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Peer to Peer Energy Trading Considering Electrical Network Constraints

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Abstract

Recent technological advances in telecommunication, informatics and data processing technologies have started to reshape the face of Electrical Power Systems as we know them in order to keep up with the ever-increasing electricity demand and higher efficiency and sustainability standards. The increasing electric power generation that starts to appear in demand-side in conjunction with the deteriorating resilience of the traditional Power Grid call for new approaches that will enable and facilitate such concepts. The most widespread of these approaches is considered to be the Smart-Grid technology and its applications.

In this work, we try to investigate technologies that surround the concept of Smart-Grids and Distributed Generation in order to tackle the aforementioned problems through a hierarchical Agent-Based Electricity Trading model that focuses on the residential and commercial sectors while integrating large-scale demand-side renewable generation and electric energy storage. The proposed model aims, while taking into consideration the stressed parts of the Grid and satisfying network constraints such as line capacity, load and generation restrictions, to enable end-users to lower their cost for electricity and in some cases even generate profit through trading in multi-layered electricity markets. Lastly, a simulation of a realistic case study is carried out, through the comparison of a traditionally operated Electrical Power System to a hybrid Electrical Power System that utilizes the proposed electricity market model.

Acknowledgments

I would like to take this moment to thank the people that made all of this possible through their seemingly discreet or direct support.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 The New Era of Electrical Power Systems

One cannot deny the vital importance of electricity on human prosperity. Over a century and a half almost, Electrical Power Systems have elevated our every-day lives in previously unimaginative levels. From heating to lighting to cooking, everything is within our reach with the flick of a switch. Transportation and hospital care as well as research are at their peak due to the enabling factor, electricity.

With that said, Electrical Power Systems have undergone significant changes throughout the years, from deregulation of electricity markets to the ever-increasing integration of renewables and infrastructure changes and advancements implemented to assist on the also ever-increasing demand for electricity.

As we move closer to green energy and away from fossil fuels and as we learn to build machines that can utilize natural resources to generate electric power, we need to develop smart mechanisms both physical and digital to successfully integrate those machines to our Power Grid. That's why for the last two decades research has been vastly concentrated on the development of algorithmic and data-driven models that can transform the traditional Electrical Power System and its procedures to a more naturally-powered system.

Motivated by those research applications, in this work we attempt to create an agent-based electricity trading model with a hierarchical topology that focuses on the residential and community sectors through algorithmic price scheduling and integrates Renewable Generation and Electric Vehicles. For this, we will be utilizing concepts like Multi-Agent Systems, Fuzzy Logic, Smart-Grids and Peer-to-Peer.

1.2 Introduction to Multi-Agent Systems

An agent can be a physical or virtual entity that can act, perceive its environment (in a partial way) and communicate with others, is autonomous and has skills to achieve its goals and tendencies. It is in a multi-agent system (MAS) that contains an environment, objects and agents (the agents being the only ones to act), relations between all the entities, a set of operations that can be performed by the entities and the changes of the universe in time and due to these actions.

A huge number of different schools of MAS persist, all coming from different theoretical backgrounds. These include the American DAI school (Lesser, Gasser, Sycara), the Rational Agents branch (Rao and Georgeff, Shoham, Castelfranchi), the branch focusing on Speech Acts (Finin), on Petri nets (Estraillier), the Reactive Agents branch (Brooks, Steels, Drogoul, Ferber, Demazeau) and those focusing on learning (Weiss and Sen). These researches, although having different points of view, are very complementary, and each have their own applications [3].

The main application of multi-agent systems at the moment can be listed as follows:

- Problem Solving
- Multi-Agent Simulation
- Construction of Synthetic Worlds
- Collective Robotics
- Kinetic Program Design

This work's agent-based model is categorised as a Construction of Synthetic World as it aims to describe specific interaction mechanisms and analyse their impact at a global level, that of an Electrical Power System.

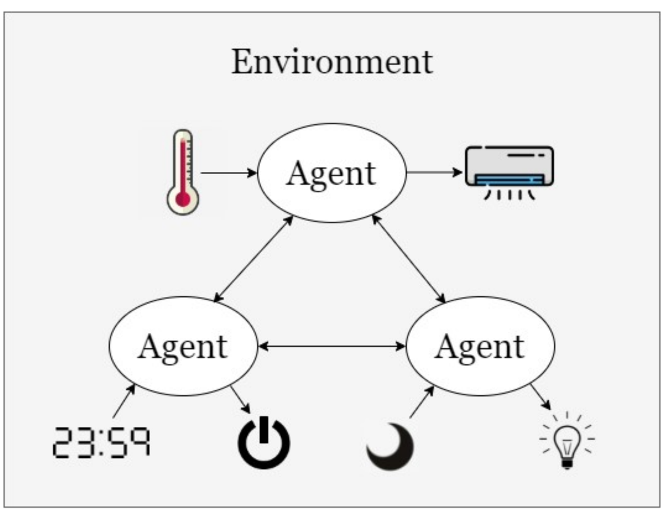


Figure 1.1: Simplified Multi-Agent System Schematic

1.3 Introduction to Fuzzy Logic Systems

A fuzzy logic system (FLS) is unique in that it is able to simultaneously handle numerical data and linguistic knowledge. It is a nonlinear mapping of an input data (feature) vector into a scalar output, i.e., it maps numbers into numbers. The richness of FL is described by the sheer number of possibilities that lead to different mappings. Nevertheless, this richness does require a deep understanding of FL and the elements that comprise it. One can challenge the validity of some of the possibilities due to the model's free nature but that can also be said for every representation problem.

A FLS maps crisp inputs to crisp outputs Fig. 1.2. It contains four components:

- rules
- fuzzifier
- inference engine
- defuzzifier

Rules can be extracted from numerical data. They are expressed as a collection of IF-THEN statements, e.g., "IF u_1 (input 1) is warm and u_2 (input 2) is low, THEN v (output) is high". This is an accurate example that tells us that in order to come up with a rule we need an understanding of: (1) linguistic variables versus numerical values of a variable, (2) quantifying of linguistic variables (u_1 may have a finite number of linguistic terms associated with it, ranging from extremely hot to extremely cold), which is done using membership functions, (3) logical connections for linguistic variables (e.g., "and", "or", etc.) and (4) implications, i.e., "IF A THEN B". Combination of more than one rule is also possible.

The fuzzifier maps crisp numbers into fuzzy sets. It is mandatory as rules are interpreted as linguistic variables, which have fuzzy sets associated with them.

The inference engine of the FLS maps fuzzy sets into fuzzy sets. While the defuzzifier maps output sets into crisp numbers. For example, in a control system such a number corresponds to a control action.

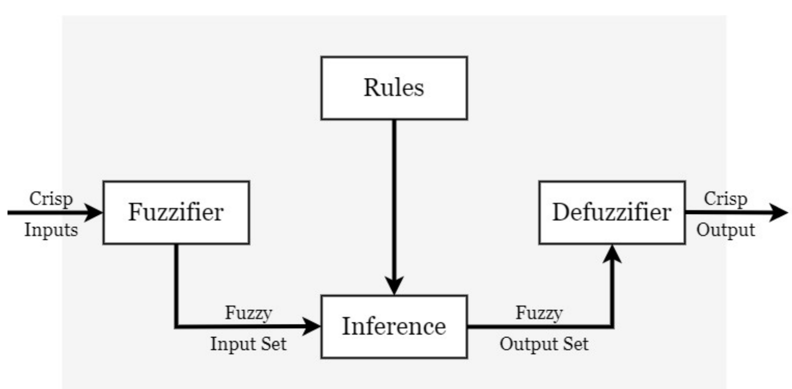


Figure 1.2: Fuzzy Logic System Schematic

In this work the FLS is used as a way of calculating the bids for the peer-to-peer market. It takes into account objective and subjective parameters as input variables and generates prices with which a particular participant will submit their bids.

1.4 Thesis Organization

Our work has been organized in *6 Chapters*:

Chapter 1 describes the current state of Electrical Power Systems while highlighting the importance of developing modern technologies to facilitate the integration of renewables and our approach to that problem. In this chapter we also introduce the concepts of Multi-Agent Systems and Fuzzy Logic Systems.

Chapter 2 goes through the history and the fundamentals of Electrical Power Systems while introducing the concept of Smart-Grids and its impact on the traditional Power Grid as well as Distributed Generation.

Chapter 3 establishes the notion and operation of Electricity Markets while diving into the concept of Peer-to-Peer Trading.

Chapter 4 points out similar to this work's studies and then describes the proposed Agent-Based Electricity Trading Model.

Chapter 5 presents the findings of our work and compares the traditional Power Grid to our proposed model for a specific scenario.

Lastly, *Chapter 6* summarizes this work's main concept and contribution, indicates the advantages and disadvantages that may stem from it and suggest specific areas of interest that would benefit future work.

Chapter 2

Electrical Power Systems

2.1 History of the Electrical Power System

The electrical power system as we know it, initially started in the 1800s from the humble efforts of a number of electricians in England that would use the power of water to generate current.

In 1882, Thomas Edison would go on to build the first electric company by the name of Edison Electric Light Company. Located on Pearl Street of New York. At one point, Edison's company would generate enough electricity to power 3000 lamps for a total of fifty nine customers. The current that was generated was DC at the time and due to losses the generating station could not be located more than half a mile away from the supplied end-users.

It was Lucien's Gaulard and John's Gibbs contribution with the transformer that raised the potential of electrical power systems which had now the capability to transmit electricity over vast distances. By 1890 the transformer-enabled networks were appearing everywhere and went on to elevate humanity's standard of living for the years to come [4].

2.2 System Overview

Electric power systems are real-time energy delivery systems. Real-time meaning power is generated, transported, and supplied the moment it is requested. Electric power systems are not storage-intended like water and gas systems. Instead, generators produce the energy which can be utilized at that exact time only.

Fig 2.1 shows the basic notion as well as the three most abstract sectors of an electric power system. (1) The *Generation*, (2) *Transmission* and (3) *Distribution* sectors [5].

Generation describes the process of generating electric power from sources of primary energy such as oil, coal, natural gas etc. It is the stage prior to the delivery of the produced electricity and it is being administered from power plants by electromechanical generators, primarily driven by heat engines fueled by combustion or nuclear fission among other means.

Transmission refers to the bulk transfer of power by high-voltage links between central generation and load centres. The interconnected lines which facilitate this movement are known as a transmission network. The high voltage requirement for this network stems from

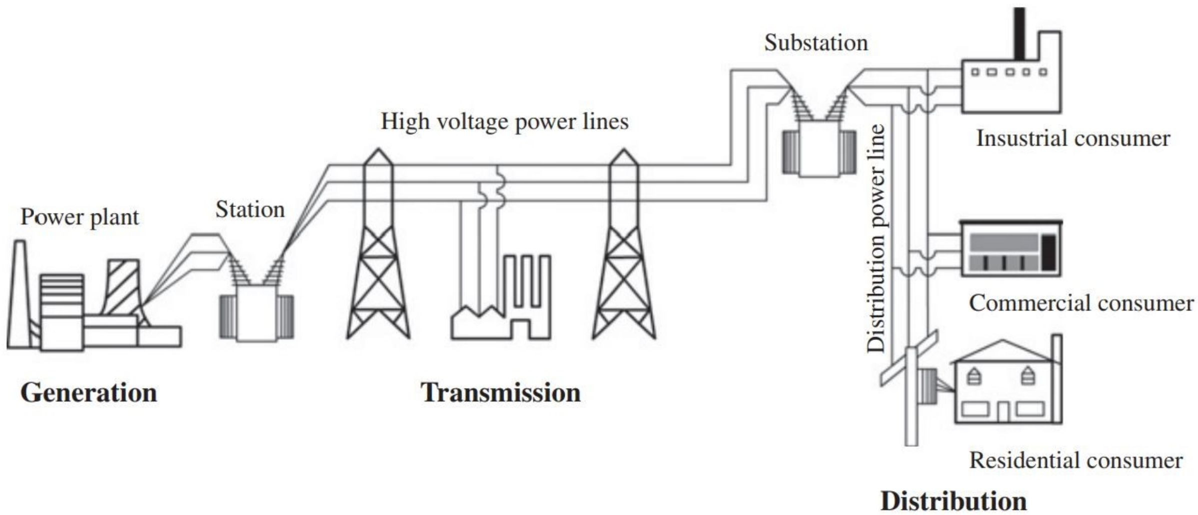


Figure 2.1: Electrical Power System Overview

the fact that through vast distances wires produce losses which in turn lower the voltage that passes through. Transmission lines mostly use high-voltage AC (alternating current), with some cases using high voltage direct current. The voltage change is conducted through the use of transformers which either step up or down the nodal voltage between transmission lines and transmission-distribution lines respectively.

Lastly, *Distribution* refers to the last sector of an electrical power system. This sector complements the *Transmission* sector as it delivers electricity to end-users through lowering the transmission voltage. Firstly, Distribution substations take the incoming transmission voltage and lower it to a "medium-voltage" normally thought between 600V and 35kV. Distribution transformers then, that are located near the end-users, lower that voltage to utilization voltage (commonly 120-240 V) ready for consumption [6].

2.3 Smart Grid

2.3.1 Introduction

Traditional Electric Power Systems were initially designed to include centralized generators, unidirectional high-voltage electricity transport from those to the rest of the grid, delivery to end-users via voltage step-down, and centralized control centers collecting information from fixed points of interest throughout the span of the network. Four major issues have emerged as a result of our current system's century-old design and those are the following:

1. **Demand for electricity** has outgrew and continues to outgrow the demand for any other form of energy globally with it averaging a 4% increase annually. As a result, grids are getting increasingly stressed day-by-day making the network's expansion unavoidable and imminent [7].

2. Century-old infrastructures are less and less capable of meeting the **quality requirements** for the increasing adoption and expansion of the grid, exacerbating the energy losses and undermining the involved economies.

3. With the ramping integration of **variable renewable energy** to the grid one can see the dire need for the development and execution of smart technologies that can take advantage of the non-dispachable nature of these resources in an efficient manner.

4. **Distributed Generation** and it's applications cannot be fully utilized as they require bi-directional electricity flows that are not inherently supported in the existing traditional grids.

Smart Grid Definitions

As there hasn't been a unanimous definition for the concept of Smart Grids, below one can see various definitions that aim to encapsulate the basic ideas of the concept and are coming from different parties across the globe.

The European Technology Platform [8] defines the Smart Grid as:

"A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to its generators, consumers and those that do both-in order to efficiently deliver sustainable, economic and secure electricity supplies."

According to the U.S. Department of Energy [9]:

"A smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electrical system from large generation, through the delivery to consumers and a growing number of distributed-generation and storage resources."

Through the above definitions one can describe smart grids as the compound of digital information and communications technologies for the management of both the bi-directional data flow between components and users as well as the bi-directional power flow between interconnected infrastructures.

At this point it is worth mentioning that this work focuses on the Distribution sector of a Smart Grid and more specifically on the network's subsystem of components and actors that participate to the retail market. In order to get there we would, first, need to elaborate on the idea of Smart Grids and their implementation at Generation, Transmission, Distribution and Consumption levels.

2.3.2 Smart Generation

In order for the grid to be able to moderate in an efficient way its electricity usage across its spanning infrastructures, there needs to be controlled generation at power plant and distributed generation levels. The more information each generating unit has at it's disposal as far as smart-meter data flows are concerned the better energy allocation decisions will they be able to make at a given scenario minimizing costs while maximizing efficiency for the whole system.

2.3.2.1 Centralised Generation

In traditional electrical power systems the unidirectional flow of power and data meant that there was little to no room for redistribution of generation and load across the system. Considering a Smart Grid environment, each generating unit has access to a vast amount of sensor data and IT solutions interconnected via modern communications networks in *Wide-Area Network (WAN)* which render them capable of anticipating load and generation shifts much more quickly and precisely.

Some other monitoring & control systems and processes that are bound for optimization to meet the Smart Grid's requirements are the *Wide-Area Measurement System (WAMS)* and the *Wide-Area Monitoring & Control (WAMC)*.

2.3.2.2 Distributed Generation

Similarly to the concept of Smart Grids, there is not a definite scientific answer on what Distributed Generation is. The idea has been around for several decades when Thomas Ackermann et.al [10] first tried to give the following definition:

"Distributed Generation can be defined as electric power generation within distribution networks or in the customer side of the network."

Distributed Generation is possible due to Distributed Energy Resources (DERs). These systems usually utilize renewable energy sources such as hydro, solar and wind power as well as biomass, biogas and geothermal power. More often than not they are integrated to smart grids as they enable on-site generation which also minimizes transmission energy losses.

Having said that, there are some challenges presented with the introduction of this technology that have to do with uncertainty of generation. Due to the nature of most DERs and the randomness on time and amplitude of it's power outflows, imbalances are introduced into the system. Moreover, the relationship between buyers and sellers complicates even further while the power equilibrium of the system gets disturbed at voltage and frequency levels. As a result, more sophisticated systems are needed to tackle these anomalies and the upfront cost of the construction of such systems is, as of this moment, still relatively high.

Despite all that, and due to the low pollution, on-site placement, more sophisticated procedures and ability to take load away from power plants make Distributed Generation a more and more compelling option for end-users at commercial and residential levels.

2.3.3 Smart Transmission

With the increase in electricity demand one can see the inevitable and imminent increase in transmission line capacity. While Smart Grids manage to lower the strain of power plants across the grid, they introduce higher voltages and currents at specific parts of the grid due to the nature of distributed generation. That along with the need for more energy volumes require the expansion and optimization of the current Transmission System.

As technological advancements surge across the Distributed Generation and Smart Grid concepts transmission lines may find themselves between DERs and Distribution Systems. Some of the systems and processes that are required to be enhanced to cover Smart Grids requirements are the *High Voltage Direct Current (HVDC)*, the *Flexible AC Transmission Systems (FACTS)* and the *Fault Current Limiters (FCL)*.

2.3.4 Smart Distribution

The Distribution sector is considered the most vital part of a Smart Grid. It encapsulates the idea of Distributed Generation, interconnection between end-users, and autonomous operation. The reduced distances between generation and loads through the utilization of DERs set fertile grounds for enhancements of the voltage profile, reduction of distribution and transmission bottlenecks, lower losses, utilization of waste heat, and postpone large-scale power system expansion plans [11].

The interconnection between end-users through the distribution network opens the realm of possibilities enormously as it enables peer-to-peer electricity trading, islanding operation of grouped sections called Micro-Grids as well as increased efficiency with the use of waste heat and reduction of line losses.

2.3.4.1 Micro Grid

To utilize the concept of Distributed Generation inside Smart Grids in the most efficient manner, there should be subsystems that circulate their load and generation in a modular way that could at a moment's notice decouple from or assist the rest of the grid. These subsystems are referred to as Micro Grids. The problems that arise from this revolutionary concept mainly concern the probable extensive custom engineering that might follow it. To tackle that, Micro Grid's participants and components are equipped with peer-to-peer and plug-and-play mechanisms [12].

The peer-to-peer concept ensures that there is no master controller or specific component of the grid whose operation is critical for the rest of the grid. A possible outage of that component would not lead to the deactivation of parts of the grid. That requires more than one generation source.

Plug-and-play refers to the capability of the system to integrate new components without the need of re-engineering the control system. A similar example could be the ease of use of household appliances. Their connecting and disconnecting is straight-forward, seamless and each appliance doesn't interfere with the rest.

2.3.4.2 Renewable Energy Sources

Renewable Energy Sources as the name implies are naturally replenishing but flow-limited sources of energy. They are practically inexhaustible but are also capped per unit of time for the amount of energy they can generate.

The largest adopted types of renewable energy sources are:

- Hydropower
- Solar
- Wind
- Geothermal
- Biomass

In 2020 alone, renewable energy covered 12% of total U.S energy consumption Fig. 2.2 while solar and wind continue to gain popularity with wind power surpassing hydroelectric power in generation Fig. 2.3.

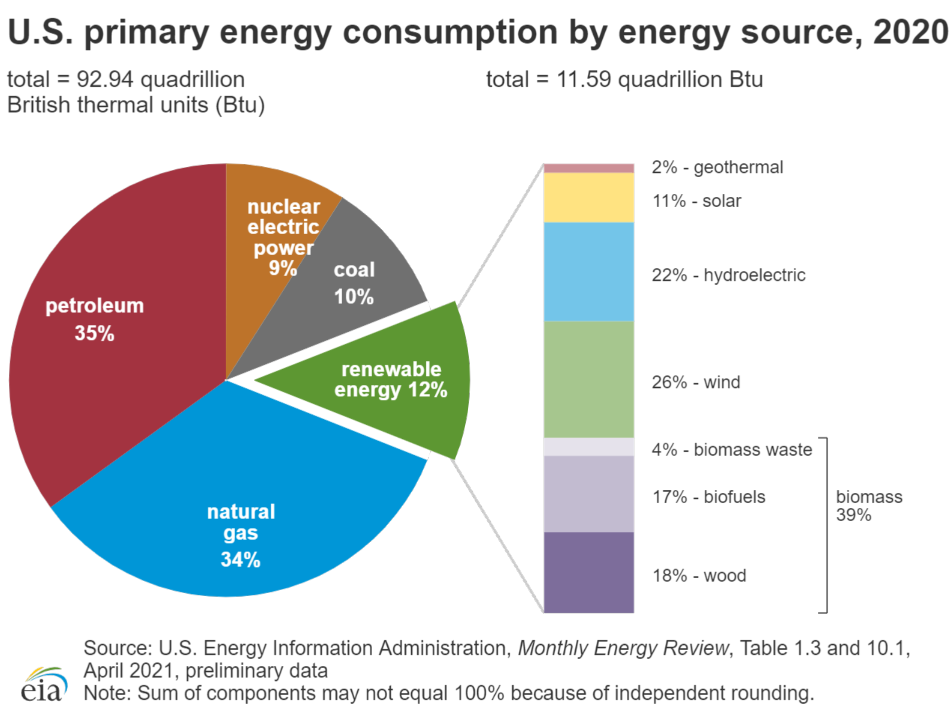


Figure 2.2: U.S. primary energy consumption by energy source, 2020

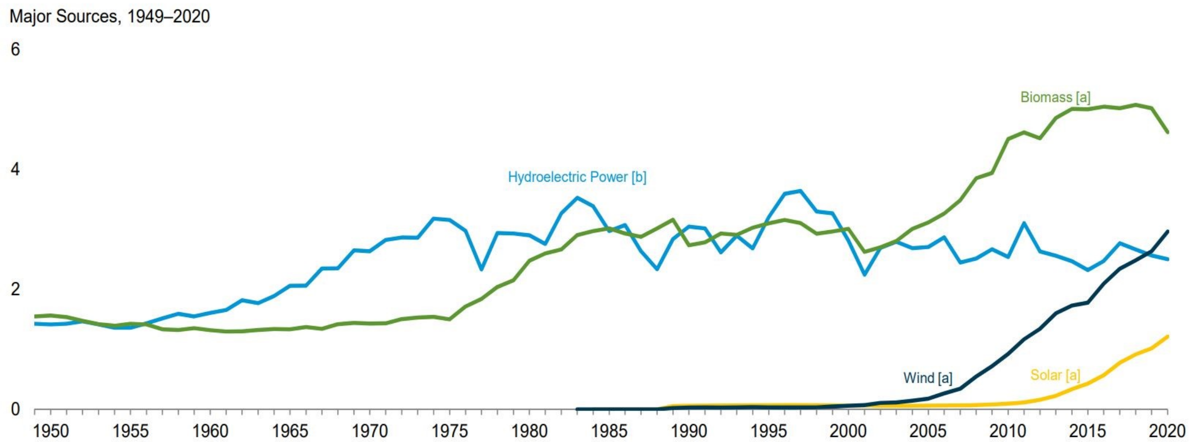


Figure 2.3: Major renewable sources 1949-2020 [1]

2.3.5 Smart Consumption

End-user contribution in the form of load-balancing, V2G configuration, and peer-to-peer electricity transactions is key for reliable and consistent operation of a Smart Grid. As such, the residential sector has been of great interest to researches as more and more effort is being put around optimizing household power consumption.

Smart Consumption refers to the idea of controlling one's consumption through the use of local and on-grid data as well as sophisticated algorithms to maximize efficiency and minimize costs.

2.3.5.1 Smart Meters

A very common, and rapidly adopted, way of optimizing the consumption-side of the grid is through the use of smart meters. Devices that are accompanied by multiple sensors whose job is to meter power and data flows as well as component-states and broadcast them to the customer's monitoring & control system. Smart meters have the potential to lower the power system's strain as for the first time they provide end-users with a real-time feedback tool to monitor their consumption.

2.3.5.2 Electric Vehicles

The future of fossil resources isn't quite bright as humanity has been given a clear deadline for it's fossil fuel consumption due to it's limited supply and damage to earth. Considering that and the fact that the majority of cars run on fossil fuels, any probable solution for this issue involves Electric Vehicles (EVs).

Currently there are three types of EVs:

- Battery Electric Vehicles (BEVs)
- Hybrid Electric Vehicles (HEVs)
- Fuel-Cell Electric Vehicles (FCEVs)

Battery Electric Vehicles are considered to be 'all-electric' cars. Meaning, they are powered exclusively by electricity,with their electric motors drawing current from the attached battery. They are the most expensive, from the list, to manufacture due to the high costs of batteries.

Hybrid Electric Vehicles combine a conventional internal combustion engine (ICE) with an electric motor and battery pack to reduce fuel consumption. The motor is used ,instead of the ICE on inefficient for the ICE circumstances, on a car that would otherwise resemble a typical ICE vehicle. More sophisticated variations of the HEVs are the Plug-In HEVs (PHEVS) which pack a larger battery and can, similarly to the BEVs, top up with electricity other than fuel.

