Abstract

Electrical grids are extremely large, highly complex and dynamic systems. The depletion of natural resources used for power generation has led to the facelift of the traditional grid system to a more efficient and smarter grid system. Smart grids aim at better energy utilization, right from generation to consumption. The electrical grid is similar to the computational grids in many ways where the issue of resource utilization has been researched upon. In a computational grid the resources are usually CPU time or storage space and the producers and consumers of the resource are the computers themselves. In an electrical grid, the resource is the electricity, a house (a neighborhood, a city, a country) can be considered as the network, the producers are generation stations & distributed sources and the consumers are the various appliances at home. In the present scenario all the appliances connected to the grid have unrestricted access to electricity, meaning that all devices can consume electricity at will. This setup on a global scale is very expensive to maintain as a high reserve capacity is required to meet the dynamic and unanticipated demand which is inefficient. In this thesis, a market based approach is proposed for efficient allocation of limited resources. The introduction of a consumption limit in the system leads to a more optimal and efficient grid which helps in load forecasting, reduction in the amount of spinning reserves and dynamic pricing. By using a combination of producer pricing policy (perfect competition and monopoly) and agent bidding strategies (prioritized bidding and budgets limits) we are able to achieve a suitable level of resource utilization and device utilization pertaining to the needs of the end consumer. By achieving a satisfactory level of operation at a household level when a consumption limit is introduced, we can achieve better resource management and stability at the higher system levels.
Agent Based Economic Framework For Resource Distribution in Household Smart Grid

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by

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born in Coimbatore, India
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I dedicate this work to my parents and to my wonderful sisters for their continued love and support
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The present electricity generation and distribution system is based on an old model established in the 1950’s [10]. The technological advancements of the other fields such as computers and telecommunications have left the electrical grid far behind, which is still relatively in the bronze ages using primitive technology. In recent times, the advancements in grid technology have begun to grow and are waiting to make a major impact on the world as we know it. The major energy source used for power generation is still fossil fuel. The world estimation for power generation from sources other than oil, natural gas, nuclear and coal would be only 8.1% by 2020 [8]. For a sustainable future, the focus should not only be in sustainable power generation but also on efficient power distribution and use at the consumer end.

A generator when running at rated load conditions is at its maximum efficiency. During the day the generators are under heavy load conditions and are usually over loaded thus operate at reduced efficiencies. It is also not advisable to invest in more machines to handle a few hours of peak power every day. For instance, in Spain about 4000 MW are required to attend 300 hours of peak consumption per year [25]. In recent years much time and effort has been spent not only on renewable energy but also on effective load management schemes to achieve load levelling leading to reduced peak consumption. Although appliances are designed to operate with high efficiency, peak demands still remain at large. With the advent of smart grid a new dimension to power generation, distribution and consumption is in play.

1.1 Power grid operation

Power grid operation consists of four primary functions namely,

1. Power generation
2. Transmission
3. Distribution
4. Control

Power is generated from various sources such as hydro, coal, tidal, wind etc., usually in remote areas due to factors like resource availability, land availability, safety and environmental issues. The power generated at a power station is then pumped
to higher voltage of 110KV and above for transmission as high voltage transmission has reduced losses. The transmission system has various configurations and the most popular configuration is 3 phase AC for long range transmission and HVDC for ultra-long range for distances greater than 600 Km. The transmission system connects the generating station to sub stations in different parts of the country. The sub stations steps down to power to operational levels of 11KV for industrial and 230V for domestic appliances in most cases. From the substation onwards, the system becomes a distribution system, distributing power to the individual subscribers. It is necessary to monitor and control the grid for reliable operation. Every time a load is added or removed from the grid, it leads to a change in voltage level, if voltage change goes beyond a certain level, they can be harmful to the devices. Thus a stable value of voltage has to be maintained at all times, between 220 - 230V for safe operation of a device. Thus control of power becomes an important aspect of power system operation.

