its distribution. The lower right picture shows the cumulative amount of energy sold by the tariff market that ranges up to 30 million MWh in a period 20 days.

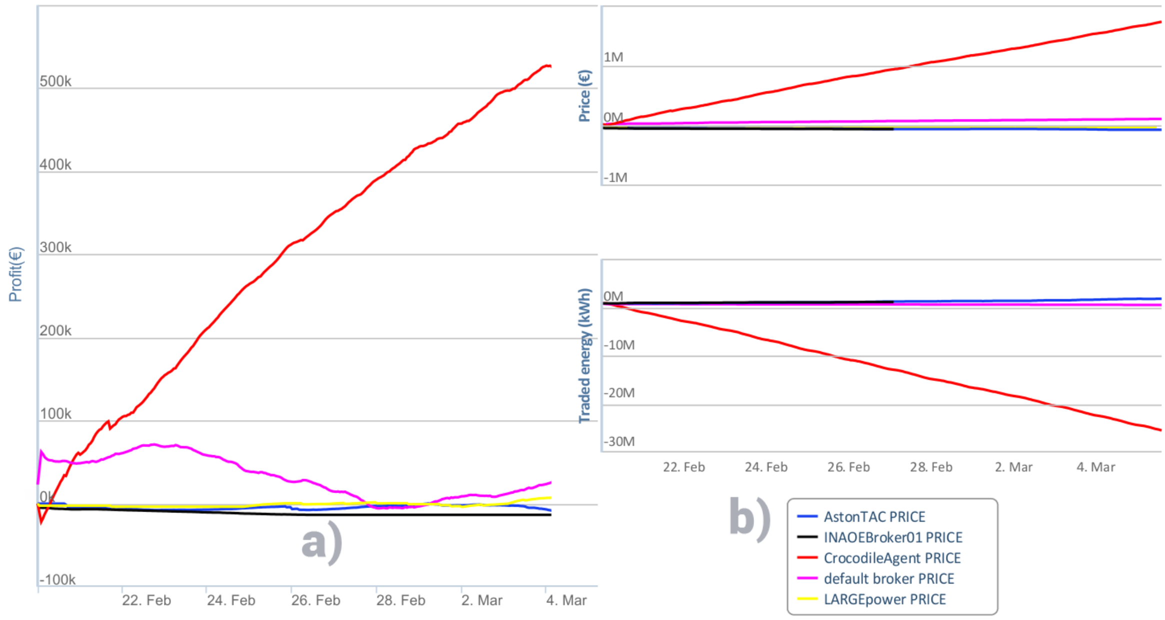

Figure 6.2: Graphical representation of the total cash balance (left) with the cumulative revenue acquired in the tariff market (right, upper graph) and the cumulative energy traded (right, lower picture) in the tariff market during game-49

Figure 6.3 represents the exact graphical representation of the game-69 with the addition of the cumulative customer subscriptions graphs which is now located on the bottom left. In this scenario we may observe that the Broker had difficulties in the total cash balance during the first 20 days of the game resulting in the negative cash balance of more that 200 thousand Euros. After it has achieved stability in its work we see an obvious and linear increase in the total cash balance. Additionally, it is interesting to observe the top right graph where we see that the Broker's profit from tariff market is almost the same as for the MLLBroker (pink), but the MLLBroker's total cash balance is sinking from the beginning of the game. After post-game analysis we have discovered that MLLBroker only offered unprofitable tariffs and did not buy enough energy in the wholesale market which resulted in extreme balancing penalties that overcame the profit from the tariff market. The CrocodileAgent clearly balances its consumption and the activities for buying the energy in the wholesale market therefore reducing any imbalance penalties. The negative cash balance in the beginning in the case of our Broker is caused by very high tariff publication prices and since the Broker publishes a large number of tariffs this resulted in a distinctive cash loss. Lastly, in the bottom right picture we may observe an anomaly where the total number of customers available in the game was reduced due to the outage of the UTest broker. Namely, the customers subscribed to those tariffs at the moment of the outage were completely lost which is obviously a mistake in the work of the server. These customers should have been transferred to the default tariff from the default broker upon this issue (the problem is fixed in the new server