Fuel-Cell Electric Vehicles are similar to BEVs in that they only use electrical energy to drive, however the way they store energy is very different. Unlike BEVs, which store electrical energy drawn from a charger, FCEVs create their own electrical charge through a chemical reaction generally involving hydrogen. So, FCEVs can be filled with hydrogen and don't require topping up with electricity [13].

From the aforementioned EV types, BEVs and PHEVs are able to interact with the electricity grid through the V2G and G2V protocols. These protocols enable bidirectional power flow between EVs and the rest of the Grid to tackle challenges of faster charging and provide ancillary services.

Chapter 3

Electricity Markets

3.1 Definition & History of the Electricity Market

Electricity Markets are considered commodity markets, meaning they deal explicitly with the trade of a commodity, in particular electricity.

In the early days, followed the building of the first electric company by Thomas Edison, electricity trading was vastly unregulated and monopolized. Limited ability to accurately monetize electricity's production expenses, uncertainty regarding capital appreciation over the long-run for investors trying to get into electricity production and the need for accurate load forecasting to perfectly match with generation were the main reasons for the monopolizing tendencies that emerged. It is worth noting that the only regulation at that time was dictated by the state at a symbiotic manner with the monopolized companies.

That was until after the Wall Street Stock Exchange Crash in 1929 and the Great Depression that followed. By 1932, the energy industry was still unregulated and a staggering 73% of the investor-owned electric industry was owned by eight of the largest utility holding companies in the Unites States.

To avoid unfair practices, in 1935, Congress passed the Public Utilities Holding Company Act (PUHCA) that remains till this day one of the most catalytic factors on how the energy industry continued to operate. PUHCA practically clustered the holdings of companies based on jurisdiction and decoupled non-utility businesses from utility businesses. By 1948, holding companies divested around $12 billion in assets after compliance to the PUHCA regulations.

Until 1970 energy and specifically electricity markets where still state-regulated. In developing countries, that meant low capital inflows to the industry as well as sub-optimal management from government agencies, a destructive mixture. While electricity markets in developed countries didn't struggle with government funding, by forbidding private investing they were actively causing a bottleneck in their system. So the pressure for every electricity-powered state on the globe was pilling up. Then the 1970 Energy crisis hit and brought the whole industry to it's knees as governments tried to regulate their way out of a second Great Depression. That brought to the table the concept of deregulating the energy markets to which idea most western countries have moved to since then.

In 1992, the National Energy Police Act was issued creating the outline for a competitive wholesale electricity generation market close to what we see today. Since then more and more countries and states have moved to fully or partially deregulated energy markets while the sectors of generation transmission and distribution were also decoupled from holders [14].

A partial form of deregulated market is also currently found in Greece's electricity market which is the main focus of this work's case study.

3.1.1 Vertically Integrated Electricity Market

Vertical Integration refers to the organised ownership of the generation, transmission and distribution sectors under a single firm.

This structure is mainly seen in unregulated markets as a response to the underlying market conditions.

In addition to producing energy, the vertically integrated utilities are responsible for providing electricity to their customers with a fixed rate. These utilities also seek to purchase power from independent energy suppliers and approval for energy investments from state commissions, which also oversee the rate of return on utility investments and determine the rates.

As a result of concerns from mainly western countries for the ramifications of the vertically integrated structure there has been a massive movement towards restructuring the Electricity Markets that stretch to this day [15].

3.1.2 Restructured Electricity Market

Under the restructured configuration of energy trading, markets are operated by the Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) with the intention of providing oversight and non-discriminatory access to transmission. State commissions, similarly to vertical integration, still determine the rates that retail customers pay.

In most restructured areas of the grid customers are offered the option to choose the supplier of their electricity as a result boosting the competitive environment between electricity suppliers and lowering overall prices.

3.2 Types of Electricity Markets

Although electricity can be considered a commodity, electricity markets differ substantially from other commodity markets due to the physical characteristics of electricity which are as follows [16]:

- *Time*: Electricity cannot be stored with conventional ways and in large quantities. Therefore, production should continuously follow the demand.
- *Location*: Electricity is the only commodity that the end-use of which can in fact disturb the prior to consumption sectors and cause cascading failures and outages. For that matter the larger the area of distribution and consumption the higher the risk for complications.

- *Flexibility*: Generation must match consumption at all times to maximize efficiency of the system. However, demand and the availability of renewable energy resources can vary drastically from one moment to the other. This calls for a level of resilience from the system to be able to withstand fluctuations while serving customers.

The three aforementioned physical attributes give the reason why there are more than one existing electricity markets. The amounts of energy, transmission capacity and flexibility are scarce resources and should be priced accordingly.

3.2.1 Long-term Markets

In these markets electricity suppliers provide long-term contracts that can last from one to five years. Some of the more common long-term energy plan lengths include 12, 24 and 36 months. These types of electricity contracts usually have rates that remain the same regardless of changes in market prices [17]:

- *Forward Energy Markets*
- *Forward Transmission Markets*
- *Forward Capacity Allocation Markets*

3.2.2 Wholesale & Retail Markets

Wholesale electricity markets can be found in both traditionally regulated or in restructured market environments. ISOs and RTOs run competitive markets allowing for independent power producers and non-utility generators to sell their power. Renewable resources when integrated also participate in this market with their total electricity traded to account for only a fraction of the total power supply. The role of the wholesale market is of vital importance as it defines the price trend for spot electricity trading.

Furthermore, wholesale electricity markets markets provide significant efficiency in real-time dispatch of system resources as they minimize system costs and facilitate access to a broad range of options that increase system flexibility [18].

Retail markets, on the other hand, and how they are regulated are determined at the state level and can be found in traditionally regulated or restructured markets. In a vertically integrated market, consumers purchase power from the utility that serves their area. Competitive retail markets give customers the option to choose their retail electricity supplier.

3.2.2.1 Day-Ahead Markets

The Day-Ahead Energy Market lets market participants commit to buy or sell wholesale electricity one day before the operating day, to help avoid price volatility. This market produces one financial settlement. Day-Ahead Markets usually follow an hourly clearance with market participants submitting buying and selling bids to responsible auction-administering operator.

3.2.2.2 Intra-Day Markets

Intra-Day Markets or otherwise referred to as Real-Time Markets or Balancing Markets let market participants buy and sell wholesale electricity during the course of the operating day. They balance the differences between Day-Ahead commitments and the actual real-time production and demand for electricity. They also establish the real-time locational marginal price (LMP) that is either paid or charged to participants in the Day-Ahead Energy Market for demand or generation that deviates from the Day-Ahead commitments [19].

3.2.3 Ancillary Services Markets

Ancillary Service Markets can be described as a financial instrument that aims to facilitate the operation of the electrical power system. There are two categories of ancillary services currently offered through bid-based auction markets in RTOs: regulation services and operating reserves services[20]. Those services are needed to ensure the security and stability of the power system and mainly include: (1) Frequency regulation, (2) voltage regulation, (3) load shedding and automatic islanding and (4) others such as black start services and power quality services.

3.3 Market Auction Design

With the transition from regulation to competition, electric power systems have adopted new procedures to guarantee the security and economic welfare of their operation. Auctions were introduced as a mean for the competition to unravel. Throughout the years multiple approaches have been made to the notion of energy-trading auction, with the most research going to single and multi-round auctions. The implemented approach follows the single-round auction methods with some variations.

3.3.1 Single-Round Auctions

In the single-round auction, the supply bids are matched with the demand bids by the market clearing algorithm without any further iteration with market participants.

The "simple" bid format consists of a pair of (hourly) values: quantity (mostly in MWh) and price (€/MWh). Each selling or buying participant can present several pairs of values for the same generation or demand unit. If there are extra operational and/or economic conditions that are added to the simple bid, the bid is called "complex".

In case of simple bids, the market clearing algorithm implemented in the simulation tool works as follows. For each hour, a supply curve is build up considering the selling bids for that hour ordered by increasing prices, and a demand curve is build up considering the buying bids for that hour ordered by decreasing prices. The intersection of the supply and demand curves determines the selling and buying bids that are accepted and the hourly market price obtained as the price of the last accepted selling bid [21].

3.3.2 Multi-Round Auctions

Multi-round auctions are based on an iterative procedure, where the generation agents update their simple price/quantity bids at every iteration or round. This iterative multi-round auction allows generating agents to minimize the risk of cost under recovery or infeasibility to deliver [21].

3.4 Peer-to-Peer Electricity Trading

Peer-to-Peer Electricity Trading describes the exchange of electricity between end-users of the grid without the involvement of an intermediary.

Higher renewable power deployment and flexibility, balancing and congestion management as well as providing ancillary services to the grid are some of the major contributions of peer-to-peer mechanisms. The Peer-to-Peer trading model is established through an interconnected platform that serves as an online marketplace. There are multiple ways of conducting such a marketplace ranging from contracting with the use of smart-contracts and block-chain technology to auctioning as per this work.

The P2P model can be established among neighbours within a local community, as well as on a larger scale, among various communities. Energy transactions that happen under P2P protocols are carried out, power-wise, by the distribution and transmission systems. As such the P2P market operator has to either be integrated with ISOs and RTOs or communicate closely with them.

Other reasons for that are the following facts [22]:

- Power flow between the P2P trading platform participants will affect the local distribution and transmission networks
- The local distribution network needs to be operated, maintained and remunerated accordingly
- There is need for buying/selling excess load/generation upstream

With that being said, the increase in renewable energy generation and overall distributed energy resources on demand-side, call for the integration of P2P markets as they constitute the catalyst for dealing with generation uncertainty and contributing in load shedding as well as reinforcing electricity quality across the grid.

Chapter 4

Proposed Agent-Based Electricity Trading Model

4.1 Related Work

The efficiency of a particular Electrical Power System is tightly correlated with the electricity tariffs that stem from it[23]. Typically, the lower the efficiency of the corresponding Electrical Power System, the higher the tariffs. That, as well as the over-flooding of new end-use sectors each year has led to even less efficient operation[24]. As a result, wholesale and retail markets are being increasingly challenged leaving more and more end-users unable to keep up with the increasing premium.

Motivated by this, among others, phenomenon, multiple Smart-Grid models have been introduced that aim to tackle the increasing inefficiency of the traditional Electrical Power System. G. Reis et al. [25] present a peer-to-peer structure to utilize residential level energy penetration of renewable generation that highlights the importance of energy transactions between community members. While their work is focused on the operation of only two actors (prosumer, consumer) they manage to outline the behavioral dimension associated with demand-side flexibility as well as the challenges that it brings forward.

Kumar Nuna et al. [26] extend the concept of DGs in Smart Grids by incorporating ESSs with their independent Storage Market (SMA) on two different agent-based energy market frameworks. On the first they proposed a top-level aggregation of bids from all sub-systems including the Storage Market while on the second they proposed a localized integration of ESSs on Micro Grid levels before the top-level aggregation. Their approach highlights the importance of hierarchical structure and aggregation of demand-side generation as well as the possible architectural approaches, at local and global levels. Peer-to-Peer solutions are also getting traction on models that are agent-based, like in [27]. In this paper, a peer-to-peer transaction model based on auctions was proposed giving measurable benefits on the concept of integrating peer-to-peer transactions on Micro Grids.

4.2 Modeling Methodology

Fig. 4.1 describes the architecture of the proposed agent-based framework highlighting the involved agents and their interactions. We adopted a hierarchical bottom-up architecture indicated by three auction levels. Prosumer Agents represent the residential load/generation users, Community Operators represent the community-level auction and settlement operators, District Operators represent the region-level auction and settlement operators, Grid Operators represent the grid-level auction and settlement operators and lastly Large Consumer/Producer Agents represent consumers from the commercial sector and power plants or resellers respectively. At this point it is worth noting that depending on the configuration of the electricity markets whether they are deregulated or regulated Large Producer Agents may represent either a single firm that controls all of generation or multiple independent firms. The numbers found next to the communication arrows refer to the time steps at which each agent communicates its information to another agent in order to organize each involved market.

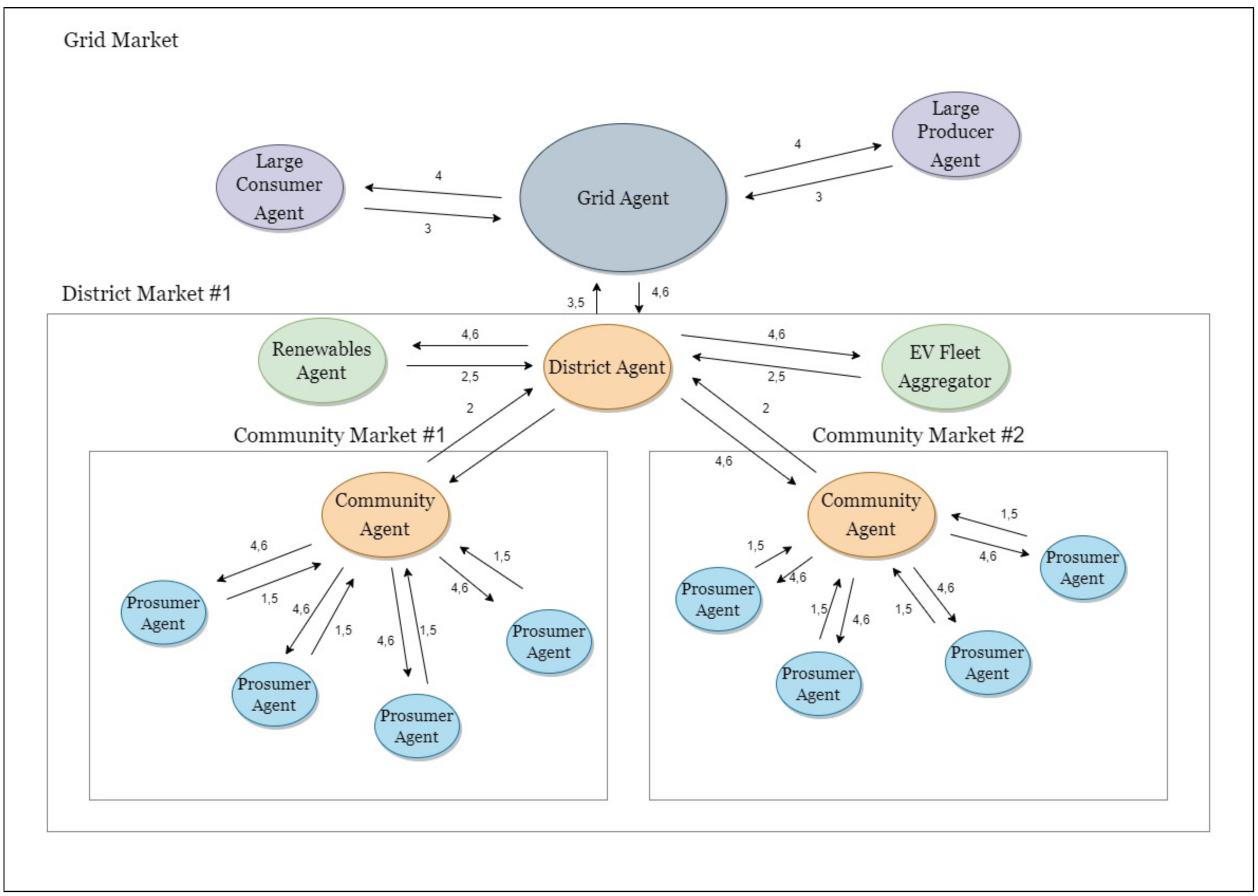


Figure 4.1: Proposed agent-based energy market framework

Community Level Market: This level corresponds to each individual community which is determined in accordance with the relevant legislation at hand. Each Community Operator gathers bids from the assigned Prosumer Operators of its jurisdiction and administers the market that the prosumers participate in. The supply and demand curve of the bids produce a specific market clearing price at which trading occurs for both buying and selling. The successfully served biders are then notified while the unserved bids get forwarded to the corresponding District market for clearance.

District Level Market: This market operates under the administration of the District Operator and similarly to the Community Level Market it can be more than one and is delimited according to regional standards. This market accepts bids from different communities as well as independent Renewables providers and EV fleet aggregators denoted Renewables Agent and EV fleet Aggregator in the model respectively. It uses the same mechanism for auctioning as the Community Level Market and follows the same principles for notifying and forwarding participants. Each unserved bid from the District Level Market is forwarded to the Grid Level Market where the last round of clearance happens.

Grid Level Market: This level acts as the last stage for price clearing of all the lower level bids as well as the only market that power plants and large-scale consumers trade energy. This market's clearing price sets the trading price for all end-users at that given time interval. It also follows the same principles as the other two types of markets when it comes to auction pricing. The unserved bids unlike the previous levels do not get forwarded to any other level. Instead, they get scheduled to participate at the peer-to-peer market at a Grid-Level scale.

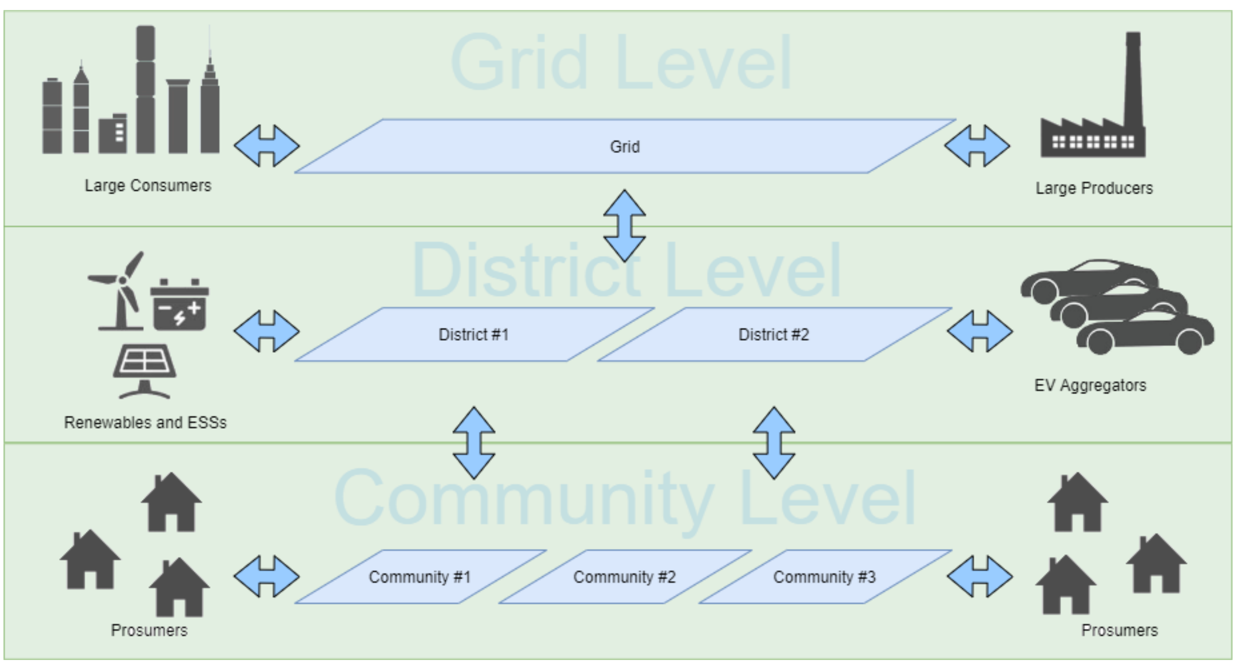


Figure 4.2: Energy Market Model levels: 1)Community Level 2)District level 3)Grid Level

For this work's Day-Ahead model a three layer approach was considered. Each level consists of its own agents as shown in Fig 4.2. The model works hierarchically as each lower level participates in the markets above it either directly or indirectly by forwarding bids as mentioned. This hierarchical architecture has the advantage of keeping the model robust and effectively modular if one chooses to rearrange it. By aggregating sections of the distribution system one can easily batch neighboring end-users and merge them to come up with more optimal micro-grid configurations that will benefit the whole.

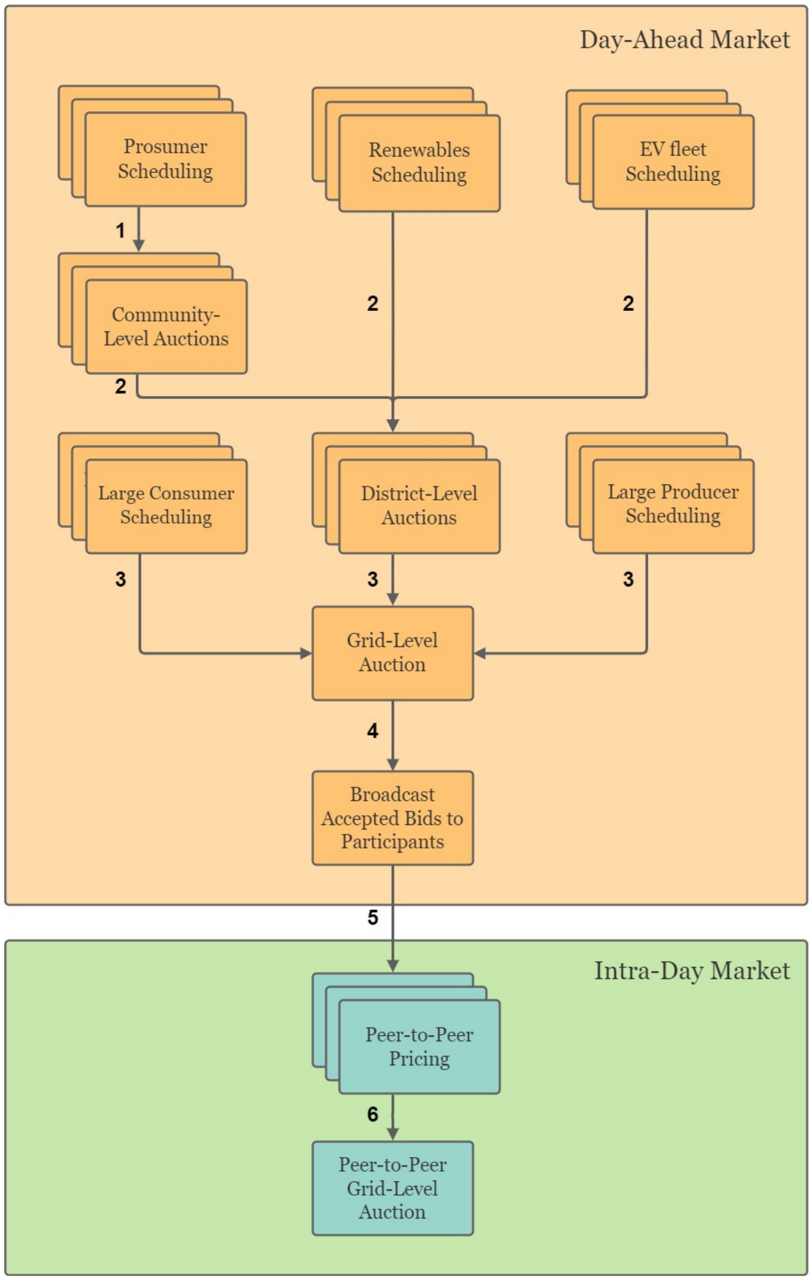


Figure 4.3: Flowchart of proposed model algorithm

4.3 Market Participants

This work is mainly focused around urban environments, and as such the market participants that are taken into account are the following:

- Prosumers
- Solar & Wind Resources
- Community Operators
- EV Fleet Aggregators
- District Operators
- Grid Operators
- Large-Consumers
- Large-Producers

All of those participants represent nodal entities to the energy trading system and are thought to make the largest percentage of them.

4.3.1 Prosumers

The word prosumer is a compound derivative word of the words producer and consumer and was coined in 1980 by American futurist Alvin Toffler. Prosumer is an individual who both consumes and produces. The last decades it has been tightly correlated with the notion of self suffice of residential households through the use of renewable energy. More and more end-users are jumping on photo-voltaic panels and other ways of generating electricity to bring down the cost of their bills and sometimes even make a profit.

In this model prosumers are considered end-user households that may or may not have photo-voltaic panels or energy storage units and certainly have a load. The Prosumer Agent calculates a day-ahead bid based on the projected energy prices and the households load and generation forecasts. They then communicate that bid to the corresponding Community Operator. After the end of the day-ahead market if their bids are still not covered they reevaluate their pricing and participate to the peer-to-peer market the next day aiming for total clearance.

4.3.2 Renewables

Renewable energy is a crucial part of Distributed Generation and one that continues to grow as it has proven to help enormously with not only generation independence but also with lowering greenhouse gas emissions. For this reason, in this work, we have integrated independent wind and solar generation as it makes up for approximately 48% of the total renewable generation in EU [28].

Every renewable energy resource, per this model, is represented by a Renewables Agent. This agent is responsible for collecting, processing and broadcasting the photo-voltaic or wind forecast data to the corresponding District Operator in order to be included in the Day-Ahead and Intra-Day markets. The forecast data are firstly gathered by the agent who then by matching them to the projected prices comes up with the bids for the upcoming markets. The projected prices are calculated internally through shifting the time-series and amplitude of the mean values of a given set of historical prices for a particular day.

4.3.3 EV Aggregators

With the rise of EVs a very practical problem also rose, that of their massive storage management. A simultaneous charging or discharging of a large fleet could greatly impact the rest of the grid resulting in serious imbalances or even an outage. That is where EV Aggregators come in. By operating as commercial mediators between a number of EVs and the rest of the grid these aggregators are able to manage the charging and discharging of their connected EVs in a way that benefits both the EV users and the grid. From the system operator's perspective, the EV aggregator is conceived as a large source of generation or load that can also provide ancillary services such as spinning and regulating reserve. EV Aggregators also participate in the electricity markets through energy supply and demand bids [29].

In this work, we have implemented an EV Aggregator model that acts entirely on behalf of it's EV clients. As such, there are no profits being made by the aggregator. Firstly the aggregator collects the maximum and minimum capacities as well as charging and discharging capabilities of a given EV fleet. With some given daily projected energy prices the aggregator then optimizes their energy inflows and outflows accordingly. At this point it is worth noting that this work's EV Aggregator model doesn't take into account charging for the sake of charging. Meaning that every EV enters and leaves the aggregator's stations with a given profit for their contribution.