The power industry has a bit of a monopolised status, since a utility company may be completely self-sufficient by attending to power generation, transmission, distribution & control and it does not make sense to invest in equipment and installations to compete with other utilities in the same region as the cost involved is very high. It is better to cooperate with neighbouring grid operators to buy/sell power which benefits both parties and increases their reliability. Since reliability is a major issue in the power grid operation, each power station has certain amount of reserves that come into play in case of a fault or failure. There are basically two types of reserves namely spinning and non-spinning reserves. Spinning reserve can be defined as "the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power" [50] or "generators online, synchronized to the grid, that can increase output immediately in response to a major outage and can reach full capacity within 10 minutes" [24]. Non-spinning reserves are offline reserves that take more time (30-60mins) to be able to supply the grid. The capacity factor for a power plant is the defined as the ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period [31]. [50] explains more about spinning reserves and how they are used in frequency control. By reducing the peak or maximum demand, the reserve capacity of a power station can be reduced and the associated costs will eventually reduce. The present grid is struggling to keep up with the growing demand for power. An extract from [19], "If the grid were just 5% more efficient, the energy savings would equate to permanently eliminating the fuel and greenhouse gas emissions from 53 million cars". A blackout causes a major inconvenience to the customers and adversely affects the economy by bringing the industries to halt, hospitals and research facilities to a critical condition, leaving people stuck in elevators and stranded elsewhere. The above highlight the need for more efficient, reliable, responsive and secure grid.

1.2 Smart Grid Vs Traditional Grid

Smart grid is a very big entity, which encapsulates many technologies into one. The conceptual model of smart grid according to the National Institute of Standards and
1.2. SMART GRID VS TRADITIONAL GRID

Technology (NIST) consists of seven domains namely, Bulk Generation, Transmission, Distribution, Customers, Operations, Markets and Service Providers [12]. From the pictorial illustration in figure 1.1, it is clear that information flow is vital for the operation of Smart Grid, connecting the various domains and forming the lifeline of the grid. It is this 2-way communication that enables the smart grid to be "SMART" and dynamic compared to the traditional grid illustrated in figure 1.2. The traditional electricity grid had information flow in only one direction from generation to the customer.

The IEEE describes the smart grid as a system of systems and each of the domains of the smart grid described by NIST is a large entity by itself. A brief description of all the domains are provided below

1. **Bulk Generation**: Bulk generation referrers to the generation of electricity from a variety of sources both renewable and non-renewable in bulk quantities used to supply the customers.

2. **Transmission**: The transmission domain handles the transmission of the electricity from distributed bulk generation sources to substations. It takes care of the operational stability of the grid by balancing the supply and demand.

3. **Distribution**: The distribution domain is a bridge between the transmission and customer domains. The distribution network connects all the customers to the grid using the smart meter which forms the information network of the grid. The distribution network connects the distributed generation points of the customers to the grids, thus enabling energy flow from and to the customers from the grid.

4. **Customers**: Customers are the ultimate stakeholders of the grid. The customer has the capability for communication to the utility company through Energy Services Interface (ESI) which is a secure interface for interactions. This can be used to provide advanced Energy Management Systems (EMS) at the customer end.

5. **Service Provider**: The service provider domain takes care of the services to support the business process of energy generation, distribution and customers. This
CHAPTER 1. INTRODUCTION

6. **Operations**: The operations domain attends to the smooth operation of the grid. Some of the functions of this domain are to monitor, analyse and optimize the grid operations, fault management and grid statistics.

7. **Markets**: The market domain is the financial end of the smart grid. It is responsible for market management and operations, retailing, trading, ancillary operations etc.

### 1.3 Demand Response (DR) and its impact

Demand response involves reducing the use of electricity (demand) rather than increasing generation (supply) to meet the needs of the electric power grid [44]. The reduction in demand of common commodities usually leads to reduced price, and in response to the high price, demand side management may be a good price mitigation mechanism for most commodities [49]. The demand of electricity is very inelastic, es-
1.4 Demand Side Management (DSM)

Demand-side management is the planning, implementation and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility’s load shape, i.e., changes in the time pattern and magnitude of a utility’s load. Utility programs falling under the umbrella of demand-side management include load management, new uses, strategic conservation, electrification, customer generation and adjustments in market share [22]. One of the main objectives of DSM is to achieve an optimal flat load curve, and according to [12] the various strategies for load shaping as illustrated in figure 1.3 are

- **Peak Clipping** - the reduction of utility load primarily during periods of peak demands.

- **Valley-Filling** - the improvement of system load factor by building load in off-peak periods.

- **Load Shifting** - the reduction of utility loads during periods of peak demand, while at the same time building load in off-peak periods. Load shifting typically does not substantially alter total electricity sales.

- **Conservation** - the reduction of utility loads, more or less equally, during all or most hours of the day.