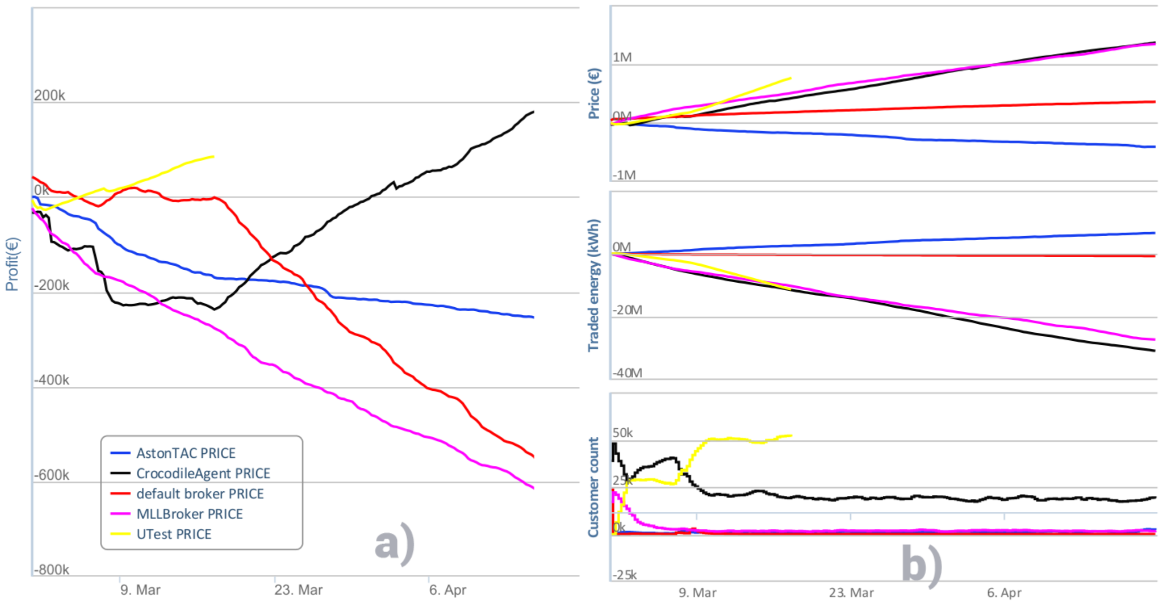

Figure 6.3: Graphical representation of the total cash balance (left) with the cumulative revenue acquired in the tariff market (right, upper graph), cumulative energy traded (right, middle picture) in the tariff market and the oscillations along with the total number of customer subscriptions (right, lower picture) during game-69

distribution version).

Tariff customer subscriptions

In this subsection we intend to show the distribution of customer subscription firstly between the brokers participating in the game and secondly between the tariff specifications published by the CrocodileAgent. Figures 6.4 and 6.5 represent these two distribution where in one row the left pie chart holds the distribution between brokers and the right pie chart the distribution between tariffs of the CrocodileAgent in that specific game. The pie charts were supplemented with two additional games (54 and 59).

The first row of Figure 6.4 shows that the CrocodileAgent had almost 90% of available customers in its portfolio which resulted in the revenue and cash balance discussed earlier. Additionally, it is interesting to observe the right chart in that row which shows that over 90% of subscribed customers to CrocodileAgent's tariffs were subscribed to only one tariff specification. In that game, if we look at the Table 6.2, the total number of published tariffs is 34, while there are 8 profitable tariffs. Upon closer inspection we confirmed that the tariff the mentioned tariff type was the most basic one, with one rate, no additional parameters and same prices throughout its whole duration. It is almost impossible that no other tariffs available in the market suited the customers and the result could be a consequence of bad tariff evaluation performed in the server environment. The second row of the same Figure