4.3.4 Large-Producers

Large Producers are considered two types of market participants, power plants and electricity resellers. If the structure of the electricity trading model is considered to be that of an unregulated market the Large-Producers are considered to be both power plants and resellers as they both would be able to participate in these markets. On the other hand, if we are talking about a regulated market environment of a vertically integrated system those participants would only be power plants. Their role is to generate and serve the largest percentage of the total system load through the wholesale, retail markets as well as OTC contracts.

4.3.5 Large-Consumers

In this work we will refer to the commercial sector as Large-Consumers not for its percentage-wise participation to the electricity market but for its relatively-high-averaging power needs. As commercial sector we define an energy-consuming sector that consists of service-providing facilities and equipment of businesses. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a wide variety of other equipment. This sector's establishments sometime include generators that support the establishment's operation [30]. It is worth noting that we haven't chose to include the industrial sector for participating to the proposed model only because there is practically less load flexibility in that sector and further measures would have to be taken to ensure the internal system stability and efficiency of this particular sector.

The industrial sector consists of large-scale energy consuming facilities that are mainly utilized for manufacturing (77%), mining (12%), construction (7%) and agriculture (4%). Overall energy use in this sector is largely used for processing heat and cooling as well as powering machinery, with lesser amounts used for facility heating, air conditioning, and lighting. This sector's facilities also more often than not include generators to aid their operation [31].

In our work, we consider the commercial sector to participate only in the Day-Ahead market that the Grid Operator administers. The reason for that is that most large commercial clients have access to over-the-counter trading of electricity due to their scale, as well as other facilities which make them more flexible compared to the residential sector. That along with the limited availability of resources at District levels and below, we claim that for this work, makes their inclusion at the peer-to-peer market counterproductive.

4.3.6 Electricity Market Operators

Market operators are independent entities with the purpose to regulate and operate the market at no participant's interest for two reasons. (1) To maintain social welfare between the participants through unbiased management and (2) to maximize the efficiency and minimize the cost of DERs. Furthermore, it is the operator's responsibility to collect the bids of the applying market participants, come up with the supply and demand curve as well as the market clearing price and match the accepted consumption bids to the accepted generation bids. The operator also schedules the deliveries and broadcasts the resulting prices and volumes of the trades to all the participants 4.4.

In this work we introduce three market operators (1) the Grid Operator, (2) the District Operator, (3) and the Community Operator. All of those operators are independent of their corresponding participants and each-other. This way, not only do we benefit from their modular nature but it also helps to differentiate between the discrete levels of price clearance that are found in the model.

4.3.6.1 Community Operator

The Community operator is the independent unit responsible for conducting the Day-Ahead market between the residents of the community in which they are operating. The operator firstly collects the orders of the participants, who in this work happen to be only prosumers, and proceeds to calculate the resulting market clearing price. With that, the operator matches the accepted orders and executes the payments and schedules the deliveries while broadcasting the resulting prices and volumes of the transactions.

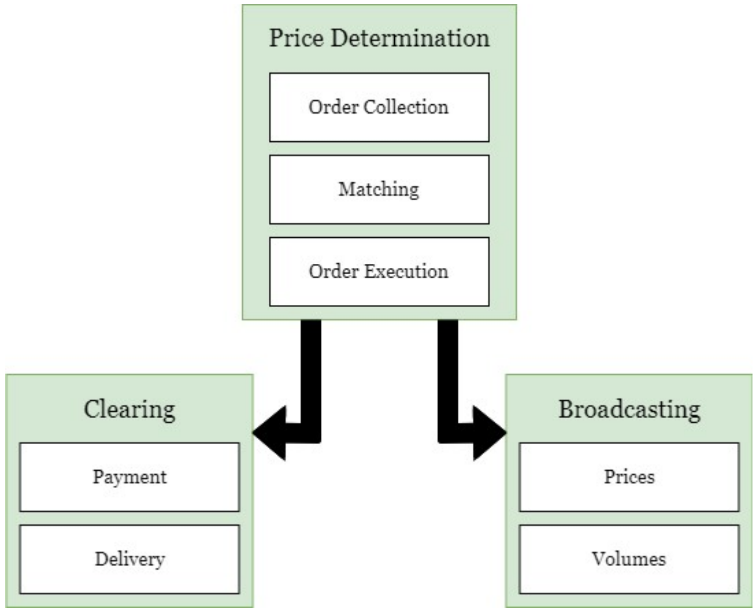


Figure 4.4: The market operator is responsible for (1) determining the electricity price, (2) clearing the order book and (3) broadcasting the resulting prices and volume

4.3.6.2 District Operator

This operator follows the same principles and procedures as the Community operator with the difference being their area of effect over the participants. More precisely, while the Community Operator gathers only short-proximity community resident's orders the District operator gathers orders that were not filled from every Community Day-Ahead market at it's jurisdiction as well as, per this model, orders from independent solar & wind generation-units and EV aggregators.

4.3.6.3 Grid Operator

The Grid Operator has the most significant impact on the energy market and "the last word" with regard to the clearance of all of the network's orders during the Day-Ahead market. It's at the Grid level that every end-user tries ordering before heading to the Intra-Day market. In this work the Grid Operator, contrary to the lower level operators, conducts not only the Day-Ahead market but also the Intra-Day market in the form of Peer-to-Peer. Regarding the Day-Ahead market, the operator gathers orders from every end-user of the grid including orders from Large consumers and unfilled orders from every District. The resulting clearance marks the end of the Day-Ahead market for the grid. In the Intra-Day market the Grid Operator is responsible for conducting the Peer-to-Peer market at which, now, only District unfilled orders are accepted for clearance. The same operating procedures apply for the Peer-to-Peer market to determine accepted order, to match them and to broadcast the corresponding prices and volumes.

4.4 Algorithm Overview

This work's algorithm can be conveniently broken down to two major sections, the Day-Ahead and the Intra-Day. The Day-Ahead section encloses all of the actions executed until the Day-Ahead Market is concluded while the Intra-Day section describes the actions that follow the day of the Day-Ahead Market including the peer-to-peer transactions. At this point it is worth noting that each sub-section of the model is entirely independent which leaves room for improvements to the code at desired levels as well as more optimal arrangements of future works. Each section can be seen in Fig. 4.5 with their corresponding sub-sections in order of execution.

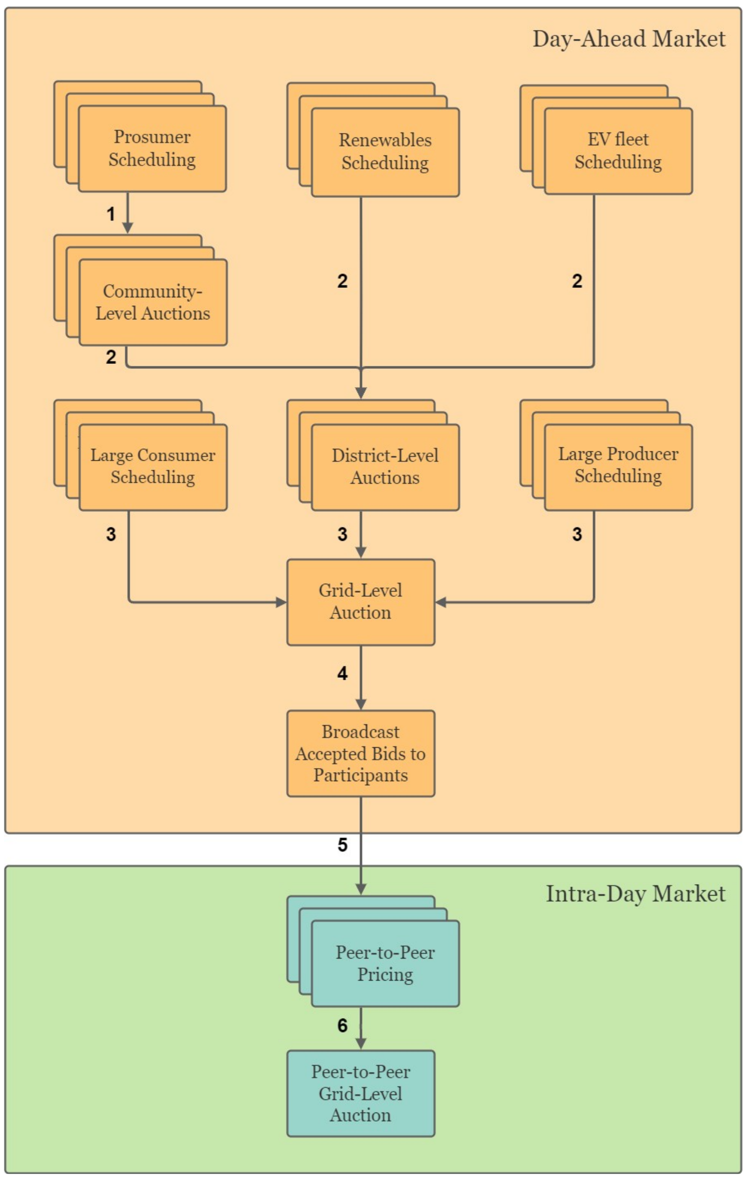


Figure 4.5: Algorithm Sections: 1)Day-Ahead Market, 2)Intra-Day Market

4.4.1 Optimization of constrained nonlinear multi-variable function

The scheduling of the household's daily energy consumption as well as battery charging and discharging can be described as an optimization problem with the following characteristics:

$$min_x f(x) \ such \ that \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ A \cdot x \leq b \\ Aeq \cdot x = beq \\ lb \leq x \leq ub \end{cases}$$

Where b and beq are vectors, A and Aeq are matrices, *c(x)* and *ceq(x)* are functions that return vectors, and *f(x)* is a function that returns scalars. *f(x)*, *c(x)* and *ceq(x)* can be non-linear functions. Lastly, x, lb and ub can be passed as vectors or matrices.

In this work, we consider the cost function of each community's i-th household to be the sum of their time-frame's (dt) consumption (x) multiplied by the current projected energy price (p_{cost}).

$$f_i(x) = \min_x dt \cdot \sum_{t=1}^{\frac{24}{dt}} p_{cost}(t) \cdot x(t)$$

The minimum household power constraints are calculated as the sum of the household's residents consumption, as predetermined by the household profiles and the appliances consumption denoted $load_{ap}$.

We also consider m to be the total number of members of the household. With wm we denote the total number of working members of the household with djm, njm, and hjm indicating the day-job working, night-job working and working-from-home members respectively. As such, we denote the minimum power consumption of the aforementioned member types as P_{dmin}, P_{nmin}, P_{hmin}, P_{pmin}. P_{pmin} indicates the power consumption of protected members.

$$lb \leq x \leq ub$$

$$lb = Pmin$$

$$P_{min} = djm \cdot P_{dmin} + (wm - djm - hjm) \cdot P_{nmin} + (wm - djm - njm) \cdot P_{hmin} + (m - wm) \cdot P_{pmin} + load_{ap}$$

The maximum household power constraints describe the physical load tolerance of the power lines of the household. We assume single phase supply at each home protected with a 35A fuse and running on 220V.

$$ub = Pmax$$

$$Pmax = 220(V) \cdot 35(A) = 8000W = 8kW$$

The daily household energy consumption constraint is calculated as follows:

$$A_{eq} \cdot x = b_{eq}$$

$$A_{eq} = \vec{1} \cdot dt$$
$$b_{eq} = E$$
$$E = E_{house} + m \cdot E_{person}$$

The A, b, *c(x)* and *ceq(x)* parameters are not used in this optimization while the initial x_0 vector is arbitrarily chosen as follows:

$$x_0 = \vec{0}$$

The cost function of the household battery's charging and discharging is described as the sum of every time step's consumption and generation (x) multiplied by the current energy price p_{cost}.

$$f_i(x) = \min_x dt \cdot \sum_{t=1}^{\frac{24}{dt}} p_{cost}(t) \cdot x(t)$$

The minimum and maximum power definition of each battery, which happens to be the lower and upper bound constraints for the optimization, are assumed to be constant at 0.5 kW.

$$lb \leq x \leq ub$$
$$ub = 0.5 \cdot \vec{1} kW$$
$$lb = -0.5 \cdot \vec{1} kW$$

The parameters A and b describe the minimum and maximum SOC constraints for the batteries. For A we would have to introduce the *lower triangular* matrix with dimensions $N \times N$ with N being the total daily time intervals. The *lower triangular* is depicted as *tril*.

$$A \cdot x \leq b$$

$$A = \begin{bmatrix} tril_{N \times N} \\ -tril_{N \times N} \end{bmatrix} \cdot dt$$

$$b = \begin{bmatrix} SoC_{max} - SoC_0 \\ -SoC_{min} + SoC_0 \end{bmatrix}$$

The A_{eq} and b_{eq} parameters are essential for each battery to reach it's determined SoC.

$$Aeq \cdot x = beq$$
$$A_{eq} = \vec{1} \cdot dt$$
$$b_{eq} = SoC_f - SoC_0$$

The b_{eq} describes the energy that the optimization will need to allocate in time to optimize the cost function of the battery. So, it is thought to be the difference between the SoC at departure and the SoC at arrival.

The parameters *c(x)* and *ceq(x)* are not used in this optimization while the initial x_0 vector is arbitrarily chosen as follows:

$$x_0 = \vec{0}$$

Lastly, for the case of the EV fleet daily battery charging and discharging we consult the findings of [32]. Through this work we extract the maximum and minimum SoC of a fleet of 10000 EVs as well as their charging and discharging depths for 30 minute intervals.

The procedure followed bears a strong resemblance to that of the household's battery optimization as the EV fleets in this work are considered to act as a cumulative battery.

The cost function of the EV fleet's charging and discharging is described as the sum of every time step's total fleet consumption and generation (x) multiplied by the current projected energy price p_{cost}.

$$f_i(x) = \min_x dt \cdot \sum_{t=1}^{\frac{24}{dt}} p_{cost}(t) \cdot x(t)$$

In order to calculate the parameters for every number of EVs we converted the extracted data to apply for a single EV unit. In that way, by multiplying with the total fleet number we get the parameters for any number of EVs other than 10000.

The extracted data consist of the $\overrightarrow{E_{max}}$ and $\overrightarrow{E_{min}}$ vectors, which describe the total available depth for the fleet's SoC for the day, as well as the $\overrightarrow{P_{max}}$ and $\overrightarrow{P_{min}}$ vectors which account for the cumulative charging and discharging capabilities of the fleet.

$$lb \leq x \leq ub$$
$$ub = \overrightarrow{P_{max}}$$
$$lb = \overrightarrow{P_{min}}$$

The parameters A and b describe the minimum and maximum SOC constraints for the fleet's cumulative battery.

$$A \cdot x \leq b$$

$$A = \begin{bmatrix} tril_{N \times N} \\ tril_{N \times N} \end{bmatrix} \cdot dt$$

$$b = \begin{bmatrix} \overrightarrow{E_{max}} - SoC_0 \\ -\overrightarrow{E_{min}} + SoC_0 \end{bmatrix}$$

The A_{eq} and b_{eq} parameters describe the constrain of the fleet's battery to meet the required SoC at the end of the day.

$$Aeq \cdot x = beq$$
$$A_{eq} = \vec{1} \cdot dt$$

$$b_{eq} = SoC_f - SoC_0$$

The parameters *c(x)* and *ceq(x)* are not used in this optimization while the initial x_0 vector is arbitrarily chosen as follows:

$$x_0 = \vec{0}$$

4.4.2 Auctioning Algorithm

This work's implementation follows the single-round auction methodology as shown in section 3.3.

Every hour, each participant presents a quantity-price pair to the auction administrator. For simplicity, every participant presents a single bid and no complex bids are supported.

After the aggregation of the buying bids by the administrator the demand curve is built up by arranging those bids in descending order. Similarly, the supply curve is built up by arranging the sellers bids in , now, ascending order. The intersection of the two curves gives the clearing price of the time interval at question as well as the accepted selling and buying bids.

For the instance that the intersection, that determines the clearing price, is met midway of an bider's quantity, the following are considered:

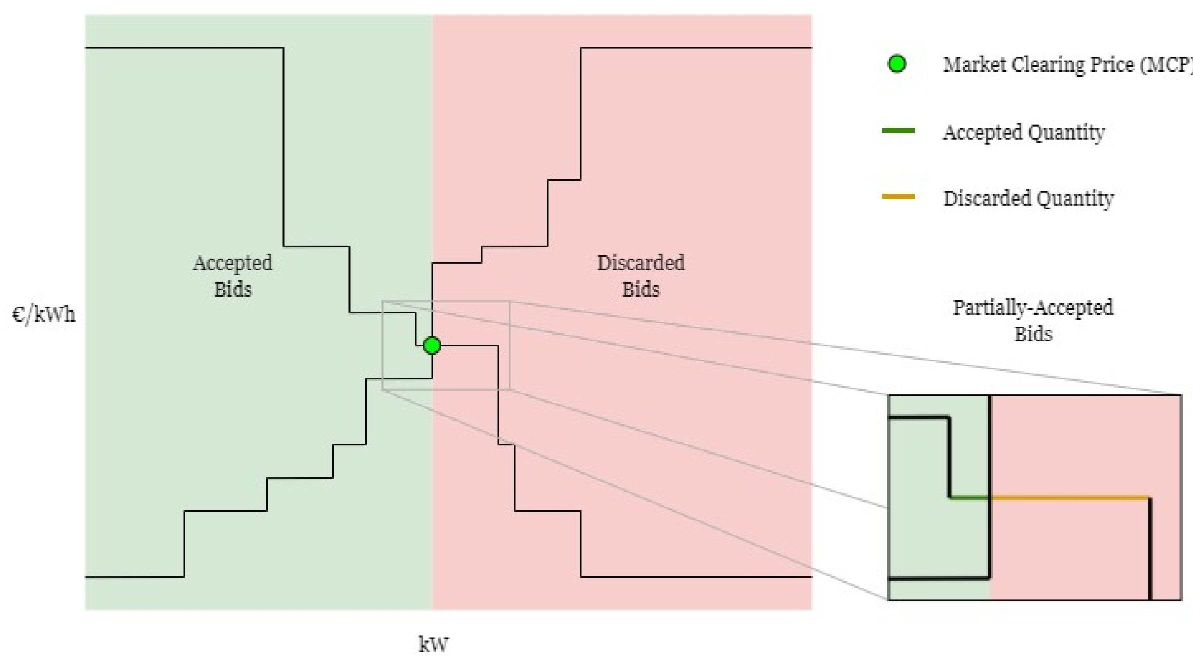


Figure 4.6: Single-Round Auction Implementation

Due to the fact that this implementation of the Day-Ahead Market does not consider a *Non-Divisible Quantity* like the Spanish Market makes it susceptible to what we call *Partially-Accepted Bids*. Partially-Accepted Bids are those whose price is equal to the clearing price and the cumulative quantity of their curve is greater than the cumulative quantity that is being determined by the x-coordinate of clearing price's intersection Fig. 4.6.

To tackle this phenomenon we considered the following approach.

Each Partially-Accepted Bid is being split into two sections 1)The Accepted quantity and 2)The Discarded Quantity determined by the point of intersection. After that, the accepted quantity is considered accepted and gets settled in the current auction, while the discarded quantity is being discarded. It is worth noting at this point that in this work the discarded quantities are being forwarded to the rest Day-Ahead Markets with a total of (at worst case) three participations for clearance (Community, District and Grid levels).

Considering the social welfare of the matter, one can also connect the risk of submitting a "close-to-probable-clearing-price bid" to a possible partial exclusion from the accepted batch. So the odds of a recurring ,to a participant, phenomenon are small.

4.4.3 Prosumer Scheduling

The first step of the algorithm is the programming of each household. That includes the collection of generation and load data, the processing of those data and the outputting of priced bids for either selling or buying to the rest of the Grid through the Prosumer Agent.

Firstly, each Prosumer Agent calculates the next day's electricity prices based on the forecasted electricity prices that are being distributed to all market participants. These are the prices with which each household will make their energy management decisions and are as follows:

$$prosumer\ prices = forecasted\ prices + 0.018 * rand()$$

The rand() function outputs a single randomly generated number between 0 and 1. This random offsetting of each household's prices also describes the random factor that comes with forecasting values and helps avoid extreme cases at which all participants prices match.

In order to generate realistic load profiles for each household the following characteristics are taken into account.

Each household can be of the three following types:

1. household of 3-6 members
2. household of 2 members
3. household of 1 member

The household members are also categorized based on their working patterns to working members and protected members. It also assumed that at least 1 of the members is a working member. The working members then are further categorized to day-job workers, night-job workers and working from home. The possibility of a working member to be day-job worker is 50% compared to 30% for working from home and 20% for night-job Fig. 4.7.

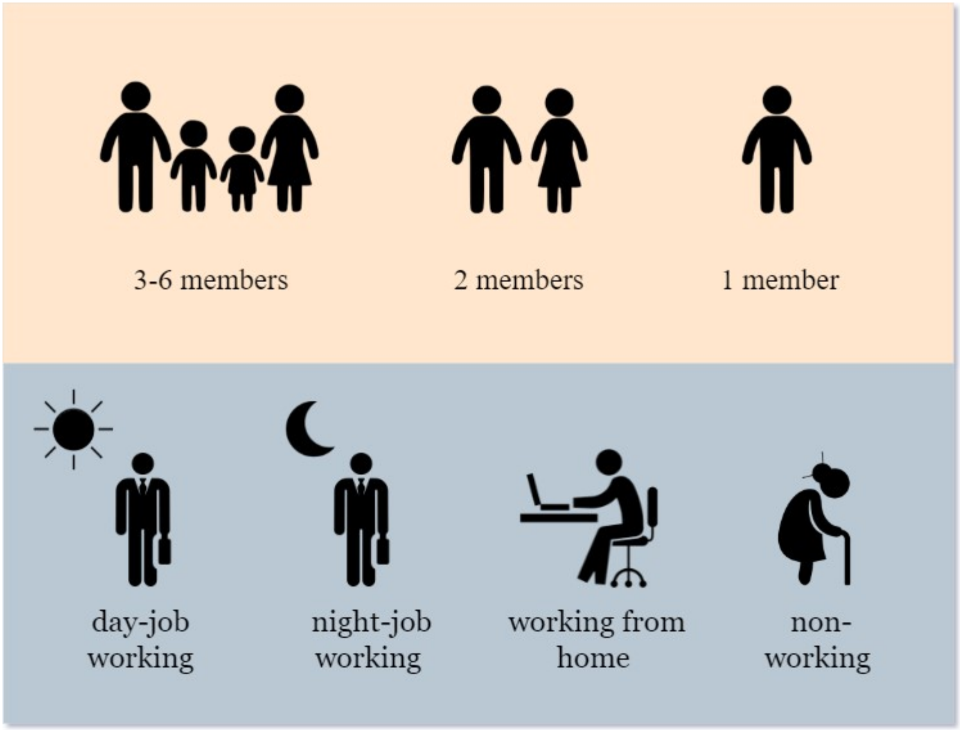


Figure 4.7: Categorization of household members

The above labels are especially useful on generating the energy consumption profile of each individual that then helps to produce the overall household consumption profile.

Next step is the segmentation of the 24-hour period. Common practices like waking up at certain morning hours (usually 5-8 a.m) or leaving work at others (usually 4-7 p.m) have been broadly adopted by most of the western population making some hours of the day largely the same energy-wise. So, by segmenting the days to different zones one can map out a baseline of variable daily energy consumption for an individual Fig. 4.8.

Four types of household member profiles are being considered:

- Day-job working household member
- Night-job working household member
- Working from home household member
- Protected household member (e.g. minors, elderly etc.)

In Fig. 4.9 one can see the levels of consumption as well as the time periods that they appear based on the subject individual and their habits.