- **Load Building** - the increase of utility loads, more or less equally, during all or most hours of the day.

- **Flexible Utility Load Shape** - refers to programs that set up utility options to alter customer energy consumption on an as-needed basis, as in interruptible/curtailable agreements.
In general, demand-side management embraces the following critical aspects of energy planning [22]:

- Demand side management will influence customer use; thus any program intended to influence the customer’s use of energy is considered demand side management.

- Demand side management must achieve selected objectives. To constitute a desired load shape change, the program must further the achievement of selected objectives (i.e., it must result in reductions in average rates, improvements in customer satisfaction, achievement of reliability targets, etc.).

- Demand side management will be evaluated against non demand side management alternatives. The concept also requires the selected demand side management programs advance these objectives to at least as great an extent as non demand side management alternatives, such as generating units, purchased power or supply side storage devices. In other words, it requires that demand-side management alternatives be compared to supply side alternatives. It is at this stage of evaluation that demand side management becomes part of the integrated resource planning process.

- Demand side management identifies how customers will respond. Demand side management is pragmatically oriented. Normative programs ("we ought to do this") do not bring about the desired change; positive efforts ("if we do this; that will happen") are required. Thus, demand side management encompasses a process that identifies how customers will respond, not how they should respond.

- Demand side management value is influenced by load shape. Finally, this definition of demand side management focuses upon the load shape. This implies an evalua-
1.5 Limitations in current DSM

Current DSM schemes are plagued by the lack of information. One of the most common forms of DSM is load shedding where the supply is cut off for a certain region for a defined period of time on a regular basis as a solution to the increasing demand. This is highly inconvenient to the end user and it is a major problem in developing countries such as India and in developed countries, DSM is usually via pricing strategies. For instance in the Netherlands, the consumers are offer double tariffs, one for the day and the other for the night. This reduced tariff at night is aimed at motivating the consumers to do their high power demand activities at night. The utility providers are coming up with lucrative offers to the customers such as prepaid energy, something adopted from the telecom industry which also aids in load forecasting. The current grid technology doesn’t boast a communication channel which is capable of providing real time or near real time data; thus seriously hampering the development of DSM strategies. Real time load data will enable the possibility of real time pricing or more accurate pricing strategies than the existing ones. This communication if 2-way can also enable in monitoring the load behaviour at the customer end. Although this may pose certain privacy issues at the customer end, these possibilities are being considered in the design of the smart grid.

1.6 Role of technology in DSM

The primary bottle neck in the development of smart DSM is the lack of availability of appropriate information at the right time at the right place. Thus technology will enable the data flow and will aid in the development of new, smart and efficient DSM schemes which include automatic load control, automatic pricing and other automated demand response techniques. Technology should address the following shortcomings for obtaining a reliable and efficient grid;

- The end users do not have an idea about their resources consumption at a given time. The current method in practice is the utility billing system from the utility company which notifies the user about their usage on a monthly basis. Technology should enable more frequent monitoring and reporting service to the customer which would enable them make a smart choice.

- Advanced metering technologies would enable real time pricing strategies

- Distributed generation sources should be connected to the grid which would offer more stability to the grid and also offer financial benefits to the customers.

- Better building Energy Management System (EMS) interconnected to the grid to offer instant demand response.

- Intelligent devices those are capable of responding to pricing and demands messages and taking smart decisions.
CHAPTER 1. INTRODUCTION

1.7 Advances in metering technology

Metering technologies have improved over the years, from manual meter to Automated Meter Reading (AMR)\(^1\) to Automated Meter Management (AMM)\(^2\) to Advanced Meter Infrastructure (AMI)\(^3\). The simple mechanical watt hour meter that was in use a few decades ago still exists in many parts of the world, including the developing countries like India. These metering systems were monitored and billed at the installed customer location at a standard rate. Then came the automated meter reading (AMR), they were simple digital meters which reduced the utility company’s visit to the customer location and brought the usage readings to utility company through a communication channel either wired or wireless link. They enabled the monitoring on an annual, monthly, daily and hourly basis.

The increased usage of pervasive communication systems in the electric grid, particularly at distribution level, has been driven by the need of more accurate and detailed information about consumers. The AMM concept introduced additional complexity as it added downstream data exchange from the energy provider to the end consumer, for management purposes. It was initially designed to manage the remote collection of data, but the concept was extended to include limited forms of control or influence the customers’ energy consumption [43].