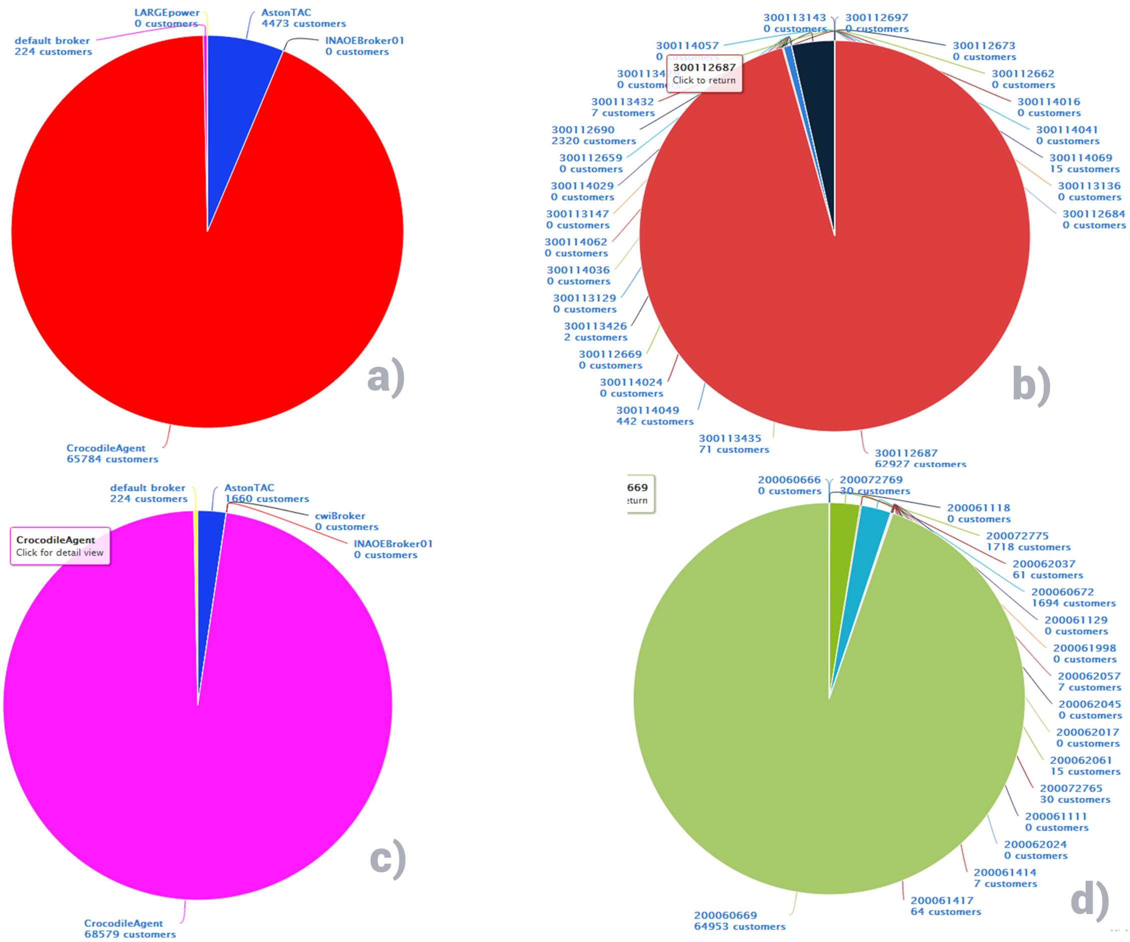

Figure 6.4: Graphical representation of the cumulative customer distribution and per tariff customer distribution (CrocodielAgents' tariffs) for game-49 (first row) and game-54 (second row)

shows almost the same results with the difference in the total share of customers between brokers (that is larger now for a few percent) and in the share of the most popular tariff (which is lesser for a few percent).

Figure 6.5 shows a little bit different results. In the first row we see that the total customer share of the CrocodileAgent is almost 80% which is a good results. The change is in the right part of the first row where these customers are divided mainly onto two tariff specification that are now evaluated as suitable.

The same identified difference is observed in the second row where the customer subscriptions are now more equally distributed among various types, but still with one tariff specification type (general type) that has the half of the total number of customers. The other half is more or less equally distributed onto 5 tariff specs. While the reasons for this distribution in the first row are not quite certain, the second row could be explained by the low share of available customers ranging only little less that 25%. Keep in mind that all of the customers were marked as yellow (UTest) are lost after broker outage and exactly these customers could have made the difference in the right pie chart if they were subscribed to the