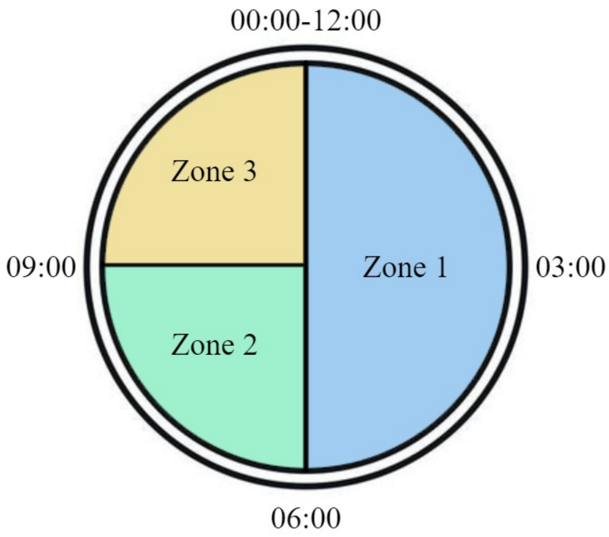


Figure 4.8: Segmentation of the 24-hour time-frame

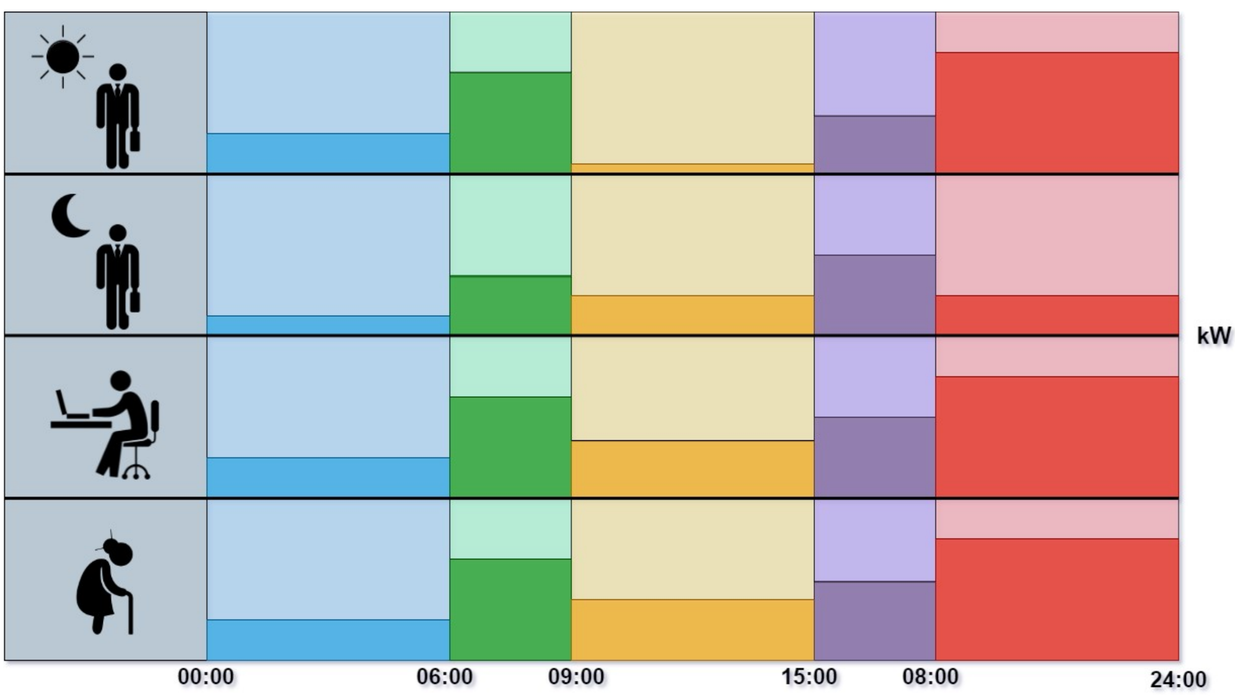


Figure 4.9: Daily power consumption per type of household member

Each household has a combination of inelastic and elastic loads. The former are being split between a minimum household load and a minimum per-member load. The overall household inelastic load is being calculated as follows:

$$Ebasic = \textit{Minimum daily household inelastic load (kWh)}$$
$$Eperson = \textit{Minimum daily person inelastic load (kWh)}$$
$$\textit{elastic load} = \textit{Total daily household elastic load (kWh)}$$
$$m = \textit{total household members}$$

$$Ebasic = 12 + poissrnd(3)kWh$$
$$Eperson = 2 + poissrnd(0.2)kWh$$
$$\textit{elastic load} = poissrnd(5)kWh$$

$$\textit{overall household load} = Ebasic + m * Eperson + \textit{elastic Load}$$

As *poissrnd(x)* we refer to the random number generation from the poisson distribution with $\lambda = x$.

Household battery scheduling

We consider 20% of the total households to be equipped with equally probable battery of the following capacities Cap:

- 3 kWh
- 4.5 kWh
- 6 kWh

The maximum and minimum SoCs as well as the maximum charging and discharging power and the starting and final SoCs are calculated as follows:

$$Pmax = 0.5kW, \textit{Maximum charging power}$$
$$Pmin = -0.5kW, \textit{Minimum discharging power}$$

$$SoCmax = 0.8 \cdot 2 \cdot Cap \cdot Pmax, \textit{Maximum SoC}$$
$$SoCmin = 0.3 \cdot 2 \cdot Cap \cdot Pmax, \textit{Minimum SoC}$$
$$SoC0 = \frac{SoCmax + SoCmin}{2}, \textit{Daily SoC at the start of the day (00:00)}$$
$$SoCf = \frac{SoCmax + SoCmin}{2}, \textit{Daily SoC at the end of the day (24:00)}$$

We consider the charging and discharging of the household batteries to take place between 80%-30% of the total SoCmax to minimize battery degradation.

Household photovoltaic-panels scheduling

As photovoltaic panels are much more common in our days for residential end-users we consider households to be equipped with PV panels with a 40% probability. Moreover each array of PV panels has one of the following random configurations:

- 150-450W peak power per panel
- 4-10 panels per household

The aforementioned configurations give us a minimum of 600W peak power array and a maximum of 4.5kW peak power array per household.

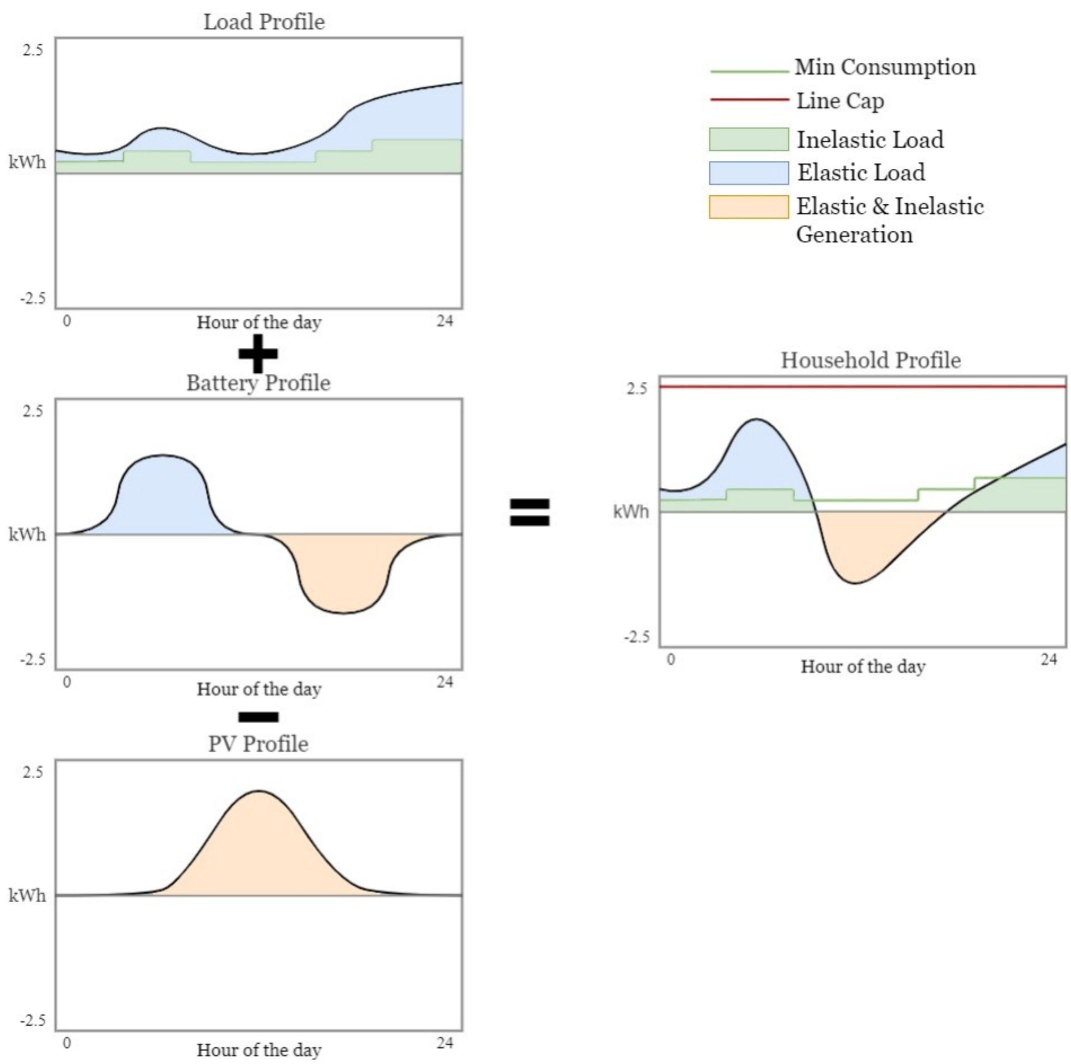


Figure 4.10: Analytical household consumption & generation profile

Adding up the generated profiles for the load, battery and PV that the optimizations return gives the overall Household Load/Generation profile as shown in Fig. 4.10. From all the three profiles mentioned only the load profile is bounded by lower and upper boundaries. The upper bounds are determined by the capacity of the household lines and is considered to be around 8kW. The sections bellow the lower boundaries and above zero describe the inelastic load while the section bellow the load and above the lower boundaries describe the elastic load.

From the resulting Household profile the Prosumer Agent identifies the buying and selling periods for the day. More specifically, for every value that is below zero the Prosumer Agent submits a selling bid at that amount and at the indicated prosumer price. Similarly for every positive value the Prosumer Agent submits a buying bid at the same amount.

Lastly, the Prosumer Agent communicates those bids to the corresponding Community Operator to participate at the Community Day-Ahead Market. For participation in the P2P market Prosumer Agents recalculate their bids internally and similarly communicate them to the Grid Operator that administers the P2P market.

4.4.4 EV fleet Scheduling

In this work we consider EV Aggregators to participate in the energy market framework as independent entities. Their contribution to electricity management has been widely appreciated and recognized while many believe that these market participants will play a vital role for the vast penetration of EVs to the Grid in the future [33]. In this work we consider their purpose to be to serve the EV owners interests. Hence, these participants are considered to be unbiased and non-profitable.

To simplify their modeling, we consider each EV Aggregator to manage a number of parking lots of the three following types:

- Residential parking lot
- Workplace parking lot
- Leisure parking lot

Each parking lot has its own working hours depending on it's type while for the scheduling of it's corresponding Aggregator we assume a cumulative 24-hour operation.

Once the optimization has finished, each EV Aggregator communicates their cumulative bids for the day to the corresponding District Aggregator who then administers the District-level auction. To participate in the P2P market each participant recalculates its bids based on external and internal data and submits them, this time to the Grid Operator who administers the P2P market.

4.4.5 Community-level Auction

In this level, the Community Operator, acts as an auctioneer gathering every participants bid for the Day-Ahead Market and then administering the auction. After they collect all the bids they proceed to make the supply and demand curves which ultimately determine the market clearing price for all the participants. For one to be accepted for energy-trading at a given time interval the following conditions must be met:

- Buyer's buying bid must be greater or equal to the clearing price
- Seller's selling bid must be less or equal to the clearing price

Every prosumer that manages to satisfy the above criteria is marked accepted for trading and get contracted to receive or deliver its bids. It is possible for a prosumer to be assigned to multiple other prosumers for delivery or vice-versa. All participants of the scheduled transactions are then notified and that concludes their communications for that given interval.

On the other hand, for every prosumer that does not manage to satisfy the above criteria they are marked as Discarded and do not get their bids served by other members of the community. Discarded participant's bids are subsequently forwarded to the next clearing level that of the District at which they participate again with the same bid at the corresponding interval.

After the completion of every community auction the action is passed to the next level of clearance, that of the Districts.

4.4.6 District-level Auction

At the District level the participants for the auction are, aside from prosumers, EV Aggregators and Renewable Generation units. At this point it is worth mentioning that if it was for the integration of ESSs it would be preferably done at this level. That is due to the market impact that the District level has, as it aggregates prosumer and EV fleet bids from different areas.

Same principles stand for the selection of the accepted and discarded bids as prior. Through running the auctioning algorithm the accepted EV Aggregators and prosumers get notified that their transactions are settled at their bid prices. The Discarded bids are once again forwarded to the next clearing level, that of the Grid.

4.4.7 Large Consumers-Producers Modeling

In order to simulate a realistic and compatible to current energy systems market we ought to integrate large producers and consumers. The former are represented by the commercial sector while the later describes electricity producers and resellers. At this point it is worth mentioning that these end-users are integrated at the retail market and do not take part at any other peer-to-peer transactions per this model. It is also worth mentioning that the focus of this work is on the residential and commercial sectors as well as the distribution networks and the tactics followed do not impact the industrial sector.

For the commercial sector we utilized forecasted data for the daily consumption of a number of public and private companies and services such as schools, hospitals, shopping centers etc [34]. The forecasted data are then priced and identified to generate the corresponding bids for the Grid-Level auction.

Large producers are the only end-users of the energy system whose participation in the energy market is mandatory. Meaning that any other participant has the option to abstain from the aforementioned procedures if they so desire.

Output Power of Large Producers

Let's consider P the Output Power of a power plant. The cost of production is defined:

$$F(P) = (a \cdot P^2 + b \cdot P + c) \cdot fuel_{cost} \tag{4.1}$$

This function is minimized for:

$$\frac{dF}{dP} = EP(t)$$

Where EP(t) describes the electricity price for time t. Consequently by taking the derivative of 4.1 and solving with respect to P you get the following:

$$(2 \cdot a \cdot P(t) + b) \cdot fuel_{cost} = EP(t) \Rightarrow P(t) = \frac{\frac{EP(t)}{fuel_{cost}} - b}{2 \cdot a} \tag{4.2}$$

Given that we already know the forecasted electrical prices we can derive the forecasted Output Power of the power plant. At this point it is worth mentioning that we consider the Large Producers Output Power to equal that of the power plants to simplify the model.

4.4.8 Grid-level Auction

This level is the last opportunity for it's participants to achieve clearance before the end of the Day-Ahead Market. Large Consumers and Producers as well as Prosumers, Renewables and EV Aggregators participate and the resulting clearing price is being set for every end-user of the Grid.

The Grid Operator is responsible for carrying out the auction as well as matching the bids between it's participants. The method used for the auctioning procedure at the Grid level is considered to be this work's simple auction variant.

After the matching of the bids the Day-Ahead Market is concluded. The resulting Discarded bids are forwarded to the peer to peer market for further clearance.

4.4.9 Peer-to-Peer Market

After the conclusion of the Day-Ahead Market and at the start of the day of dispatch end-users that did not manage to match their bids can participate in the peer-to-peer market to achieve clearance. In cases of mismatches due to delivery failure, end-users will also be able to participate in this market.

In the peer-to-peer market, at 15,30 or 60 minute time frames, end-users of the same Grid can submit bids to the the Grid Operator who then matches them based on this work's simple bid auction. The market works continuously throughout the day while receiving bids only during each determined time frame and determining clearing prices at the end of it. If the participants do not get clearance even in this market they communicate their generation and load to neighboring Grids.

End-user pricing for the Peer-to-Peer Market

There are many reasons that would lead to a participant's particular choice of pricing for either selling or buying electricity. They can range from completely objective available market data to subjective personal preferences.

In this work we attempt to illustrate this behavior and identify the choice-patterns, for pricing on the peer-to-peer market, of different end-users by using Fuzzy-Logic.

The suggested models are assessed on Mamdami FIS(Fuzzy Inference System)[35] with rules generated on verbose format. The first model describes the peer-to-peer buyers and the second the sellers. The inputs to our models are considered metrics from which we are able to extract a useful output price bid for the participation to the peer-to-peer market. The minimum and maximum output values are determined by a nominal minimum trading price and a nominal maximum trading price defined by the Grid. We also consider our inputs to the models to be of the two following types:

1. Internal
2. External

The inputs that are identified as Internal share a subjective element as we consider them to be coupled to habits and preferences of the end-users rather than facts and metrics. For instance, we consider the Internal input variable *Interest*, which takes values between 1 and 10, to act as a manual knob that translates to the willingness of a particular end-user to participate on the peer-to-peer market. If, for example, an end-user bids to buy energy and has high conviction, the *Interest* input is set to *high* and the price of the bid gets driven higher from the competition.

External are the inputs that refer to metrics and factual statistics and are thought to be objective. For example, the current temperature may be thought as an External input.

As a result, the pricing of a specific bid is determined from both subjective and objective factors based on the end-user's personalized needs.

Below, we define the membership functions for our input and output variables.

Temperature: This External input variable has three states, warm, normal and cold. It is proven that temperature is one of the most accurate indicators for electricity consumption. As such one can consider the fact that during the more temperature-heavy days there is little to no tolerance for unserved electricity loads. On the other hand, on mild temperature days end-users can fend for themselves much more easily due to less urgent needs for consumption. The Membership functions of the current variable are set to overlapping Gaussian distributions in order to generate correlation between the adjacent intervals.

Time of the Day: We have already established the idea of Daily time-zones and their impact on energy-consumption. With this External input variable we attempt to build on that by weighting the output price depending on the current time-frame. In high-demand periods the output price is influenced to the upside while in low-demand periods one can expect the opposite. The Membership functions of the current variable are also set to overlapping Gaussian distributions.

Load Indicator: In order to manage the load flowing through the distribution and transmission lines we have considered this input variable to be a signal from the control system of the transmission and distribution lines that is triggered depending on the load of those lines. More specifically we consider this variable to take values between 0 and 1 with 0 meaning no load and 1 meaning maximum load. The membership functions are set as two lines, one descending and one ascending from 0 to 0.2 and 0.8 to 1 that feed the low and high output membership functions respectively.

Buyer Dominance: This External input variable takes into account the population proportions between the Buyers and the Sellers to give an angle on the supply and demand at hand. It takes values between 0 and 1 and it can be computed through the following:

$$Buyer\ Dominance = \frac{\#\ of\ Buyers}{Total\ \#\ of\ Participants}$$

A close to 0 value of this input will output a *low* signal for the buyer's buying price.

Load Dominance: Another significant External input variable for the output price for the buyers is the Load Dominance as it paints a perfect picture for the supply and demand at hand. It also takes values between 0 and 1 and it is computed as follows:

$$Load\ Dominance = \frac{Total\ Load\ Quantity}{Total\ Load\ and\ Generation\ Quantity}$$

For input values close to 0 the output price value is set to *low* for buyers and for input values close to 1 the output price value is set to *high*.

Seller Dominance: This External input variable takes into account the population proportions between the Buyers and the Sellers to give an angle on the supply and demand at hand. It takes values between 0 and 1 and it can be computed through the following:

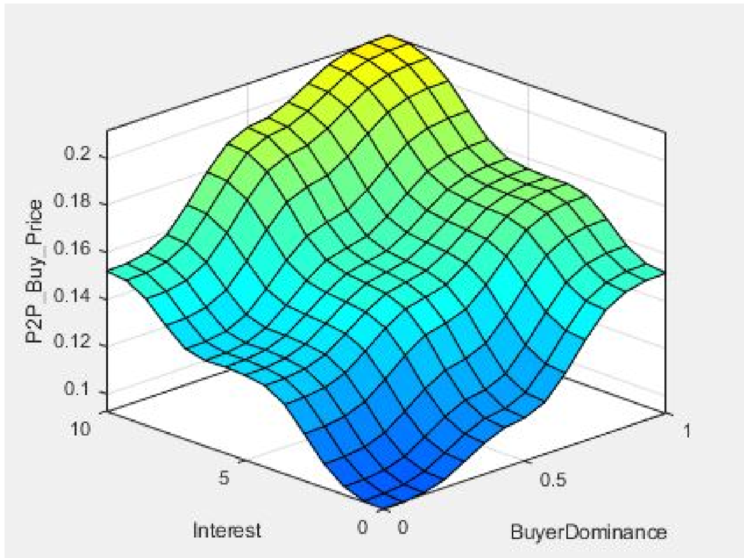
$$Seller\ Dominance = \frac{\#\ of\ Sellers}{Total\ \#\ of\ Participants}$$

A close to 0 value of this input will output a *high* signal for the seller's selling price.

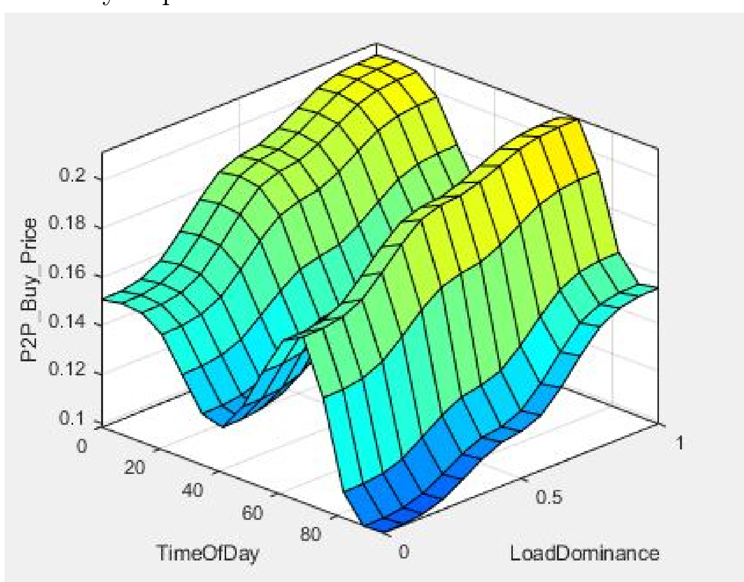
Generation Dominance: A significant external input variable for the sellers is the Generation Dominance as it gives information about the supply and demand distribution. It also takes values between 0 and 1 and it is computed as follows:

$$Generation\ Dominance = \frac{Total\ Generation\ Quantity}{Total\ Load\ and\ Generation\ Quantity}$$

For input values close to 0 the output price value is set to *high* and for input values close to 1 the output price value is set to *low*.



(a) Impact of *Interest* and *Buyer Dominance* on Peer-to-Peer buyers prices



(b) Impact of *Time of Day* and *Load Dominance* on Peer-to-Peer buyers prices

Figure 4.11: Surface plots between different FIS input variables and the output buying price.

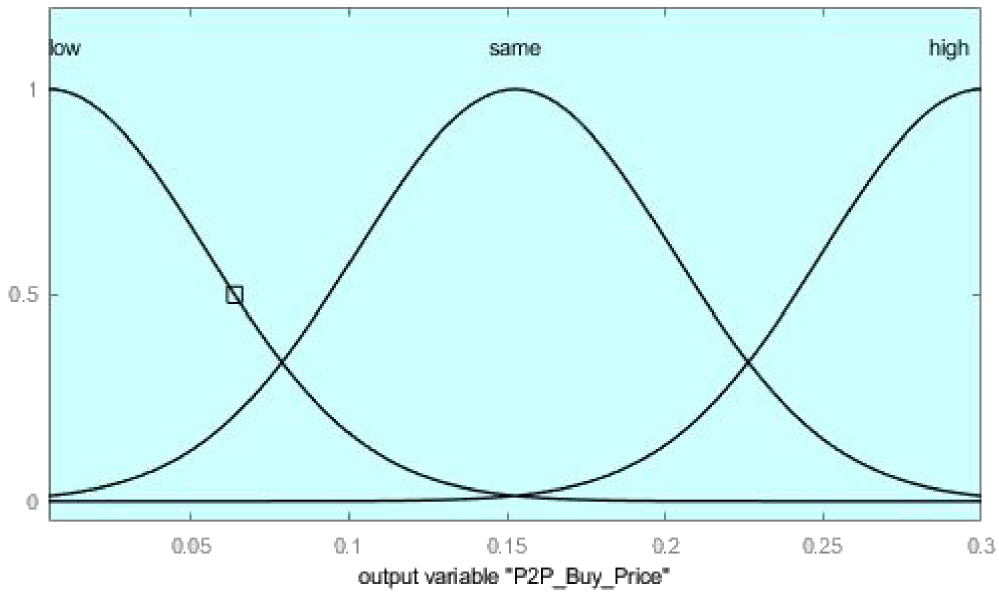


Figure 4.12: Membership functions for the Peer-to-Peer selling and buying price

Interest: This input variable is identified as Internal as it describes the end-users urgency for clearance. It ranges from 1 to 10, 1 meaning lowest interest in buying or selling and 10 meaning highest interest on buying or selling. As such, closer to 1 gives an output value of *low* for buyers and *high* for sellers, while closer to 10 gives an output value of *high* for buyers and *low* for sellers. Input closer to 5 is interpreted as *average* and is being outputed as *same* for both buyers and sellers. All three membership functions (*low, average, high*) are represented by overlapping Gaussian distributions.

P2P Buying Price: This is the output variable of the buyer's FIS system and it defines the price with which an individual buyer will participate in the peer-to-peer market. The membership functions of the P2P Buying Price are named *low, same* and *high* and are described by Gaussian distributions. The *low* function is centered around the nominal minimum trading price while the *high* is centered around the nominal maximum trading price. To ensure that the peer-to-peer price action is relevant to the Day-Ahead Market's action, the *same* membership function is centered on the clearing price of the same time-interval as the Grid-level Day-Ahead market. In that way, prices of the peer-to-peer market are more predictable and stable which contributes positively to the social welfare of the market.

P2P Selling Price: This is the output variable of the seller's FIS system and, similarly to the buyer's, it defines the price with which a seller will participate in the peer-to-peer market. The configuration of its membership functions is the same as that of the P2P Buying Price.

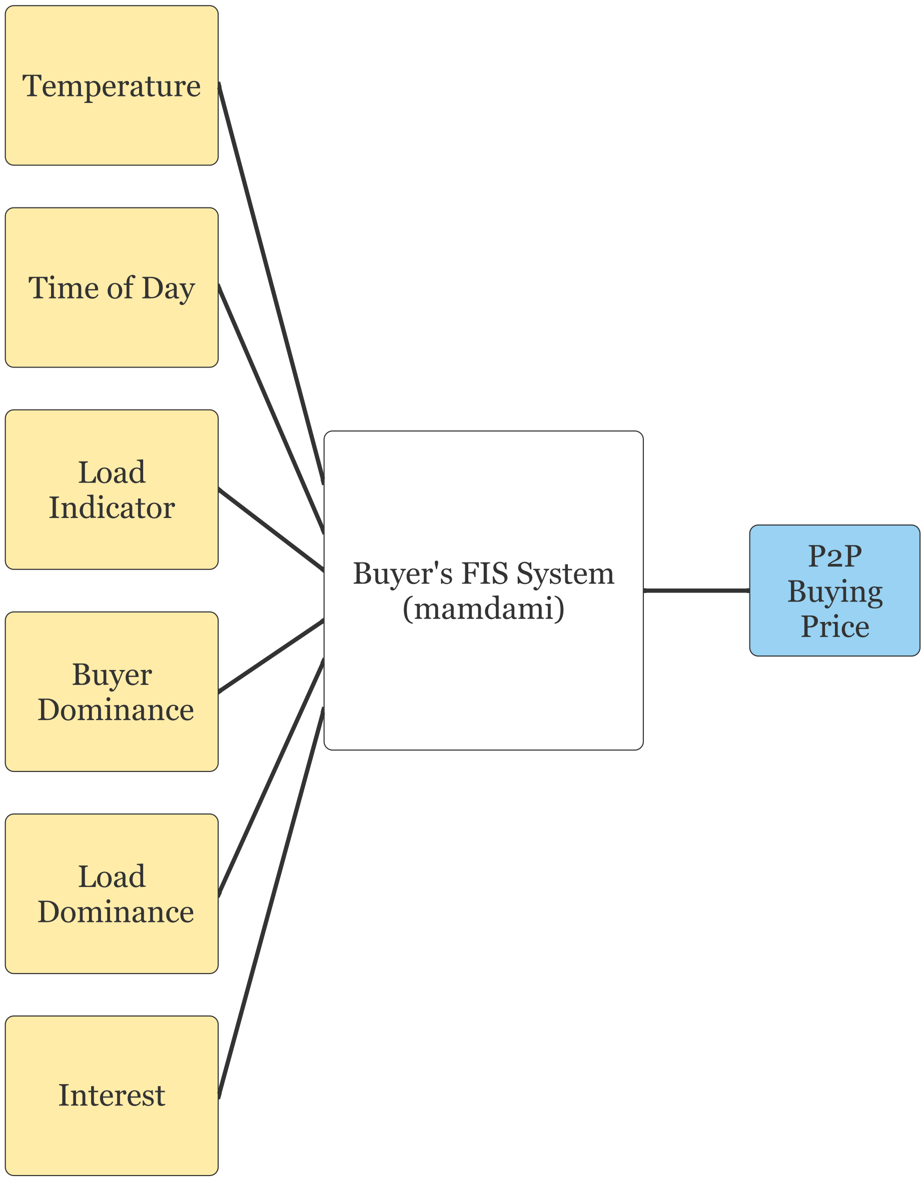


Figure 4.13: High-level representation of proposed buyer's Fuzzy Inference System

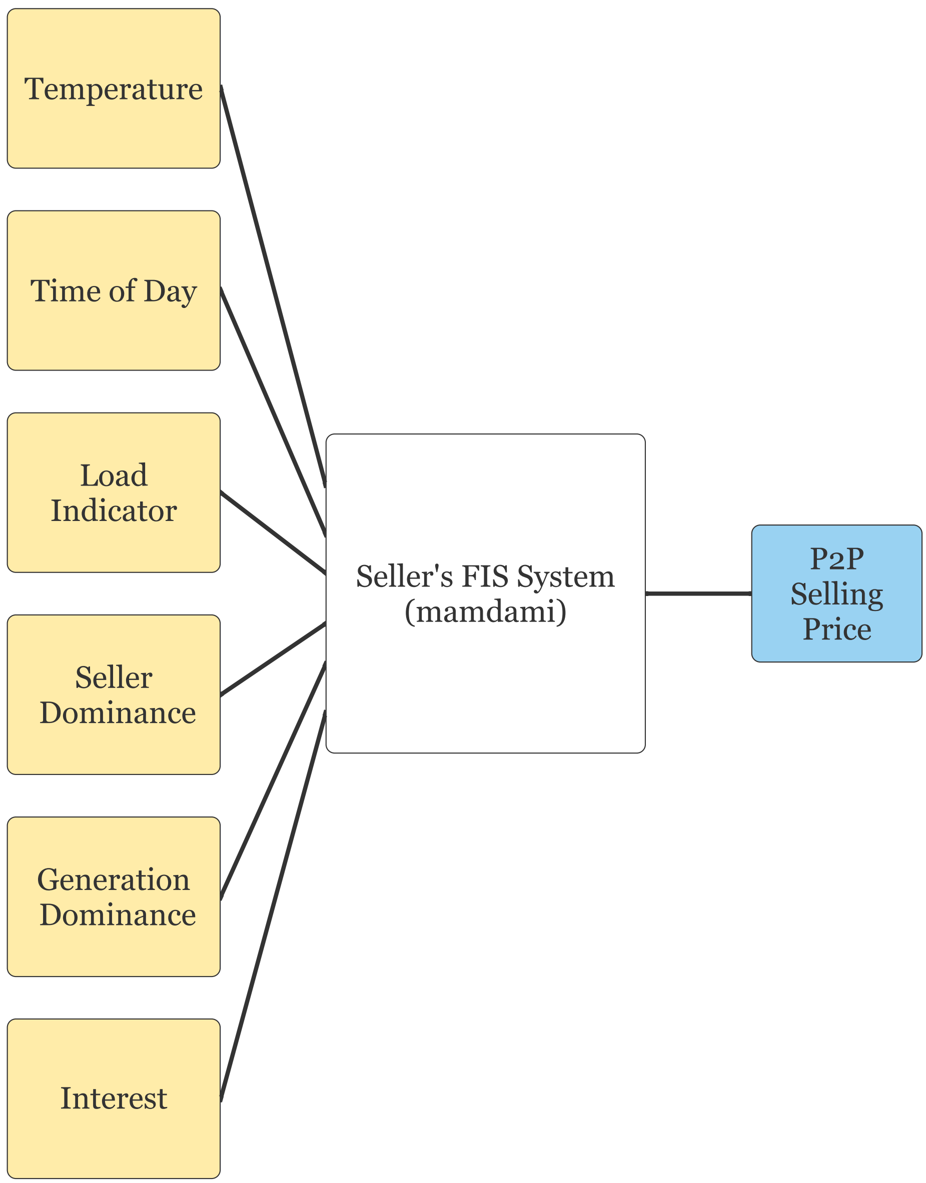


Figure 4.14: High-level representation of proposed seller's Fuzzy Inference System

Peer-to-Peer Auction and Clearance

After the end-users, that are willing to participate to the peer-to-peer market, successfully calculate their bids they present them to the Grid Operator. After having collected all the bids, the Grid Operator then proceeds to administer the proposed simple auction. These auctions happen every 15, 30 or 60 minutes depending on the configuration. The bids can be communicated until the last moment of each time interval at which time the accepted bids are announced. The discarded bids are then communicated out of the system and to a different section of the same Grid or another Grid at which point no further clearance happens.

Chapter 5

Results

5.1 Case Study

In this Chapter we attempt to simulate the proposed agent-based algorithm in a scenario that involves the Electrical Power System of Crete. This particular system, to our eyes, is of great importance as it happens to have perfect environmental conditions for the mass deployment of renewable generation. Through this simulation,one can glimpse through the future of renewable energy generation and integration as well as measure the processes needed to achieve a more decentralized and power-autonomous grid as Smart-Grids dictate.

Figure 5.1: Crete's Electrical Power System

5.1.1 Crete's Electrical Power System

Crete's Electrical Power System generation makes for a total of 820.02 MW installed power with around 635 MW peak power. It comprises by three major power plants located on the island, namely those of Chania, Linoperamata and Atherinolakos Fig. 5.1. All power plants consist of 27 power units in total [2]. Their characteristics as well as their costs for running are presented in tables Table 5.1 and Table 5.2.

	Nominal Power (MW)	Real Power (MW)	Summer Power (MW)	Minimum Power (MW)	FUEL
LINOPERAMATA					
STEAM 1	6	6	6	4	Mazut
STEAM 2	14	14	13	8	Mazut
STEAM 3	14	14	13	8	Mazut
STEAM 4	24	24	23	18	Mazut
STEAM 5	24	24	23	18	Mazut
STEAM 6	24	24	23	18	Mazut
DIESEL 1	11	11	11	3	Mazut
DIESEL 2	11	11	11	3	Mazut
DIESEL 3	11	11	11	6	Mazut
DIESEL 4	11	11	11	3	Mazut
GAS 1	15	15	13	3	Diesel
GAS 2	15	15	13	3	Diesel
GAS 3	43	43	41	5	Diesel
GAS 4	14	14	12	3	Diesel
GAS 5	28	28	25	5	Diesel
CHANIA					
S.C.	132	126	112	35	Diesel
GAS 1	16	14	11	3	Diesel
GAS 4	24	20	19	3	Diesel
GAS 5	30	28	27	5	Diesel
GAS 11	59	58	54	10	Diesel
GAS 12	59	58	54	10	Diesel
GAS 13	28	28	25	10	Diesel
ATHERINOLAKOS					
DIESEL 1	51	50	50	35	Mazut
DIESEL 2	51	50	50	25	Mazut
STEAM 1	44	43	44	22	Mazut
STEAM 2	44	43	44	22	Mazut
TOTAL	803	783	740		

Table 5.1: Power units of the Electrical Power System of Crete [2]

	a (kg - lt)	b (kg/MWh)	c (kg/MWh^2)	d (kg/MWh^3)	Cost of fuel (€/kg-lt)	Start-up cost (€)
LINOPERAMATA						
STEAM 1	17,377	-167,2	727,6	0,001	0,4149	2500
STEAM 2	0,476	-11,824	378,937	0,001	0,4149	2500
STEAM 3	0,476	-11,824	378,937	0,001	0,4149	2500
STEAM 4	0,18	-8,053	355,088	0	0,4149	4000
STEAM 5	0,092	-4,166	300,58	0	0,4149	4,000
STEAM 6	0,092	-4,166	300,58	0	0,4149	4,000
DIESEL 1	10,421	-8,378	230,368	0	0,4149	220
DIESEL 2	0,421	-8,378	230,369	0	0,4148	220
DIESEL 3	0,421	-8,378	230,368	0	0,4149	219
DIESEL 4	0,421	-8,378	230,369	0,01	0,4148	220
GAS 1	2,48	-5,87	881,5	1,2	0,6982	179,1
GAS 2	0,3195	-6,777	280,49	1622,8	0,6982	500
GAS 3	0,0001	0,2533	197,65	2418	0,6982	1413
GAS 4	0,0001	0,7913	234,95	1093,8	0,6982	858
GAS 5	0,001	0,3605	196,29	1675,8	0,6982	350
CHANIA						
GAS 6	0,001	0,01	145,54	5120	0,6962	440,01
GAS 7	0,001	0,01	145,64	5120	0,6962	440,41
GAS 1	0	0,01	267	2170	0,6962	99
GAS 4	0	0,01	219	2865	0,6962	1300
GAS 5	0	0,01	275	3757	0,6962	400
GAS 11	0,001	0,01	227	5000	0,6962	0,1
GAS 12	0,001	0,01	227	5000	0,6962	0,1
GAS 13	0,001	0,3605	196,29	1675,8	0,6962	858
ATHERINOLAKOS						
DIESEL 1	0,017	-1,3	222,6	0,27	0,3919	270
DIESEL 2	0,017	-1,3	222,6	0,27	0,3919	270
STEAM 1	-0,003	-0,958	282,91	0,8	0,3919	350
STEAM 2	-0,003	-0,958	282,91	0,8	0,3919	350

Table 5.2: Parameters of all power units of the Electrical Power System of Crete [2]

5.1.2 Scenario: Hybrid Crete

Before proceeding to the simulation we made certain assumptions about some of the system's parameters as well as gathered information based on the system's data in generation and consumption sides. A rudimentary representation of the Grid can be seen in Fig 5.2. The grid connects the island's only resources and loads without taking into account electrical connections with regions outside the island.

Figure 5.2: Crete's Smart-Grid overview

5.1.2.1 Assumptions and Constraints

Our simulation assumes that the traditional Electrical Power System coexists with our proposed model. It is also assumed that the infrastructure that is needed for such a connection both in the transmission network as well as the distribution network is installed and functioning as intended. Lastly, all the data and power flows of the Smart-Grid's end-users are considered to have bidirectional capabilities.

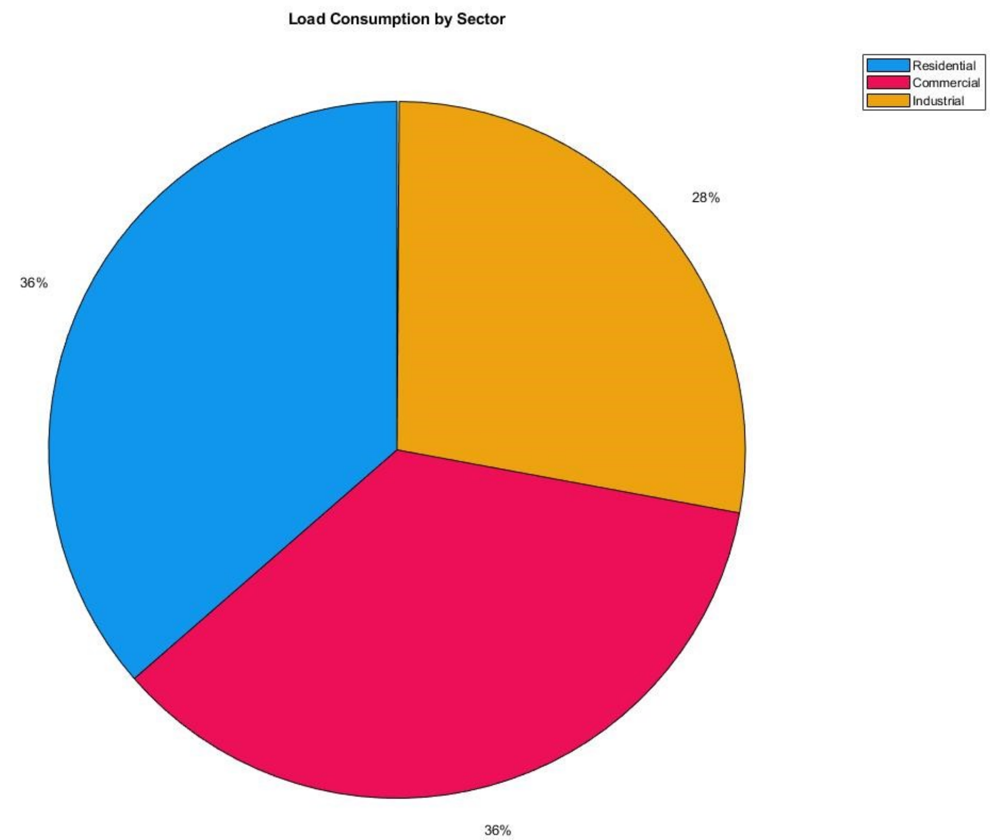


Figure 5.3: Total Load Consumption by Sector

Crete's daily load based on statistical consumption volume numbers of 2018 is around 7.78 GWh. We consider that 70% of the load (5.44 GWh) is served through the the traditional electicity market operation and 30% (2.33 GWh) is served through our proposed model Fig 5.4.

At the end of this case study we will be comparing the net cost of serving load under the two methods by comparing power-flows and cash-flows.

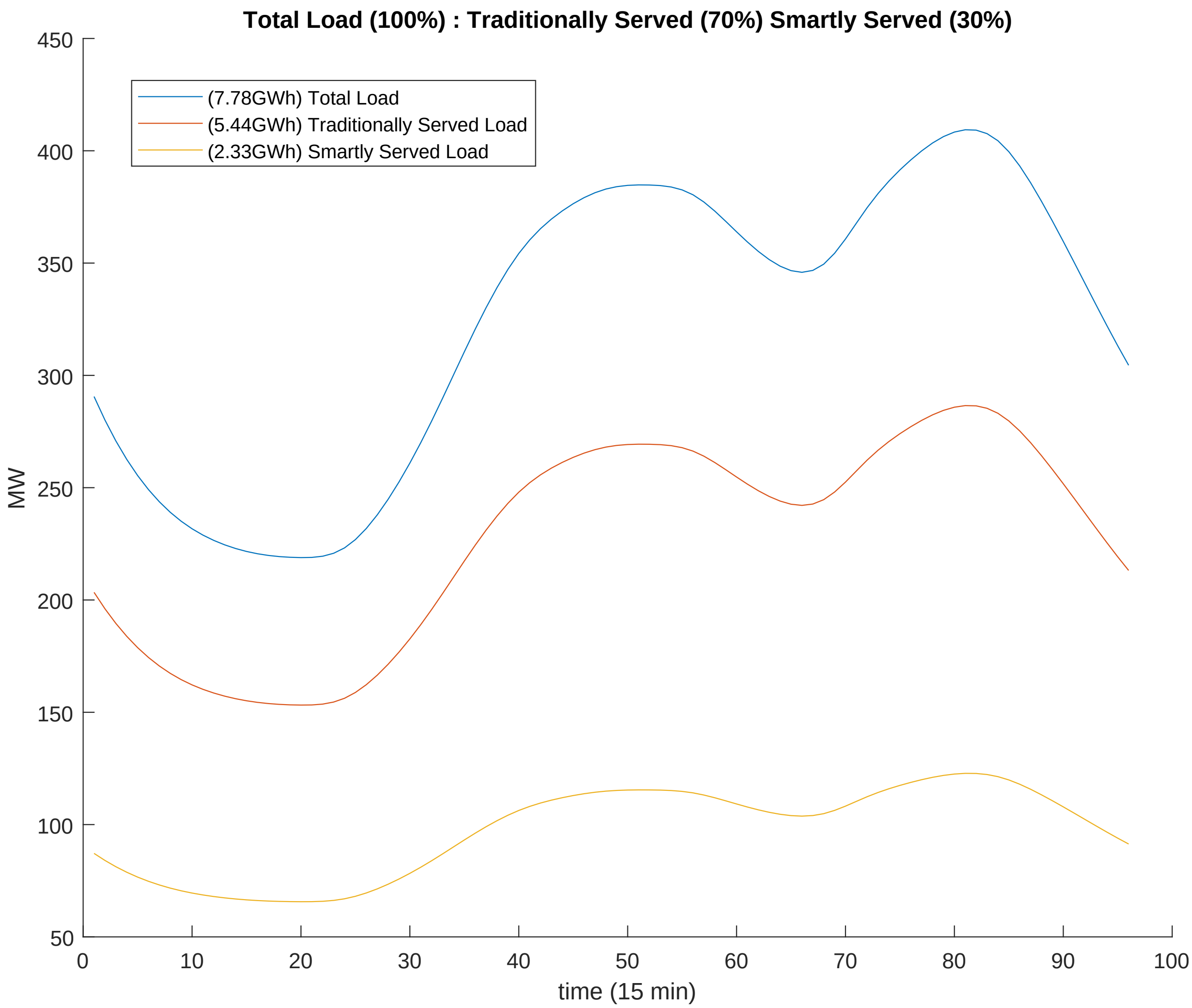


Figure 5.4: Total daily load consumption of Crete

Residential and commercial sectors in Greece make up for 36% of the total electricity consumption while the industrial sector makes up for the 28% Fig 5.3. Also, knowing that the residential and commercial sectors are the more flexible when it comes to electricity consumption leads as to the assumption that the proposed model participants are only parts of those two sectors. Specifically, out of the total 30% loads that will be smartly served 20% are from the residential sector amounting to a total of 75000 households and 10% are from the commercial sector (eg. public and private services, companies etc.) Fig 5.5.

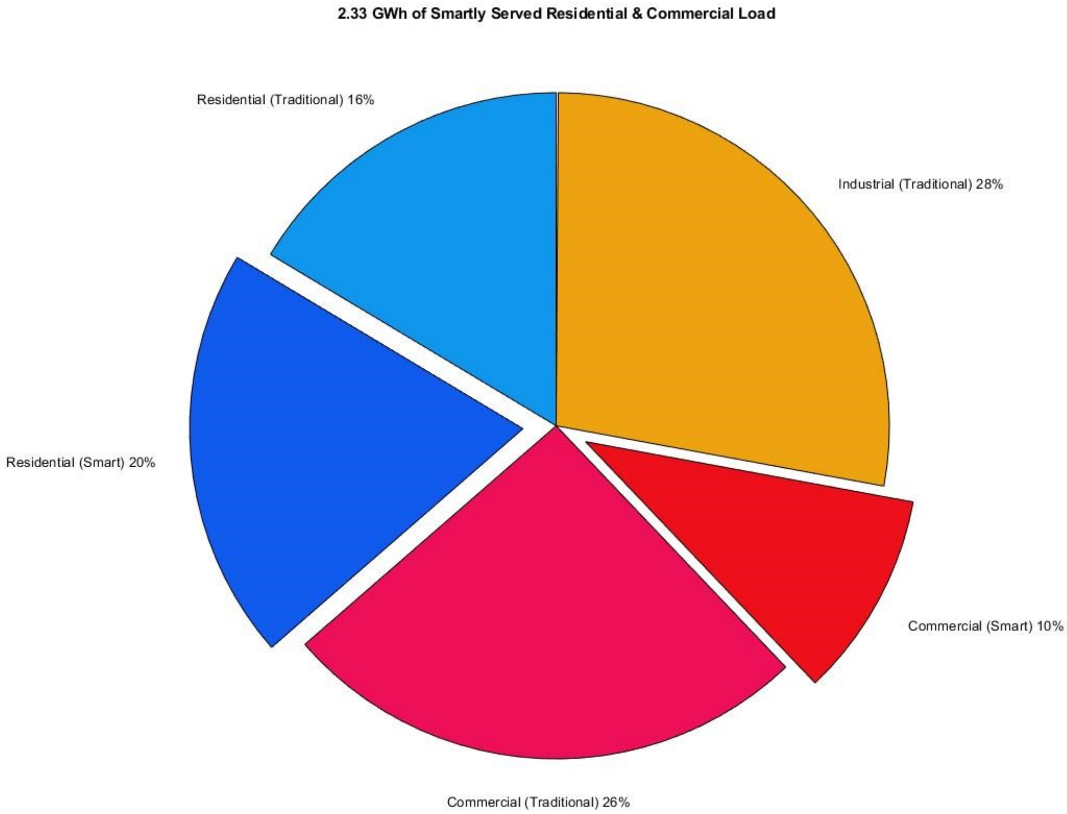


Figure 5.5: Smartly Served Residential & Commercial Loads

5.1.2.2 Simulation

In this simulation we will be following the algorithm's findings in a bottom-up pattern as it is dictated by the modelling methodology. Firstly we will be seeing prosumer's, then community's, district's and lastly grid's and peer-to-peer's markets results. We will also present findings regarding the power flows, cumulative and individual, and later on, cash flows. The parameters of the current simulation can be seen in Tab. 5.3.

Parameter	Value
Households	75000
PV parks	8
Wind parks	10
Communities	25
Districts	4
EVs	100000
EV Clusters	4
Large Producers	27
Large Consumers	15

Table 5.3: Simulation System Parameters

Prosumers

In Fig 5.6 one can see the projected electricity price for a given household as well as the load profile that is adjusted depending on the household's minimum consumption and it's members best interest following the prices. Each consecutive graph bellow the projected electricity price shows the characteristics of the inherent household load (Graph 2) as well as the installed battery (Graph 3) and PV (Graph 4) with the last being the broadcasted total load and generation profile that the prosumer agent communicates to the rest of the grid.

We can see that the addition of the battery capitalizes on the current electricity price, by charging when the prices are low and discharging when the prices are high. With that being said, the initial SoC equals the end-of-day SoC so that there are no load implications for the households from the battery's operation and a fair assessment of ESS daily operation is ensured. In this example the addition of both the Battery and the PV result in a net generation of 16.19 kWh with a total household load of 17.29 kWh. At this point it is worth noting that while some of the aforementioned generation served household's load most of it is assigned to serve the rest of the grid and is indicated by the negative values of the last graph.

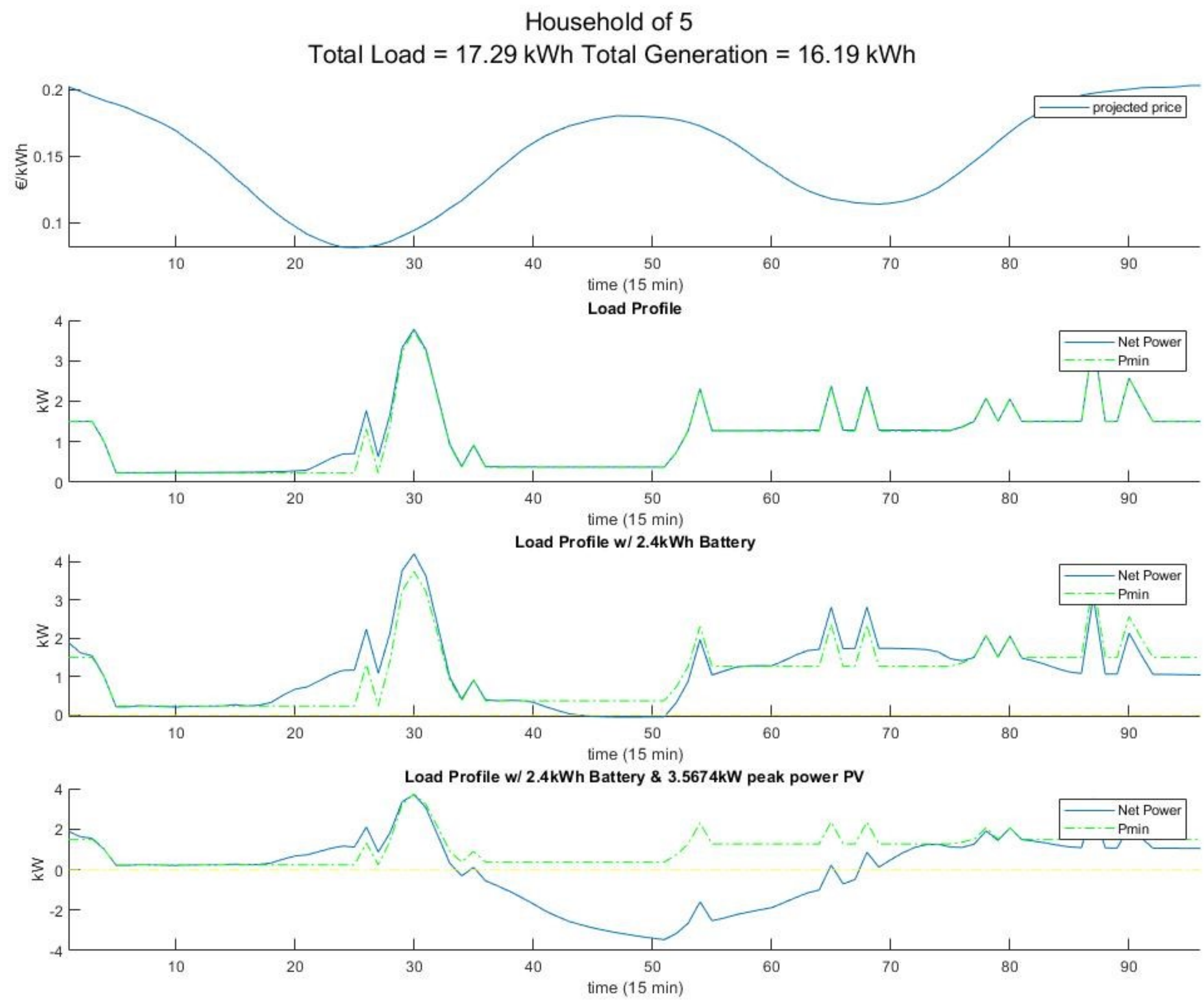


Figure 5.6: Load Profile of Household of 5

Communities

Having considered a total of 75000 households for the residential sector inside the proposed Smart-Grid and a total of 25 communities, a total of 3000 households are assigned to each community. The aggregation of a given community's households consumption and generation requirements can be seen in Fig. 5.7 (Graph 1). Due to the households individual price projections one can see a cumulative result that describes the Prosumer Agents aggressive or non-aggressive strategies that eventually alter the time-series and the amplitude of the average projected prices at a given time-frame.