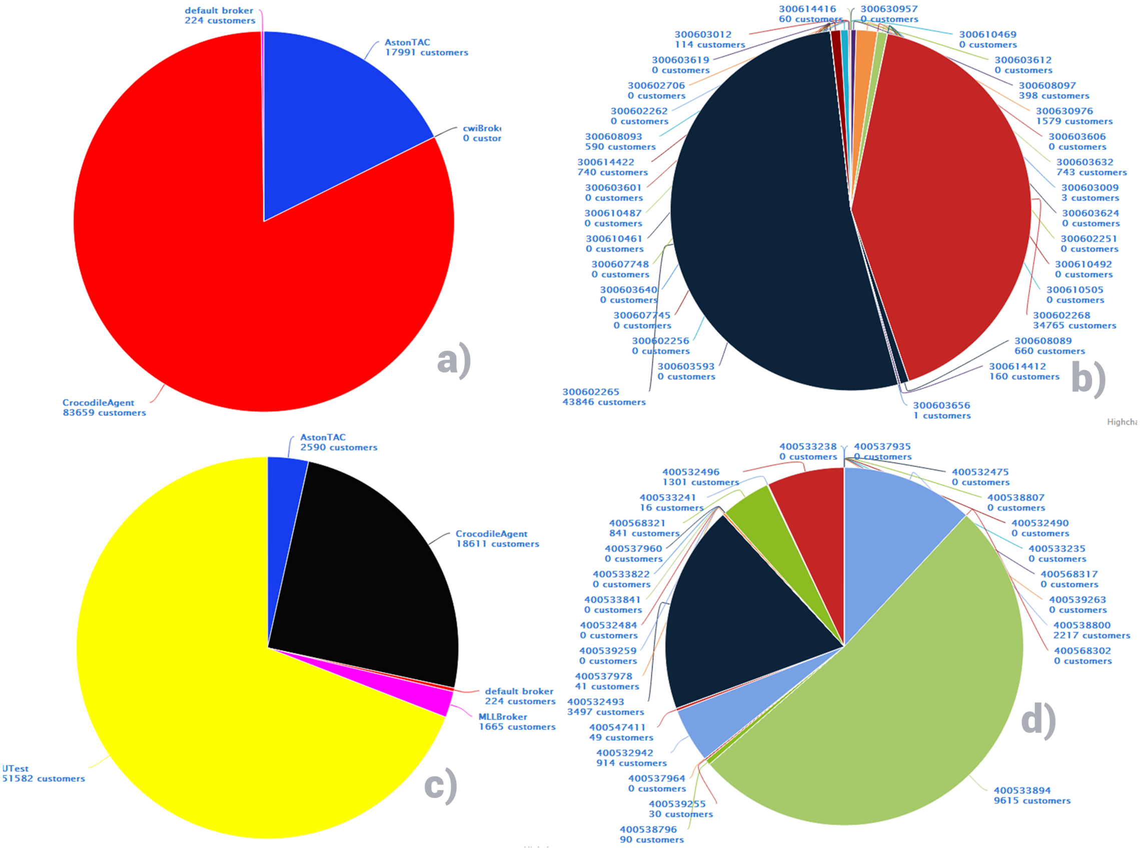

Figure 6.5: Graphical representation of the cumulative customer distribution and per tariff customer distribution (CrocodielAgents' tariffs) for game-59 (first row) and game-69 (second row)

CrocodileAgent's tariffs. Presumably, all of these customers would have subscribed to the tariff marked as light green therefore making that 12.5% share of total customers between tariffs into 80% or even more.

Transaction summaries

To continue the analysis made on the 4 games presented by pie charts it is useful to show the total shares of various transactions that may occur in each timeslot during one game scenario. Tariff transaction occur while buying or selling energy to subscribed customer, wholesale transaction occur while buying or selling energy on the wholesale market, balancing transaction occur in the end of each timeslot where the broker's balance state is either rewarded or penalized by the Distribution Utility and lastly distribution transaction cover the energy flow between the server environment and the specific broker.

In Figure 6.6 the relations between different transaction types are shown in a form of a pentagon and a line that connects the dots that are positioned on one of the five axis based on the amount and value of all transactions that were made. Each broker has its own color which is paired with the broker name in the *Index* located at the bottom of each pentagon.

If we focus only on the distribution of transactions for the CrocodileAgent we see that most transactions are made in the tariff part therefore emphasizing the importance of the *Tariff Manager* for the Broker's performance in game scenarios. If we summarize all of the values from different transaction (and taking the sign of the values into account) we should end up at the dot that is situated on the vertical line of the pentagon and labeled as Total. As you may observer, that number fits the overall cash balance that the broker acquires at the end of the game (i.e., compare the values with the previously explained graphs of total cash balance presented in Figures 6.2 and 6.3).

Some of the lines that we see are dislocated due to the possible errors of the Visualizer platform and the `Highcharts` package. Nevertheless, the results shown are correct and may be used for improving the brokers further more. For example, the goal of each broker should be to minimize balancing transaction since they reduce the cumulative income. In each of the presented games, except the last one, CrocodileAgent keeps the balancing costs to a minimum. The last game shows an incredibly high amount of transaction in the balancing section with over 1.5 million Euros of value. Upon additional analysis we have concluded that these transaction benefited the Broker since they were added to the cumulative cash balance (Broker offered energy for interruptible control and kept the imbalance at minimum which resulted in high income in the balancing market).