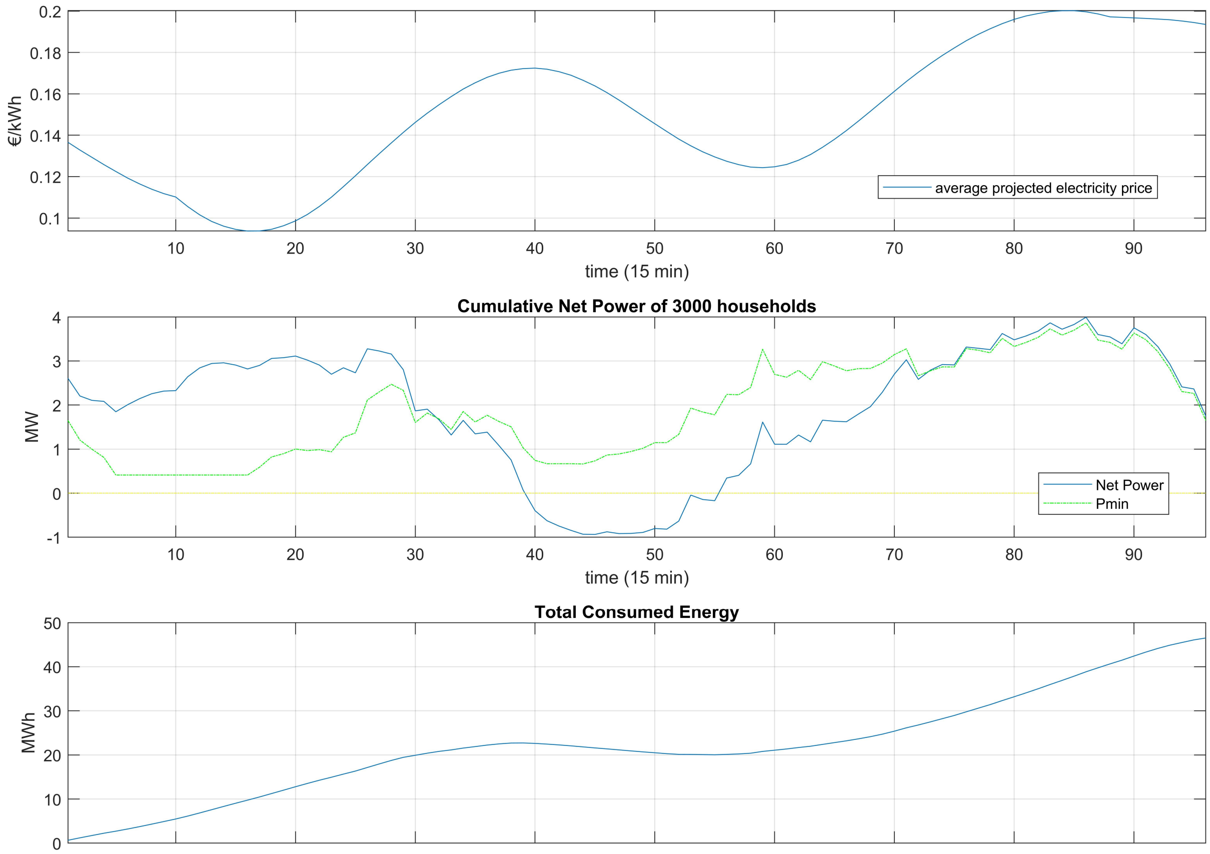


Figure 5.7: Cumulative Load & Generation Profile of a given Community

It is easy to spot the consumption and generation trends of the involved end-users, as they are starting to become a little more pronounce in the community level. More particularly, there are three areas of interest that can be seen in Fig. 5.7 (Graph 2) that are also highlighted in Fig. 5.8.

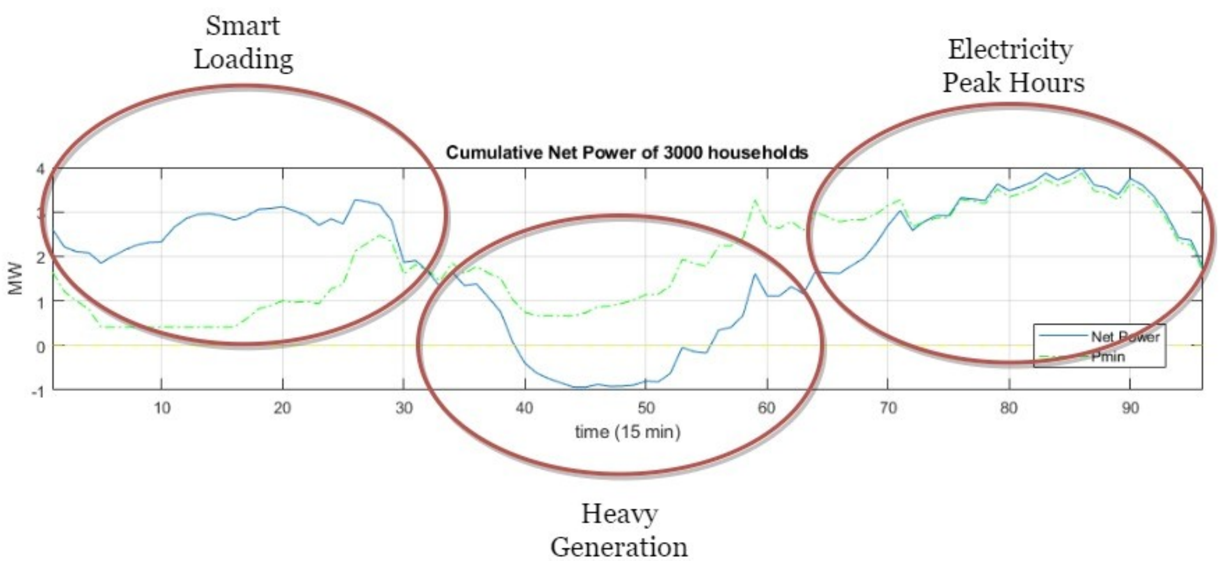


Figure 5.8: Load & Generation Trends of Smart-Grid's end-users

Those three areas are (1) the early morning hours, (2) midday, and (3) afternoon till night hours. The load that accumulates during the early morning hours is attributed to the end-users scheduling due to low electricity prices. Midday is swarmed by PV generation. The third area of interest is the increased consumption at afternoon to night hours where despite the price premium for electricity, end-users can't but satisfy their basic increased electrical needs in relation to the rest of the day.

The single round auction administered by the Community Operator similarly to every other operator of the proposed model is presented in Fig. 5.9. The clearing price is indicated by the y value of the intersection point between the producers and consumers. In Fig. 5.10 one can see the loads priced at 0.3€/kWh that indicate the non-flexible loads of the community. Those loads get prioritized at serving while priced at the producers projected price. The non-flexible loads can also be seen in the same figure which in this particular time-step help to determine the clearing price.

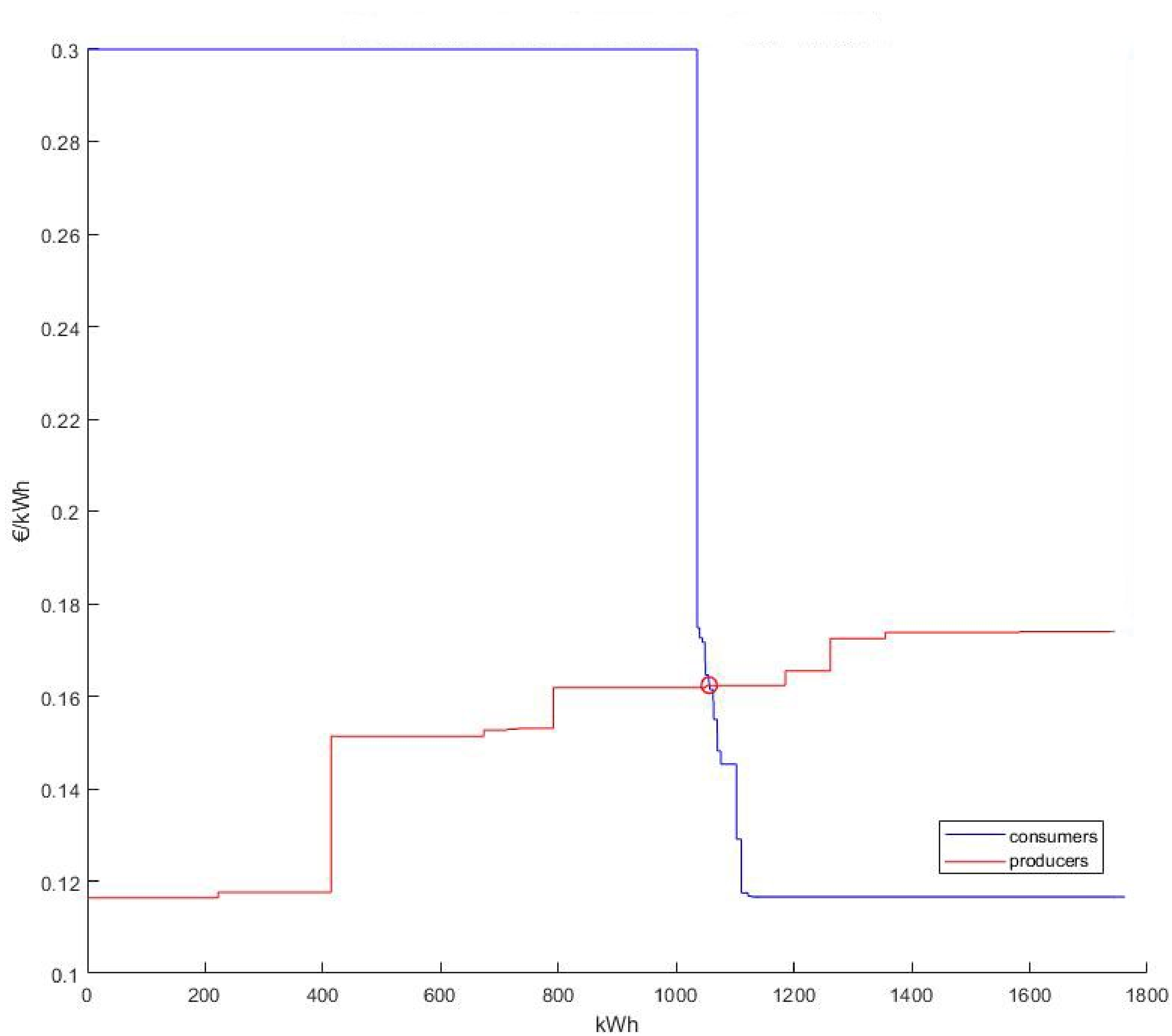


Figure 5.9: Single Round Auction administered by the Community Operator

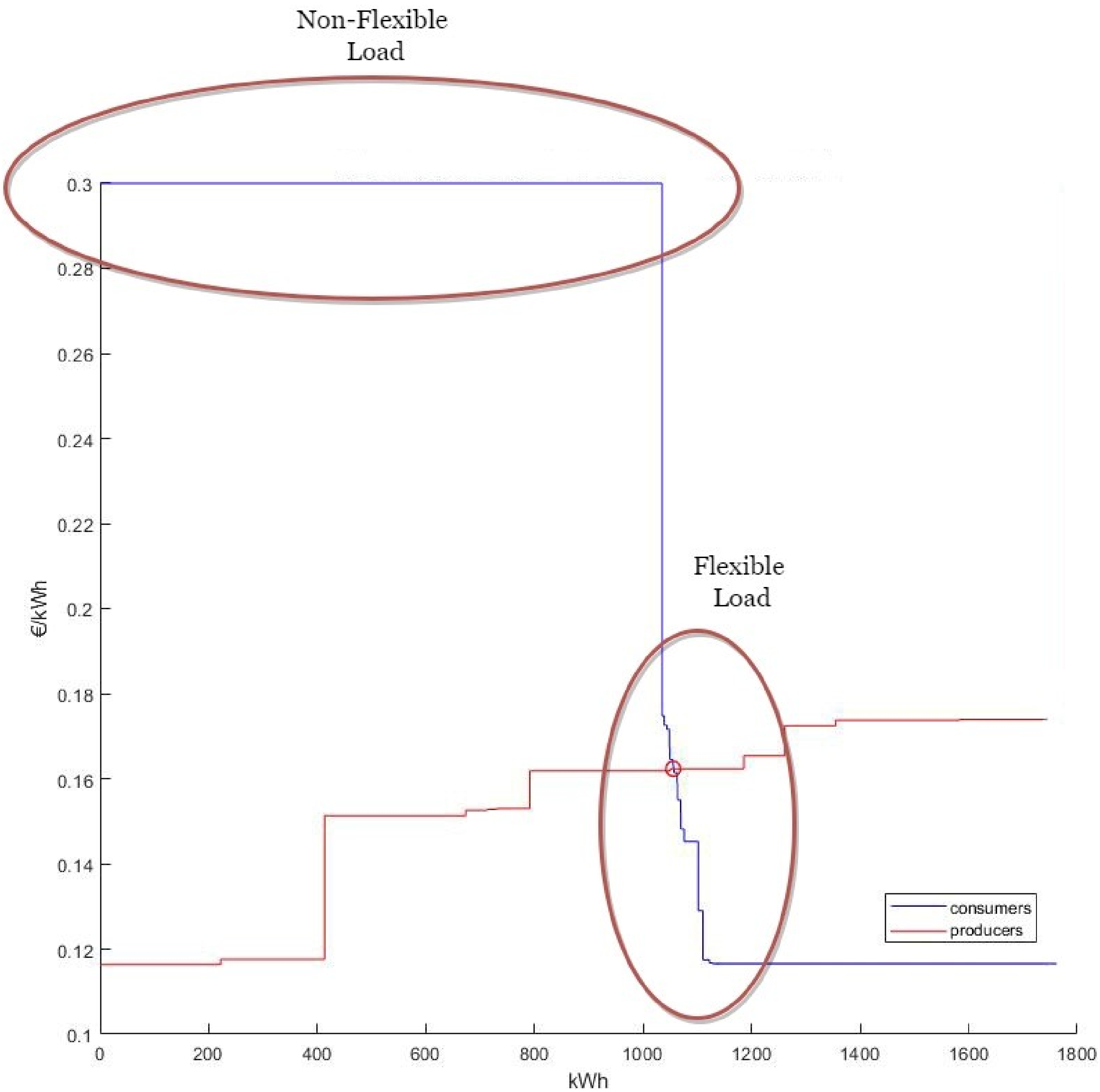


Figure 5.10: Single Round Auction highlighting flexible and non-flexible loads

Indicative cumulative load and generation of some communities as well as the amount of that that got served can be seen in Figures 5.11, 5.12, 5.13, 5.14. Through those figures one can see the time-frames resulting in clearing price through the first graph of each figure.

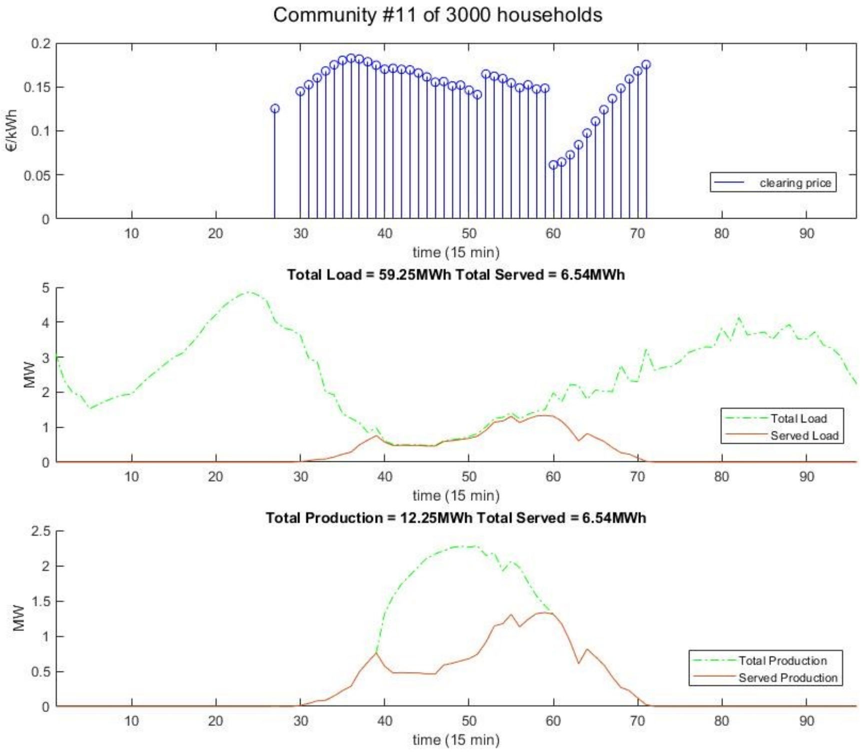


Figure 5.11: Load & Generation that got served in Community #11

The time-steps that do not have a stem value indicate markets where there was either only generation bidding or only load bidding. The intermittent green lines in graphs 2 & 3 of each figure indicate the total generation and consumption that entered the market while the orange lines indicate the total generation and consumption that got served in the community market. Through the simulation we can see that the community markets yield approximately 10% clearance to buyers and 50% clearance to sellers. At this point it is worth noting that the load entering the markets to the generation entering the markets have a ratio of roughly 5:1. Meaning that while generation gets largely cleared it is only a fraction of the consumption. That as we will see later, though, tends to even out as we move to larger-scale markets.

So as we can tell from the aforementioned figures the load that is between the green dotted line and the orange line is classified as unserved and is forwarded to the District market. The total load of 75.000 households that enters the markets at the Community Level is simulated as 1.48GWh and the load that got served at this level is 1.30GWh amounting to a total of 12% load clearance at Community Level.

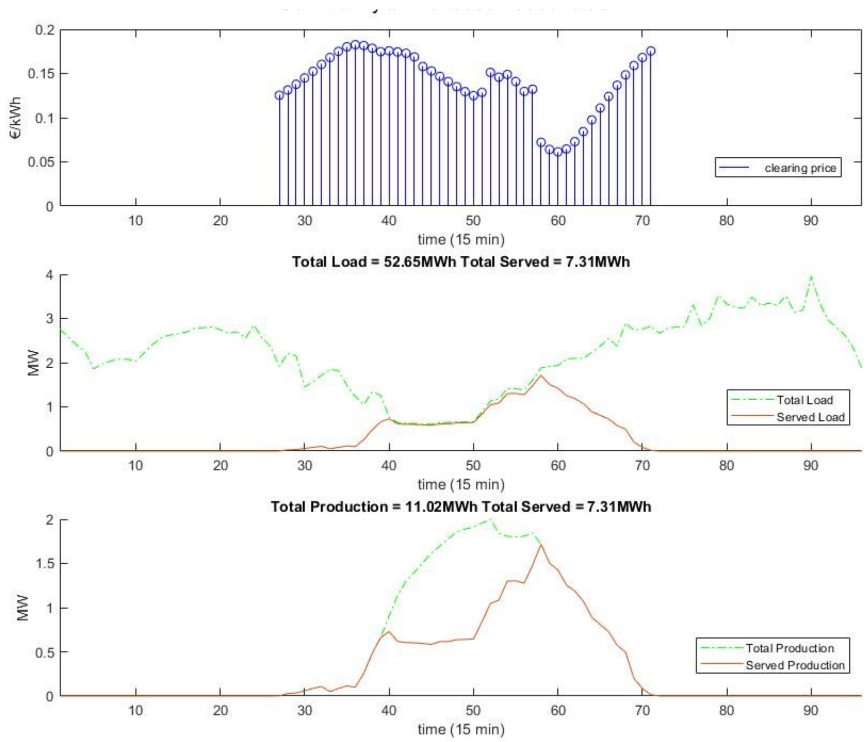


Figure 5.12: Load & Generation that got served in Community #14

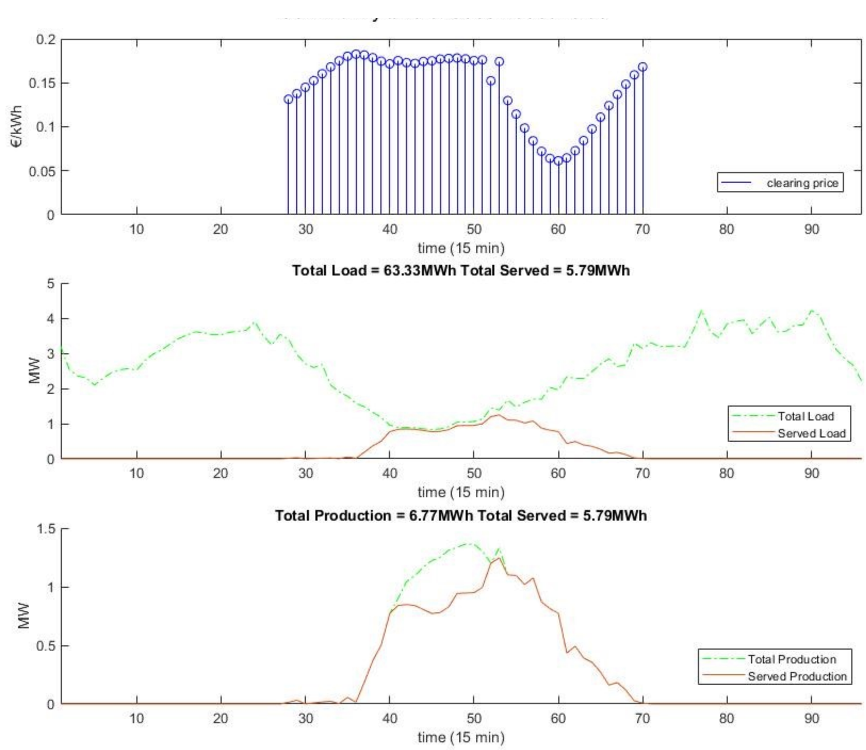


Figure 5.13: Load & Generation that got served in Community #16

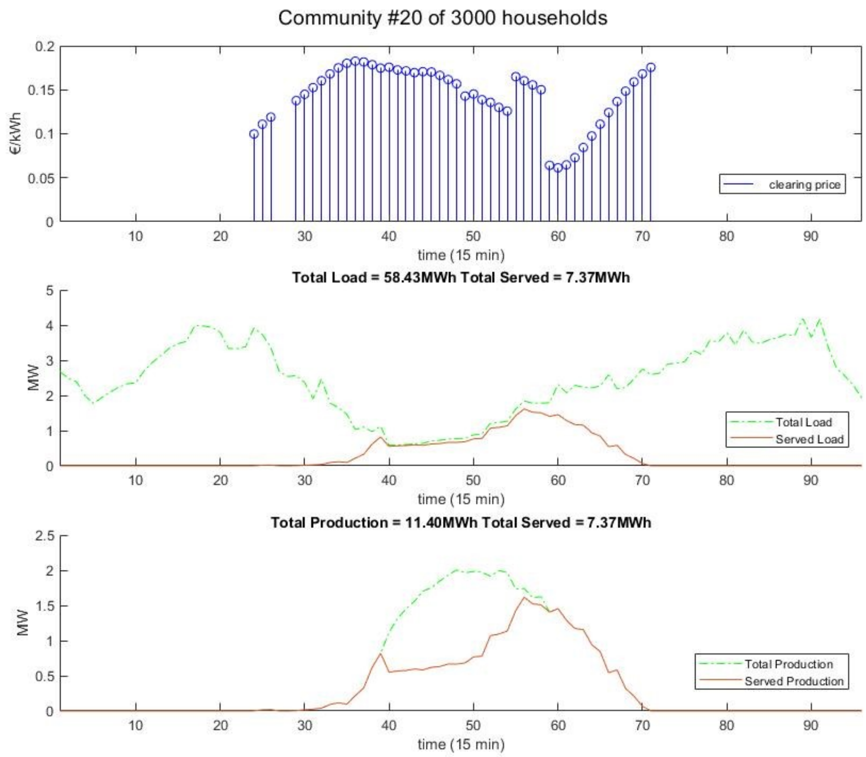


Figure 5.14: Load & Generation that got served in Community #20

Renewable Generation & EV Aggregators

We decided to share this section between the Renewable Generation and EV Aggregators as they act on the same level, that of the Districts.