6.4.3. Identifying successful tariff specification types

This section covers the second stage of the evaluation mechanism planned for the analysis of tariff types. It is important to mention that this last analysis is based only on the third competition since the tariff types and their labels were introduced in the last version of the broker. To perform the analysis we processed the *Excel* spreadsheets of all games that ended successfully (due to some server environment issues, some games were broken).

The first part of the extracted observations are shown in Table 6.3 where each `Tariff Specification` is labeled by its Enumeration in the first column and characterized by the number that represents the quality and influence of the tariff revenue in played games (counting the times the tariff performed as the best one). From the Table 6.3 we may observe that two tariff types stand out from the rest of the group followed by several more that showed reasonably good results. FIXED_TOU_DUAL_DAILY_HOUSEHOLD showed the best overall results in the complete competition. As a reminder, the type is consisted of three rates that have different energy prices (but not changeable) for time periods ranging from 0-6, 7-18, and 19-23 hours. The name dual-daily comes from the fact that there are only two different price involved since the price for periods from 0-6 and 19-23 is the same. The second best tariff type is the most basic tariff parameter that only has one rate and one fixed price for energy. From the rest of the reasonably good tariff types we may observe that non

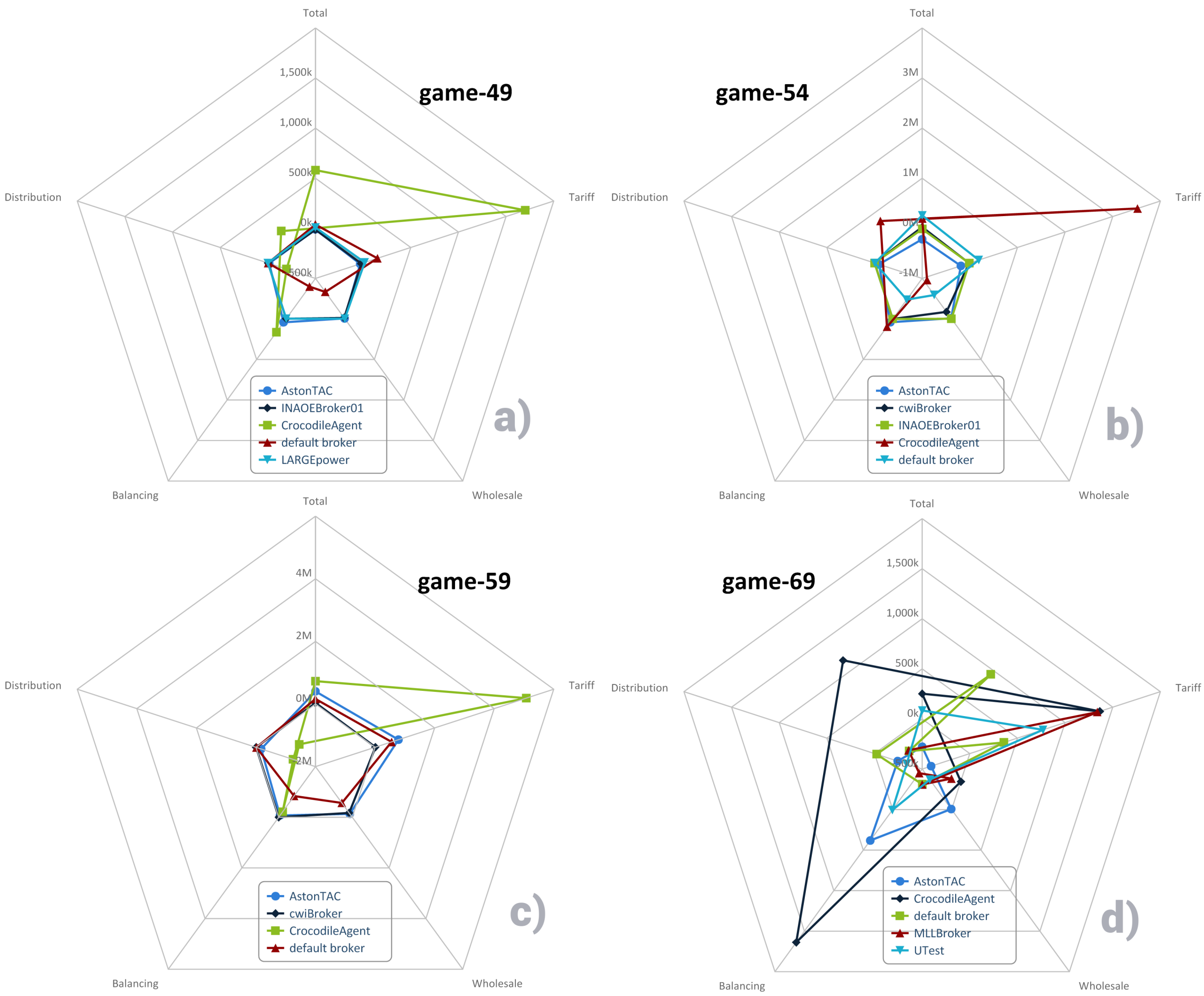

Figure 6.6: Transaction summaries that clearly show the shares of 4 different types of transactions in the cumulative transaction sum

of them are variable (these are characterized by having "HOURLYCHARGE" in their label).

We may then conclude that customers poorly evaluate variable-rate tariff specification since by human analysis we calculated that some of the tariff would be much more profitable in the variable mode than with the fixed price. In addition to that, and to show that server environment was drastically changed since the first competition we analyzed the distribution between fixed and variable pricing tariff specifications in the first,second and third competition. Results are shown in Table 6.4 where the first two competitions are divided with a double line from the third competition. We see that in the first two competitions variable-rate tariffs had a share of around 30% average, while in the third competition the share of variable-rate tariffs is distinctively small with the average around 0.24%. These results are a clear warning sign to re-evaluate the server environment and its tariff evaluation policies.

The last thing worth mentioning in the performed analysis is to check the percentage from the total amount of energy traded and the total number of subscribed customers that the best tariff specification types acquired in the last competition. To do that we took into

Table 6.3: Successfulness of Tariff Specification types based on the acquired revenue during numerous competition scenarios

TariffSpecification Type	Profit evaluation	TariffSpecification Type	Profit evaluation
GENERAL_CONSUMPTION_HOUSEHOLD	**8***	PERIODIC_FIXED_MEDIUM	**4***
HOURLYCHARGE_HOUSEHOLD	low revenue	PERIODIC_FIXED_BIG	**1***
HOURLYCHARGE_INTERRUPTABLE_HOUSEHOLD	low revenue	PERIODIC_FIXED_EXTRA_BIG	**6***
FIXED_TOU_DUAL_DAILY_HOUSEHOLD	**13***	HOURLYCHARGE_OFFICE	low revenue
PERIODIC_TOU_DAILY_HOUSEHOLD	no revenue	HOURLYCHARGE_INTERRUPTABLE_OFFICE	low revenue
PERIODIC_FIXED_SMALL	**1***	FIXED_TOU_DUAL_WEEKLY_OFFICE	**3***

consideration all tariffs of these types which means that in a specific game there could be several tariffs of the same type that performed well. The energy amount from these tariffs was summed and divided by the total amount of energy traded in the tariff market. Regarding the subscription number, the percentage of customers subscribed to these tariffs was calculated as the average of the same ratio but calculated for each timeslot. Therefore, the results may be characterized as weighted since each timeslot had its own influence.

In Table 6.5 we may see the presented results. Average percentage of the traded energy and customer subscriptions carried out by the previously mentioned "*top*" tariff specifications is extremely high with the average of 95.12%. This practically means that we could have satisfied the tariff market and all customers with only few tariff specifications, without the need to introduce more complex tariff types. These results are by far not consistent with the theoretical and empirical findings describe in the Section "Network Tariff design principles". In this case, only ToU tariff types perform with the distinguishable magnitude while all other tariffs are phased out.

Table 6.4: Distribution of acquired revenue between fixed and variable price rates in tariff specifications

	FIXED		VARIABLE				
GAME	tariff	revenue [Euros]	tariff	revenue [Euros]	OVERALL REVENUE	FIXED Share	VARIA. Share
15	24	1056853.46	50	2056095.31	3112948.78	33.95%	66.05%
17	26	6013743.41	47	2102827.231	8116570.641	74.09%	25.91%
21	24	2410204.754	50	1402721.703	3812926.457	63.21%	36.79%
30	26	4296098.987	47	1496188.57	5792287.56	74.17%	25.83%
37	28	3785227.571	48	2839635.58	6624863.15	57.14%	42.86%
43	28	7983362.68	47	3836055.17	11819417.85	67.54%	32.46%
49	32	7259058.015	47	3715133.99	10974192.01	66.15%	33.85%
53	24	4593212.776	45	727201.17	5320413.95	86.33%	13.67%
58	91	2317260.537	26	1911052.63	4228313.17	54.80%	45.20%
74	70	2827344.922	23	5225457.59	8052802.51	35.11%	64.89%
48	7	924002.09	2	1034.02	925036.12	99.89%	0.11%
49	16	9334471.24	8	24175.26	9358646.51	99.74%	0.26%
54	26	6261329.49	10	19273.19	6280602.69	99.69%	0.31%
57	23	7013940.58	11	25469.51	7039410.09	99.64%	0.36%
59	37	6121943.15	13	6517.21	6128460.37	99.89%	0.11%
64	25	3141128.18	11	11680.50	3152808.69	99.63%	0.37%
69	42	1903941.27	21	8890.71	1912831.99	99.54%	0.46%
101	26	2673900.32	12	4125.73	2678026.05	99.85%	0.15%
49	24	2944721.26	7	4756.37	2949477.63	99.84%	0.16%
73	23	2489796.37	7	912.37	2490708.74	99.96%	0.04%