We considered a total of 100000 EVs as a 1:1.25 ratio between households and EVs which even by today's standards is quite conservative. By looking at the first graph of Fig. 5.15 and 5.16 one can see the price projection differences between the two charging clusters simulating their different forecasting mechanisms. The jagged power output graph is attributed to the random fluctuations of the stations max cumulative EV battery capacity and power at a given time due to arrivals and departures from the stations. The overall energy consumed by the EV charging clusters while it's above zero, it is found to be usually in the neighbourhood of 50-150MWh.

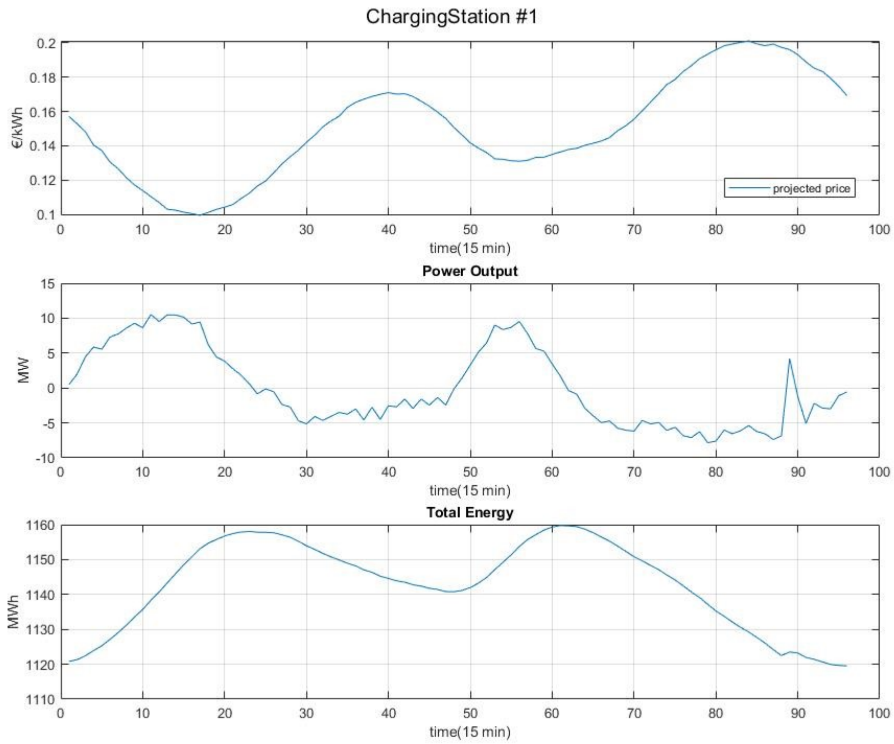


Figure 5.15: Load Profile of 25000 EV charging station

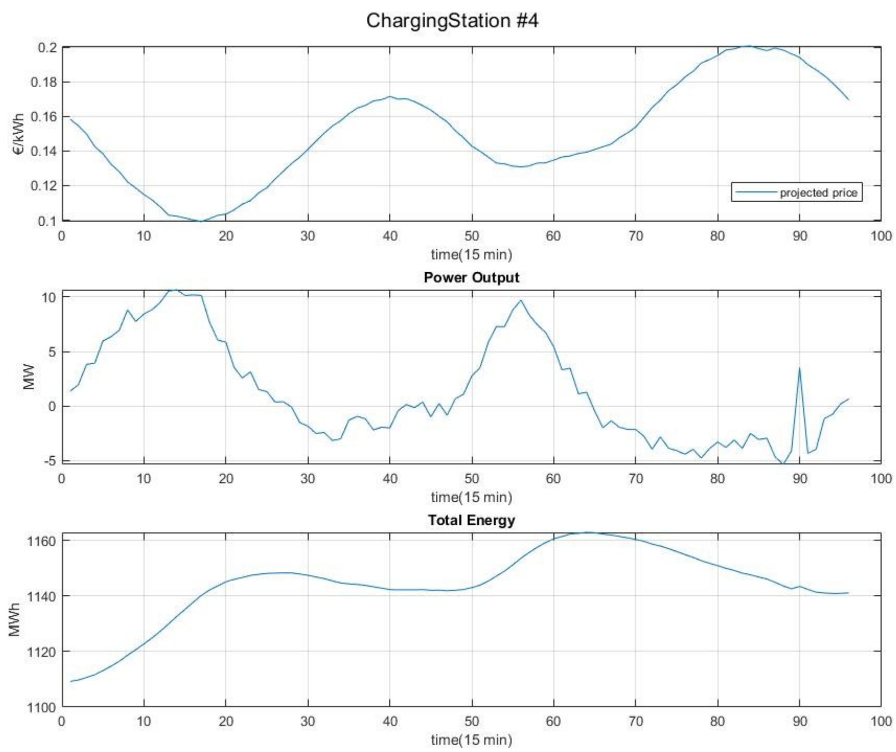


Figure 5.16: Load Profile of 25000 EV charging station

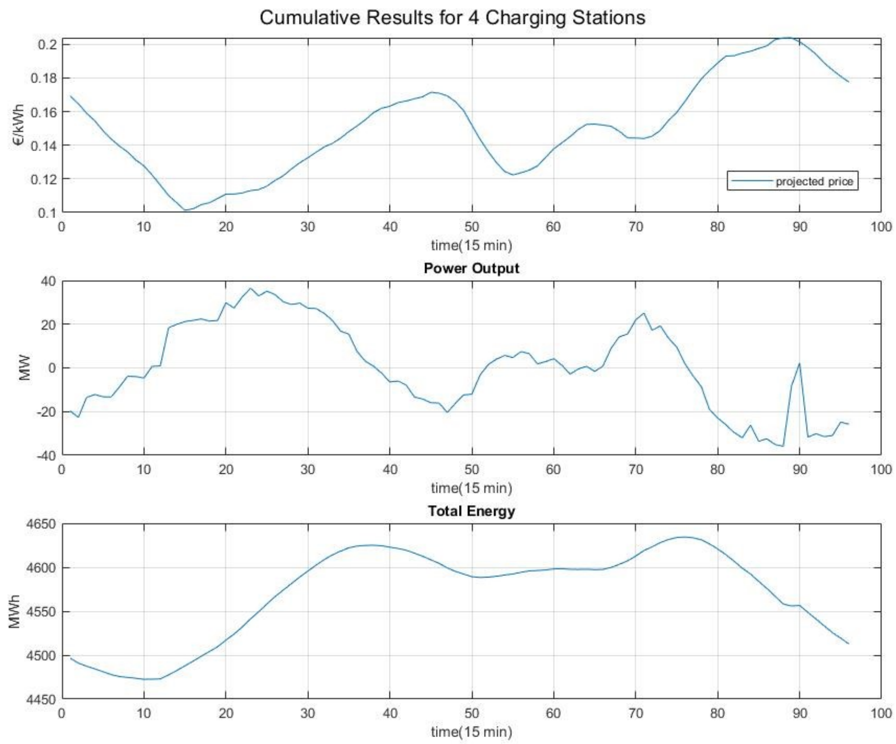


Figure 5.17: Cumulative Load Profile of all EV charging clusters

We considered the total available non-prosumer renewable generation to equal to the total renewable generation of a winter day of 2018 that accounts for roughly 900MWh of Wind generation and 135MWh of Solar generation. Having said that, for the Day-Ahead markets of the District-level and above where Renewables participate we consider only 1/3 of that generation to forecast. The rest 2/3s participate in the P2P market accounting for their uncertain nature.

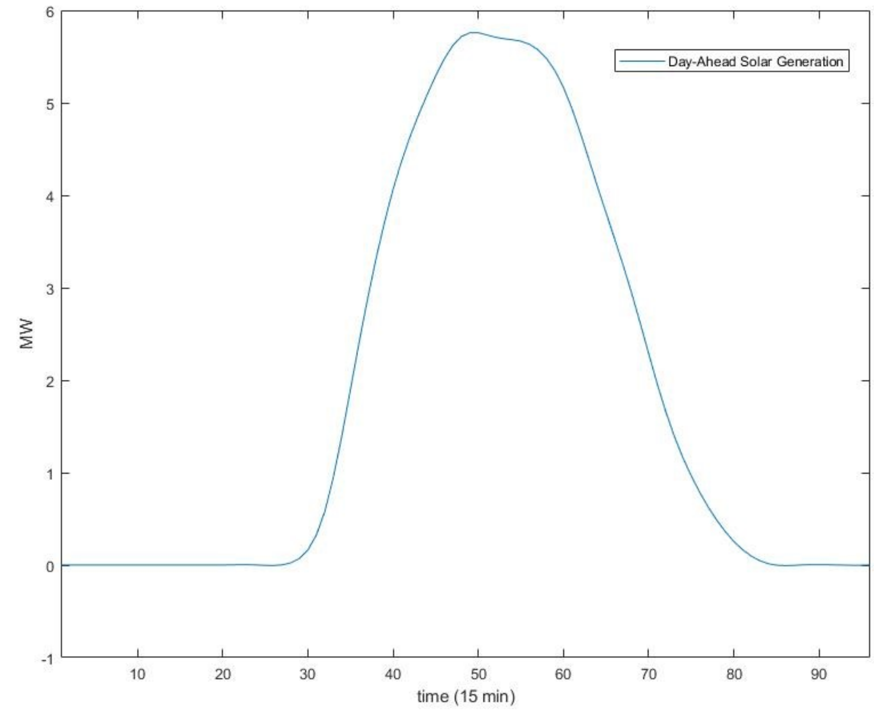


Figure 5.18: Total Day-Ahead Solar Generation Forecast

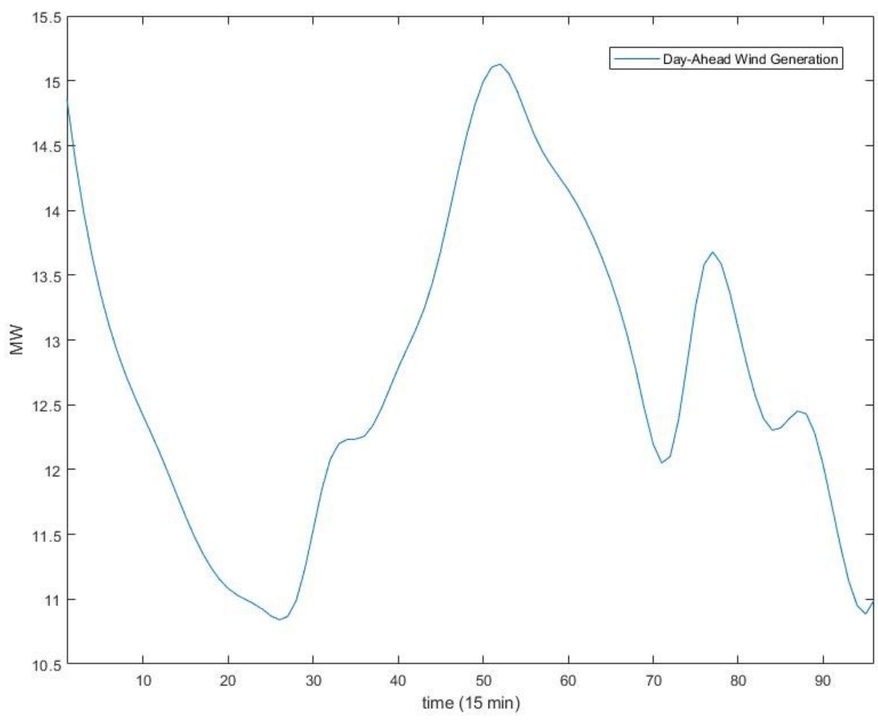


Figure 5.19: Total Day-Ahead Wind Generation Forecast

Districts

Through the Figures 5.20, 5.21, 5.22 and 5.23 one can see the load and generation that reached the District electricity markets as well as the load and generation that got served. In the District level and across all districts we see load clearance of around 25% while generation clearance reaches over 50%. This phenomenon is attributed to the greater-than-in-lower-levels participation of renewable solar and wind energy resources in the district electricity markets. In total approximately 1.65GWh of load entered the District-level electricity markets and 0.47GWh were served leaving 1.18GWh to participate in the Day-Ahead market that of the Grid-level.

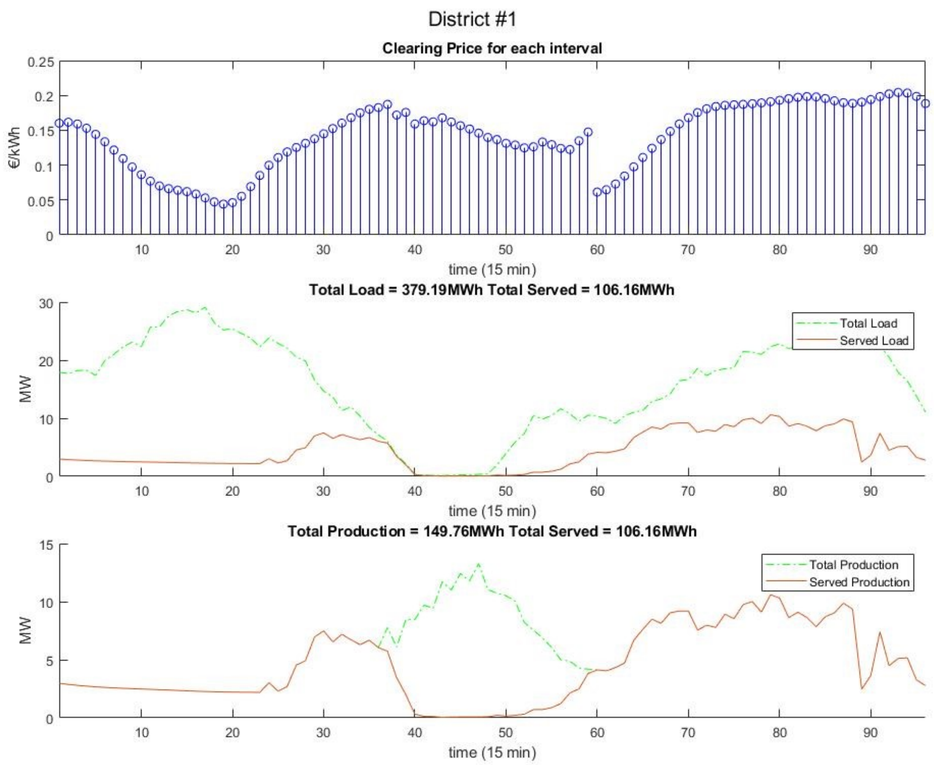


Figure 5.20: Total Day-Ahead Solar Generation

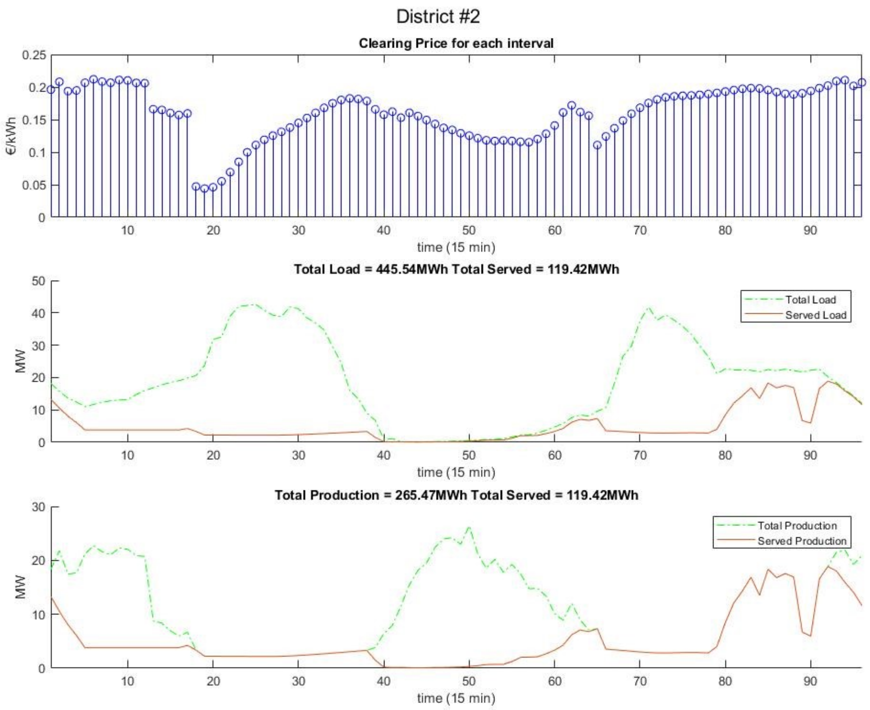


Figure 5.21: Total Day-Ahead Wind Generation

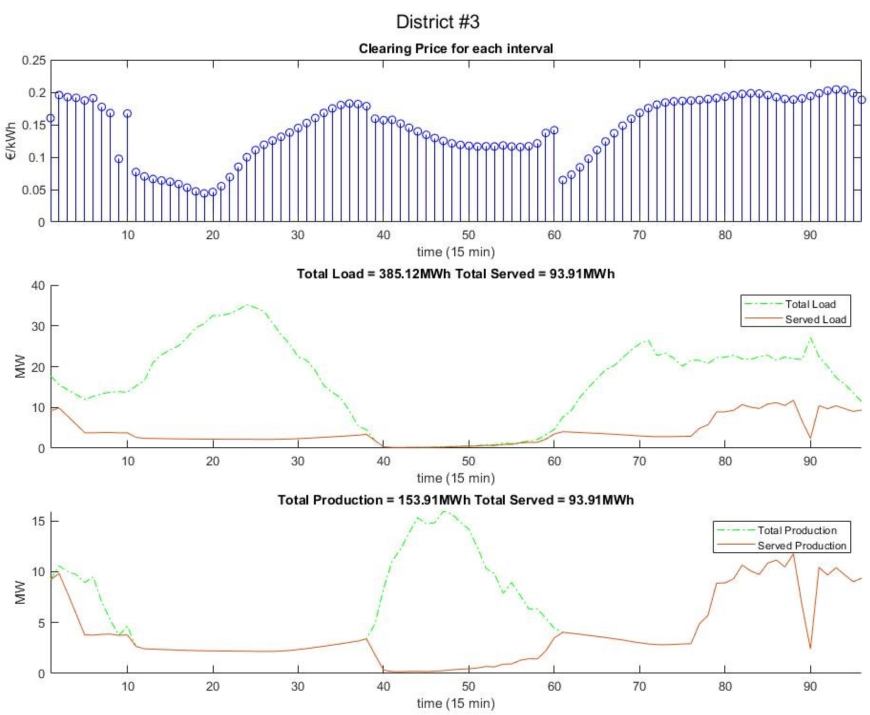


Figure 5.22: Total Day-Ahead Solar Generation

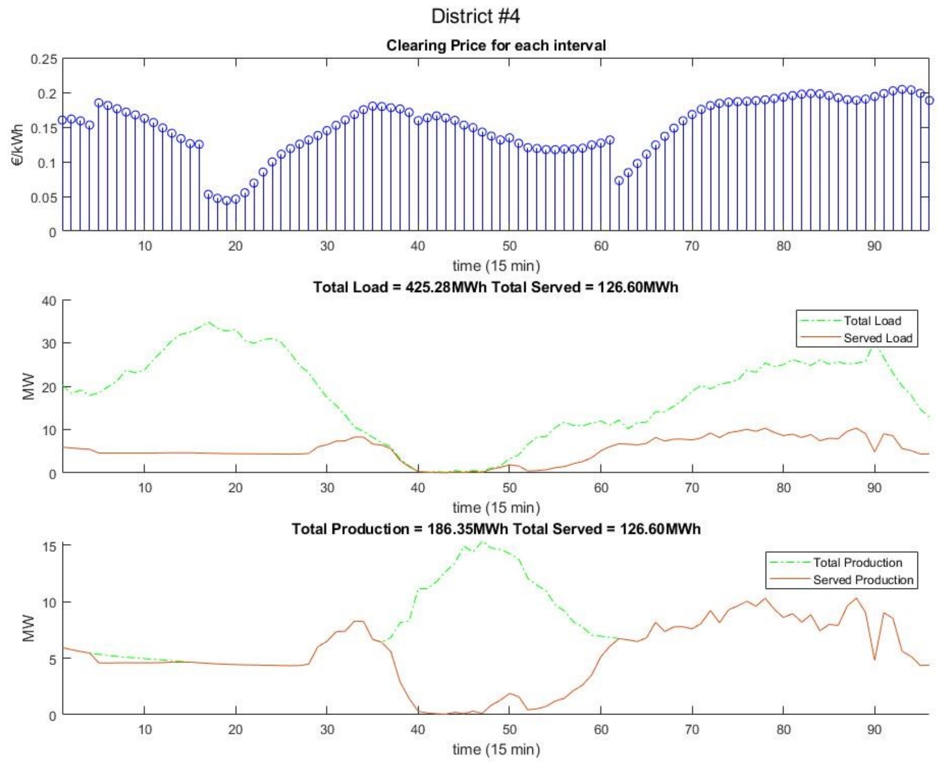


Figure 5.23: Total Day-Ahead Wind Generation

Grid

For the Grid-Level Day-Ahead market we simulate the auction between every network user that did not settle in prior levels. As Fig. 5.24 indicates, the clearing price for every time-step of the Grid's level single round auctions is being dictated by the participants projected prices. As previously mentioned, the participants tend to capitalize on electricity price fluctuations and it is shown one more time in Graph 1 by the sheer amount of load that is found in the early morning hours. Graphs 2 & 3 also indicate the total load and generation that got served. Approximately 1.27GWh out of 1.93GWh load and 1.27GWh out of 2.6GWh generation where settled.

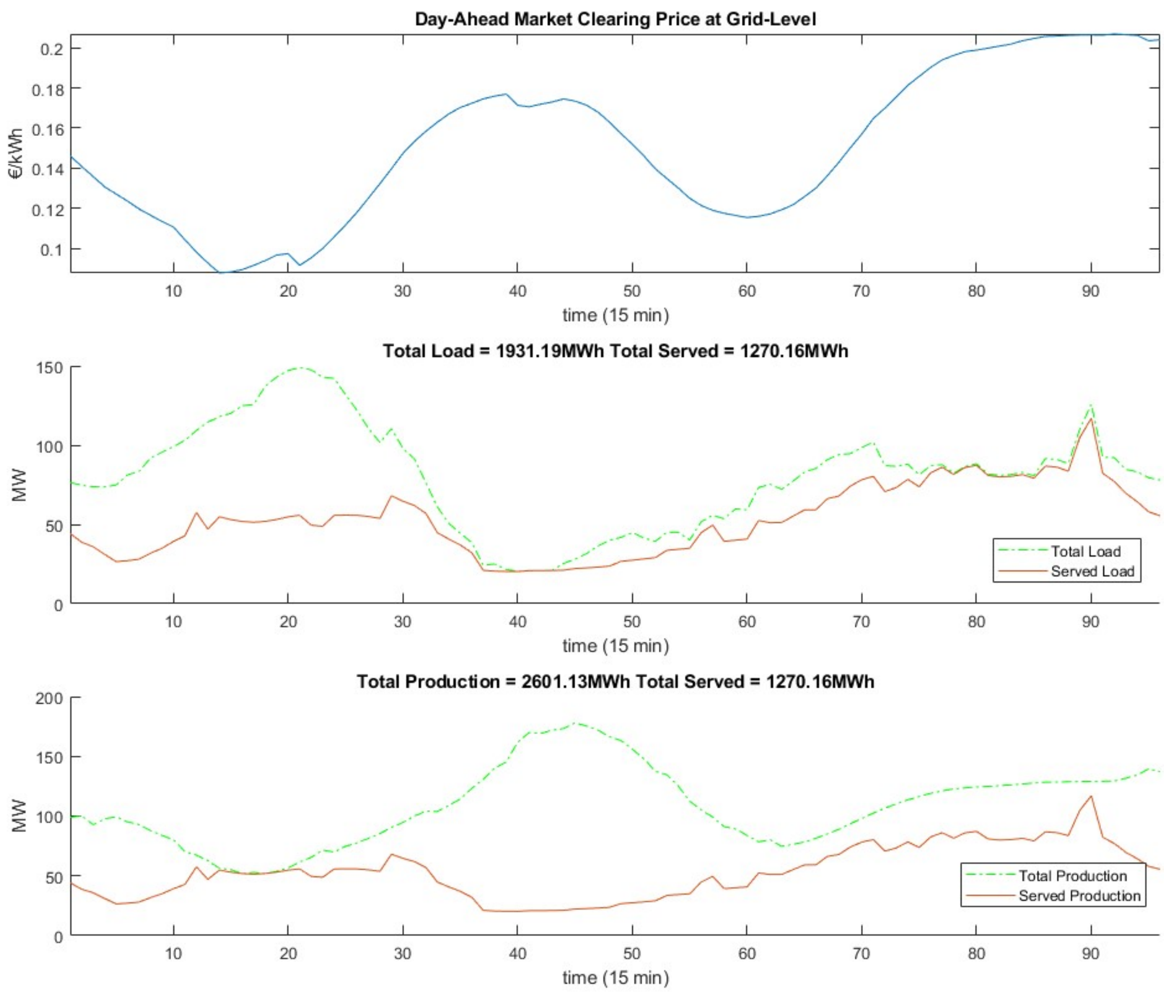


Figure 5.24: Day-Ahead Grid-Level market

Peer-to-Peer After the conclusion of the Smart-Grid's Day-Ahead market and the start of the next day, the unsatisfied end-users enter the Intra-Day market firstly through the P2P market and alternatively, in case their bids didn't match there, through the traditional grid's Real-Time market. In Fig. 5.25 one can see total grid clearing prices as they resulted from the Grid-Level auction as well as the total load and generation that are bound to participate to the peer-to-peer market. We can see that most of the load that infested the peak afternoon hours has been dissipated and transferred to the early morning hours where most of the unserved load now lies.

While there is still some generation willing to trade at the peer-to-peer market for the early morning hours, we notice that most of the generation has pilled in the midday due to vast amounts of solar generation that are generated in off-peak hours.

In Fig.5.26, and after the repricing of the peer-to-peer market's participant bids, we can see the clearance at peer-to-peer Grid-Level. As we can conclude from Graph 1 the clearing price is influenced by the fuzzy-logic pricing to higher prices in early morning hours and lower the prices of afternoon hours.

The total clearance can be seen in Graphs 2 & 3 with the total load being almost 50% served while the total generation being 20% served. The unserved generation and load are then broadcasted to the traditional system for Real-Time clearance.

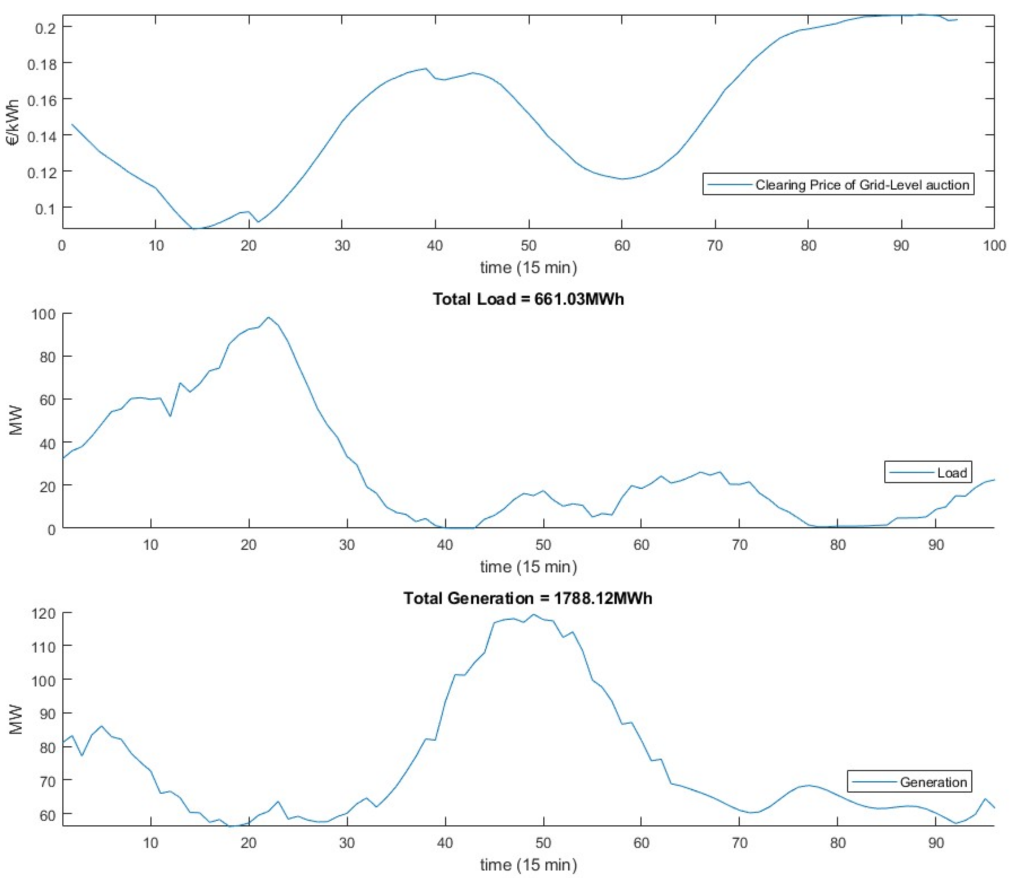


Figure 5.25: Load and Generation that participate in the Peer-to-Peer Market

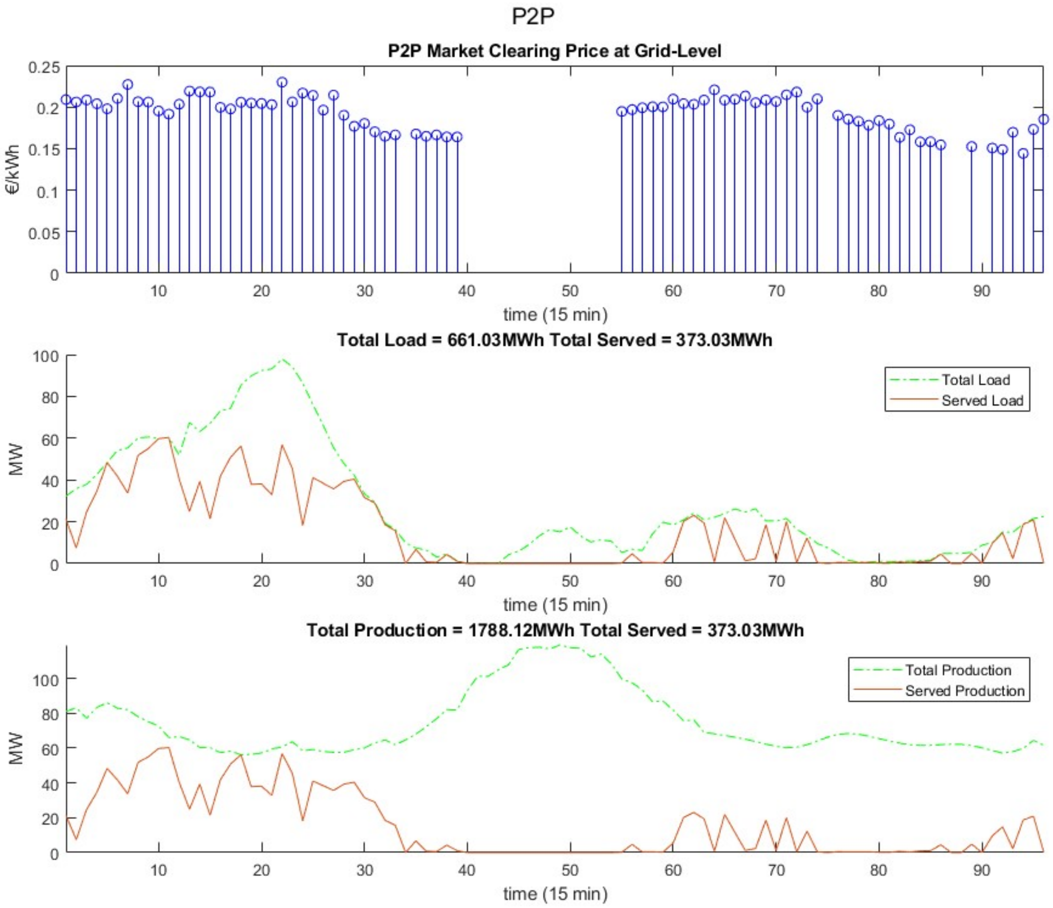


Figure 5.26: Intra-Day P2P Grid-Level market

5.1.3 Comparison between the Traditional & Proposed Markets

We consider two specific configurations for the Electrical Power System of Crete. (1) A simplified traditional Power System that considers Day-Ahead and Intra-Day markets only at Grid level with Renewables contributing as priority generation and (2) the proposed model of the Power System that considers 30% of the total load to be assigned to the Smart-Grid's residential and commercial sectors and 70% to the rest of the Grid.

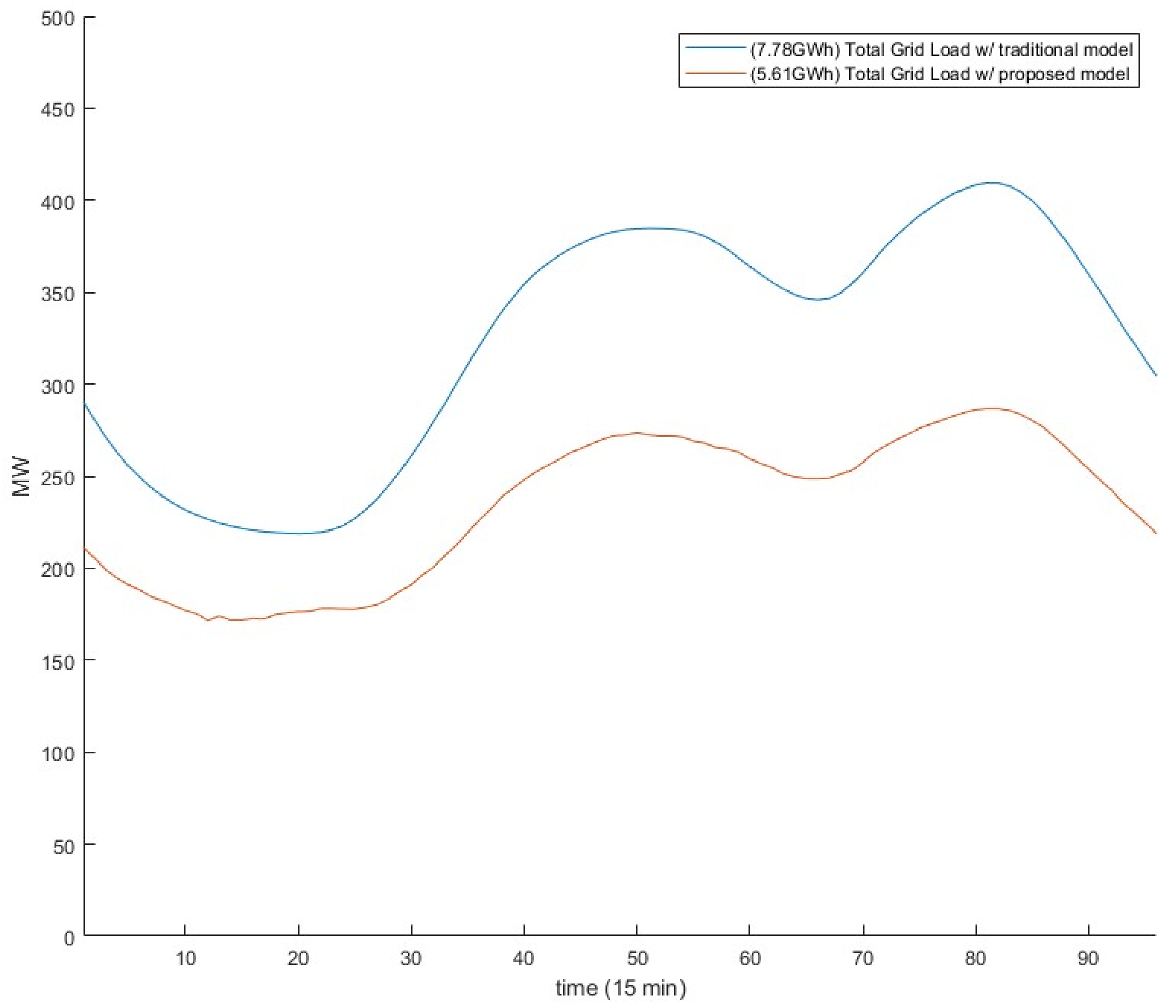


Figure 5.27: Total Load Comparison between the traditional Power System and the proposed model

In Fig. 5.27 one can see the difference in total load that reaches the grid between the traditional power system and the proposed model. It is apparent that through the multi-level clearances the load that started from the residential and commercial sides in the proposed model shrinks as it reaches the grid. In particular, the total load server at the upper level of the grid is decreased by more than 2GWh in the case of the proposed model.

This load was served in lower levels through utilizing mainly distribution as well as interconnected transmission lines between communities and districts. Due to the fact that the proposed model's market participants capitalize on projected prices, we notice a load-shift from the peak hours to the less congested hours for the load that reached the grid. This phenomenon can be observed more accurately in Fig. 5.28.

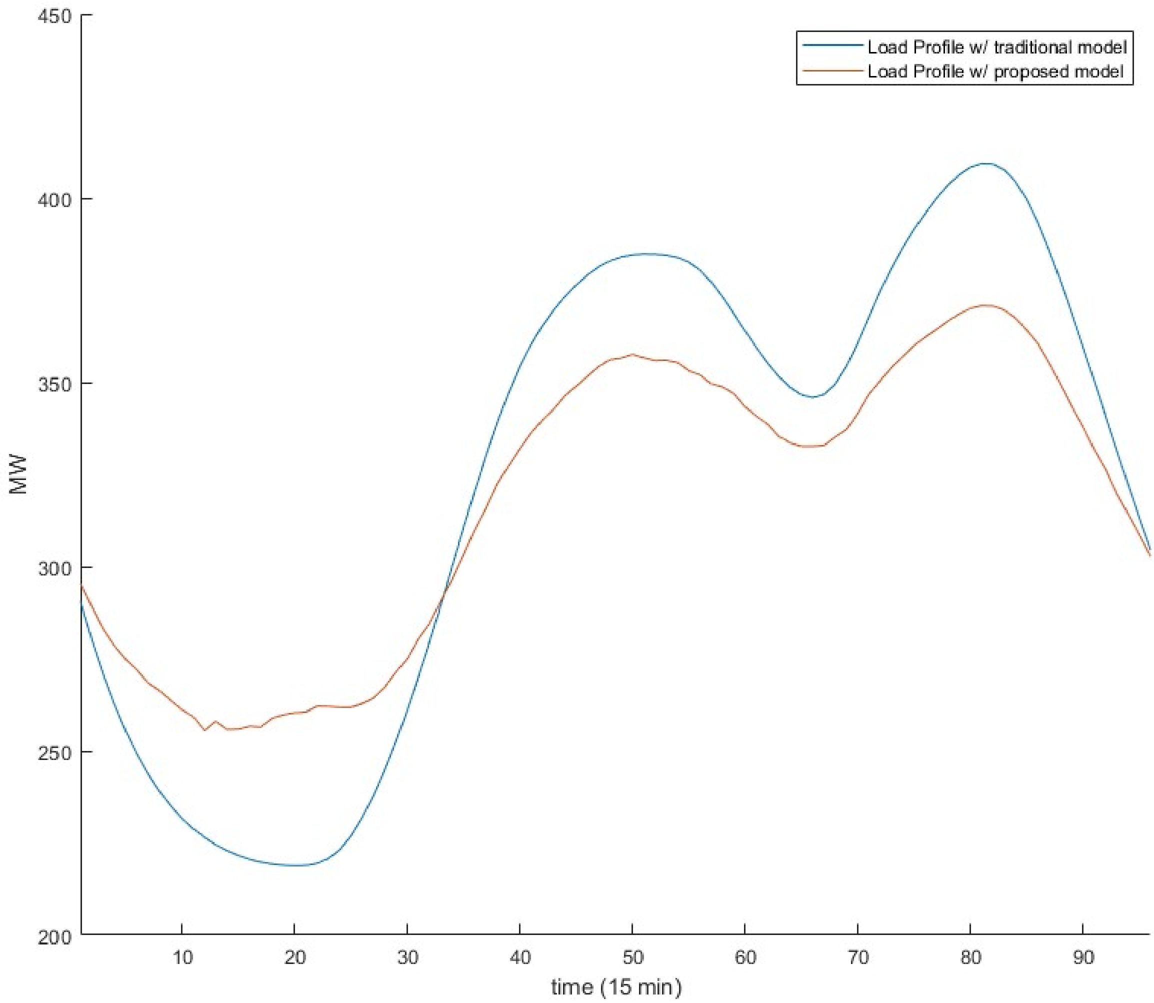


Figure 5.28: Load Profile differences between the traditional Power System and the proposed model

In every level of the proposed model we see the participation of both load and generation, something that isn't possible through the traditional power system. Through this mechanism end-users get the opportunity to trade their little or more important amounts of electricity so that no generation goes to waste. This is shown at Fig. 5.29 as load and generation trade with each other through multiple consecutive markets simulating an "iterative process".

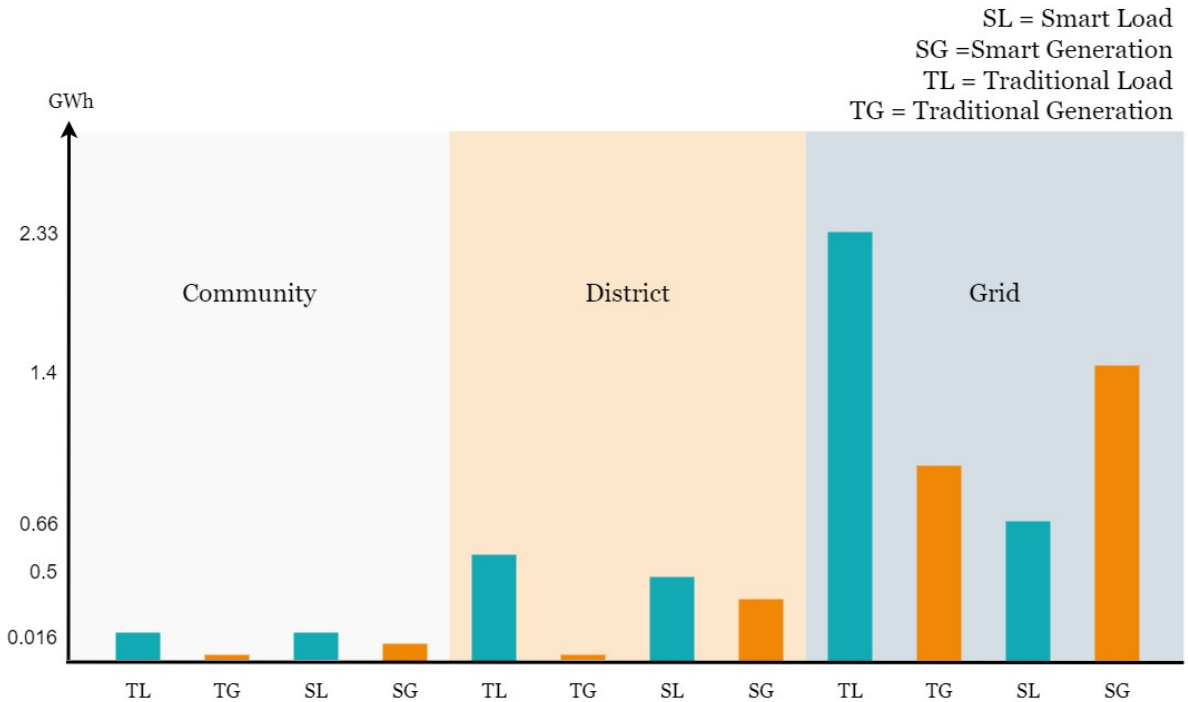


Figure 5.29: Load and Generation Volumes of every level for the traditional Power System and the proposed model

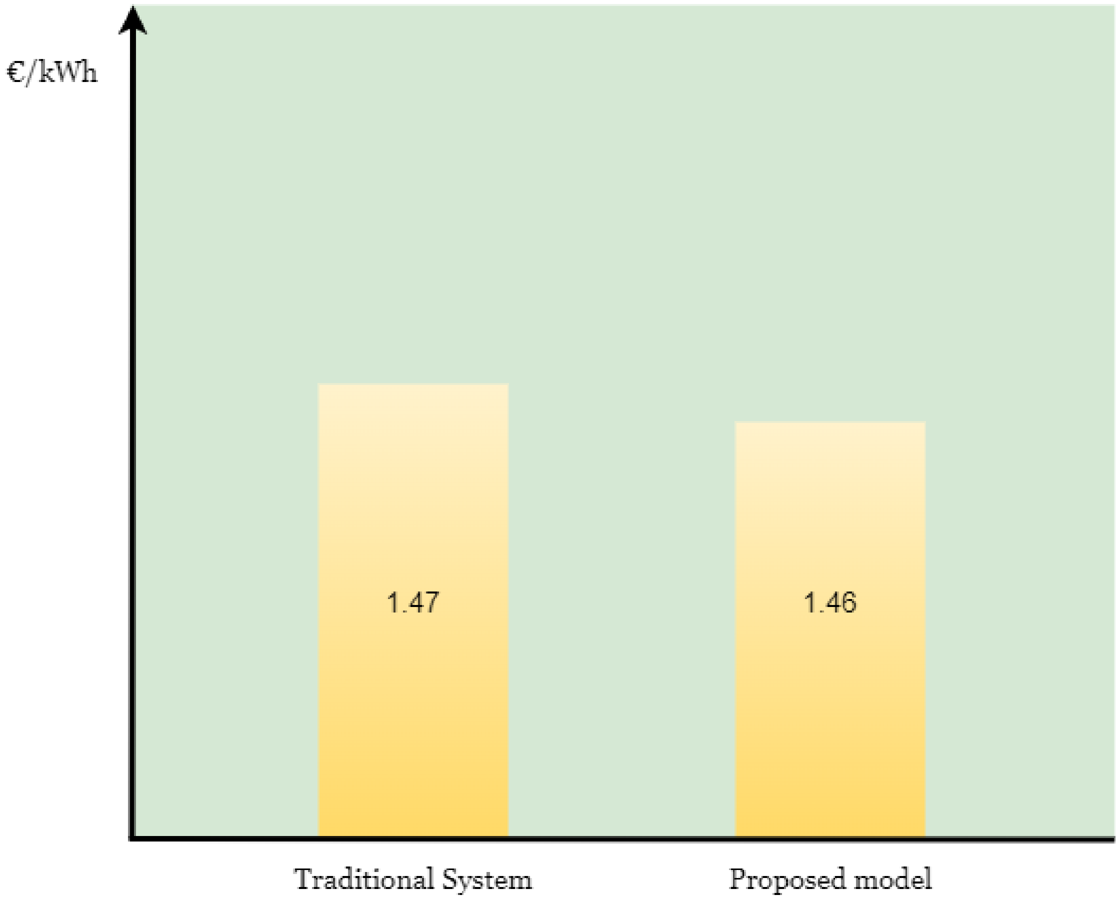


Figure 5.30: Average price of 1kWh differences between the traditional Power System and the proposed model

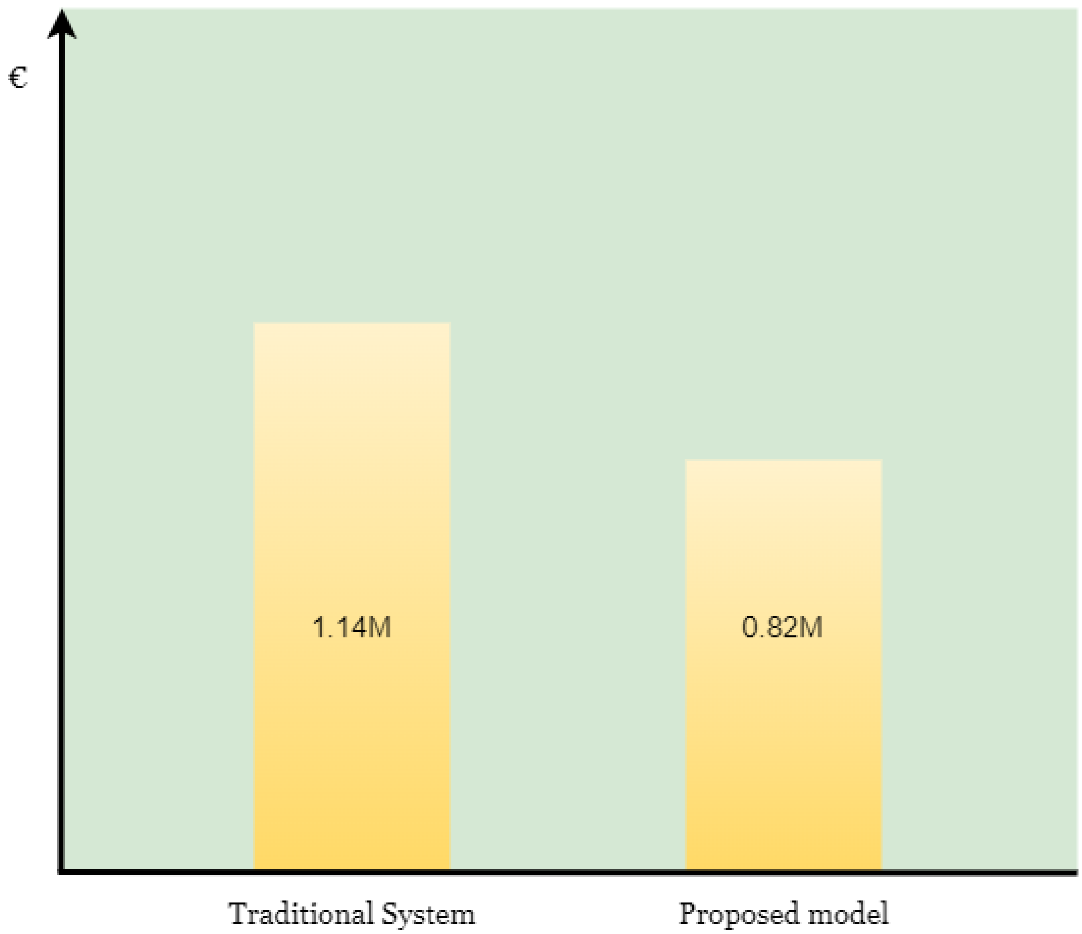


Figure 5.31: Total electricity cost differences between the traditional Power System and the proposed model

Chapter 6

Conclusion

We should start off by saying that the proposed model may provide limited merit in the sense that each system has its own implementation drawbacks, beyond the scope of this work, that may or may not play a significant role on whether such a model is actually feasible in the real world. With that being said, we reckon that the macroscopic analysis of the particular Smart-Grid-based model in combination with its comparison to a traditional system yields insight on the potential of distributed generation and it's applications while highlighting the shortcomings that traditional Electrical Power Systems face.

Our approach while tackling inefficiencies of the traditional electricity markets regarding communication of data, management of load and integration of distributed generation also assists the Grid by transferring load from stressed transmission lines and generators to the consumption-side.

Due to the nature and scale of this work we believe there are a few areas that could be further researched to yield more accurate representations and more sophisticated results. Those are data forecasting, load & generation power flow management (load-gen matching algorithms) as well as load-serving coordinated strategies between participants.

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