Table 6.5: Percentage of traded energy and customer subscriptions acquired by the top Tariff Specification identified by high income

GAME	Energy covered by **top** Tariff Specifications	Customer subscriptions covered by **top** Tariff Specifcations
49	97.80%	96.81%
54	95.20%	99.10%
57	98.27%	97.59%
59	95.14%	96.73%
64	92.91%	91.00%
69	91.20%	85.69%
101	95.32%	98.91%
average	**95.12%**	**95.12%**

7. Conclusion

The future Smart Grids are bringing a new way of the electrical energy provisioning process by introducing new services and techniques to cope with the distribution of energy and balancing of supply and demand. The new grid will provide and improve efficiency, reliability, economics and sustainability of electricity services that we lack nowadays in numerous countries all around the world.

In this thesis we have studied one of the most important sectors of the new Smart Grid, energy market modeling and its simulation. By firstly studying the available literature and analyzing the information to provide an overview of this broad field of research we gained knowledge and assumptions that were used for the development of the prime goal in this thesis, the intelligent trading agent for power trading through tariff market.

The development process of the CrocodileAgent presented by the University of Zagreb is an ongoing activity since the year 2011. The author participated in the development of the same module that we focus on in this thesis. During the work on this thesis the CrocodileAgent's software structure was completely redesigned, improved and updated with numerous new features making a truly robust, modular and scalable solution that performs in simulations with success but in the same time is ready for future improvements that will be implemented in the future.

Regarding the results acquired by statistical analysis of a vast number of simulation logs, we may conclude that some of them refute the theoretical and empirical results currently available in the research body. Firstly, the simulation environment and its virtual customer do not evaluate tariff design so accurately as the humans would do. More specifically, the usage of RTP tariff designs has proven to be successful in many real-world tests and simulation on isolated populations, but in the case of PowerTAC and CrocodileAgent 2013 we observed that customers are not keen on subscribing to real-time pricing tariffs where the price is variable and changed often on an hourly basis. Secondly, we have proven the fact observed from the same real-world simulation that emphasizes the popularity of ToU tariffs since one of the most popular (and profitable) tariff designs was the two-part rate pricing scheme with cheaper prices for energy during night and early morning, but higher ones during the day. This type of tariff design is the most popular tariff design in almost all countries (except the ones with highly developed metering systems) and also one of the most popular designs in the PowerTAC simulation environment. Therefore, the most successful tariff specification regarding its characteristics was the fixed tariff design with two rates representing prices for electricity during daytime and night. The author and the development team suspect that these results are a consequence of server tariff evaluation mechanism which obviously does not evaluate other (even more profitable from the customer's point of view) tariff designs well.

Additionally, we have presented successful solution for responsive actions that market participant may perform in order to regain lost customers once more onto the available tariff specification. However, the proposed and implemented mechanism are yet to be tested in real-world tests and environments since their applicability greatly depends on the level of IT infrastructure that would be available in the future Smart Grids. Finally, in mid July 2013, the official PowerTAC tournament is going to be held at The AAA-13 (Association for the Advancement of Artificial Intelligence) Workshop on Trading Agent Design and Analysis (TADA-13) in Bellevue, Washington, USA. The results observed there would be used for further development of the CrocodileAgent in future months.

Appendix A
Key Performance Indicators in the evaluation process

Table A.1: KPIs that were identified and evaluated during analysis

Key Performance Indicators	Description	Implications	Calculation process
Production tariffs debit and percentage of covered consumption (higher is better)	Each production tariff should produce a debit to the Broker's cash balance since the energy is bought from producer customers. The amount of energy covers some percentage of consumption.	Acquire all production customers and set prices lower than in the wholesale market	Total debit is calculated as the sum of debit of each tariff from where we calculate averages and percentages.
Consumption tariff characteristics (higher revenue is better)	Each tariff specification is labeled as non-profitable, sustainable or profitable based on the overall profit acquired	Tariffs are non-profitable if profit is less than 2000 or there is no profit at all, sustainable ones have at least a constant incline and profitable have at least 10% of the overall profit	Each tariff depending on the game is checked regarding the revenue and labeled accordingly. Additionally, the labels are counted and presented in a form of table.
Responsiveness factor (higher is better)	Responsiveness factor indicates the percentage of customers regained after a substantial loss.	Broker initiates creation of responsive tariffs after detection of noticable (over 2000) loss of customers. Tariff are intended to get the lost customers back.	Tracking the number of customer prior to response tariff being published and after during time. The number of acquired customers is divided by lost customers to calculate the factor.

Successful balancing and profit gain (lower balancing fees is better)	The games are looked as specific entities and based on some of them we may identify the successfulness of Broker's actions and strategies.	There should be no losses and Broker should have the highest cash balance. Balancing fees are minimum or there is credit given to Broker. Customer share of the Broker is distinguishable.	Analysis is made by observing behaviors in the PowerTAC Visualizer
Tariff customer subscriptions (higher is better)	Each tariff specification may have unlimited (limited by the server) subscribers available in the game. Better tariffs (from customers point of view) will acquire more customer subscribers in the process,	General share of the Broker in the market should be high - over 80% and specific successful tariffs should be identified.	In each game we calculate the average from the total customer count and label tariff types which acquired most of the customers. The results are summarized
Identification of successful tariff specification types available in the Broker's portfolio	The Broker may create tariffs from a certain group of available specification previously created with specific parameters by the developers. Each of them have their own implications and key points/goals.	Tariff specification type should acquire a certain number of customer, sell energy and generate substantial profit.	To check which of the types are the best, the calculation of the best tariff types is made in each game by checking the mentioned parameters. After that the tariff labels are counted through different games to present results.

Percentage of energy covered by the top tariff types (higher result identifies good tariffs) (calculated from the previous KPI)	We need to identify the importance of these top tariffs and see if the Broker may generate almost all profit and perform transaction with these tariffs	Large amounts of energy are sold through these top tariffs specification and the key is to see how much	The percentage is calculated by dividing the total amount of energy sold by the top tariffs with the total amount sold by all tariffs per game
Percentage of customers subscription covered by top tariff types (higher results identifies attractive tariffs)	The same explanation but the key attribute is the average number of customer subscription in the tariffs lifetime		
Share of fixed/variable rate types	Each tariff specification may have one or more rates which are applied to the tariff. Rates may be with fixed prices during time periods or with variable (changeable) prices.	Different competition show different behaviors regarding success of either fixed or variable rate types. We need to identify which or them are more suitable and concentrate on their further development	The tariffs are divided based on the payment type and the revenues are summarized. After that the revenue of each group is divided to receive the share of the overall revenue.

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Intelligent trading agent for power trading through tariff market

Abstract

The master thesis describes an intelligent agent developed for power trading in the tariff market. First, the theoretical background related to the motivation for switching from traditional grids to Smart Grids is presented. The thesis continues with the simulation platforms for agents and the key implications of real-world tariff design and principles. Lastly, the complete architecture of the CrocodileAgent is presented along with the results of the evaluation process performed on post-game data available after PowerTAC competitions.

Keywords: Intelligent agent, electrical energy trading, tariffs, pricing mechanism, artificial intelligence, responsiveness

Inteligentni programski agent za trgovanje električnom energijom posredstvom tržišta tarifa

Sažetak

Ovaj diplomski rad opisuje inteligentnog programskog agenta razvijenog za trgovanje elektricnom energijom posredstvom tržišta tarifa. Na početku rada predstavljena je motivacija za tranziciju od tradicionalnih elektroenergetskih mreža na Pametne mreže. Rad se nastavlja sa simulacijskim platformama za agente i kljucnim implikacijama za kreiranje tarifa i njihovih principa u stvarnom svijetu. Na kraju je prezentirana kompletna arhitektura CrocodileAgenta zajedno sa rezultatima evaluacijskog procesa izvođenog na podacima dobivenim od PowerTAC natjecanja.

Ključne riječi: Inteligentni agent, trgovanje elektricnom energijom, tarife, metodologije naplate, umjetna inteligencija, reaktivnost