1.8 Thesis Objectives

The traditional methods used for peak load reduction, load forecasting and demand response aren’t sufficient to introduce a positive impact on the environment. With the advancements in information technology and the establishment of smart grids, we must take full advantage of technology on offer and come up with viable solutions. Although there are several green initiatives and energy efficiency projects around the world, the percentage focused on demand response are still meagre. Since a lot is at stake and energy becoming a major factor on every country’s political agenda, the focus must now shift towards the improvements of the current methods in order to be sustainable. So the main objectives of this thesis is to identify and evaluate possible solutions which can be enabled by smart grids and is aimed at

- Reliable peak load reduction
- Dynamic demand response

\(^1\)Automated Meter Reading (AMR): AMR is the technology of automatically collecting consumption, diagnostic, and status data from water meter or energy metering devices (water, gas, and electric) and transferring that data to a central database for billing, troubleshooting, and analyzing.

\(^2\)Automated Meter Management (AMM): Automated Meter Management or Smart Metering is another expansion of a remote reading system that includes the possibility of performing technical measurements and functions and carrying out customer-orientated services via the system.

\(^3\)Advanced Metering Infrastructure (AMI): AMI typically refers to the full measurement and collection system that includes meters at the customer site, communication networks between the customer and a service provider, such as an electric, gas, or water utility, and data reception and management systems that make the information available to the service provider [9].
1.9. CONCLUSIONS

- Reliable load forecasting
- Better Resource Utilization

1.9 Conclusions

This chapter has thrown light on the working of the traditional electrical system, the limitations of the current demand response and demand side management techniques, and has introduced the structure of smart grid and associated technologies that enable smart grids. The lack of an information feedback channel has been a setback till now and the introduction of a 2 way communication channel capable of real-time information has opened up opportunities to approach the peak demand problem from different perspectives.
CHAPTER 1. INTRODUCTION
2.1 Introduction

The electrical system can be approached from two perspectives, the generation end and the consumer end. In principle the numbers of generation points are less, compared to the consumer points as the system tends to grow to titanic proportions form the point of generation. Let’s take an example to understand the size of the electrical network, let’s take a worthy adversary such as the Internet, it is a very wide spread phrase and presumably the largest growing network in the recent years. The internet connects 2,095,006,005 users worldwide [11]. Now pitching it up against the electrical network, let’s take India’s electrical grid, this crippled electrical grid alone connects about 80% of the total population of the country [7, 26], that’s around 968,154,738 people connected by the electrical grid. Thus it becomes evident that the electrical network or the power grid is fundamentally a complex network, inherently becoming very difficult to model.

2.2 Complex systems

Let’s try to define a complex system, as the name suggests one can understand that its complex. But what are the boundaries of a complex system or what are the characteristics of a complex system. Gary William Flake defines complex systems as "a collection of many simple nonlinear units that operate in parallel and interact locally with each other so as to produce emergent behaviour" [21]. Complex system can be imagined as a structured system made of independent components whose iterative interactions leads to a global phenomenon or an emergent behaviour. Some of the examples of natural complex systems are the human brain, the immune system, living organisms, our planet, the galaxy, the universe, etc. Now let’s look at some manmade complex systems, or let’s put it this way, the manmade systems that became complex. Examples include the power grid, the internet, the telephone networks, the transportation system, etc. Fixating on the line "manmade systems that became complex?", let’s take the example of transportation to understand better. A car by itself is a complex system, but in the context of the transportation system, it is a very basic entity whose actions are predictable. A single car on an empty highway travelling from Delft to Amsterdam is very easy to model mathematically and calculate how long it will take to reach there when travelling at 60km/h. But when there are more cars on the road, weather, the mathematical equations start to have too many variables and it becomes harder to model, for instance, when the system grows in terms of no. of cars, it gives rise to traffic, which causes accidents which in turn leads to traffic jams etc. Now let’s extend the situation a bit more, say the travel is from Delft to Coimbatore (India) with even more cars on the road and the road filled with pot holes. Well calculation of travelling time in the first scenario was distance over
speed, for the latest scenario, it is a function of various factors such as traffic at different towns, the possibility of the car getting stuck in traffic, the possibility of the car running out of gas, needing repair/service due to hitting a pot hole, the probability of being in an accident etc., the list just keeps growing.

The common trait in complex system is that they evolve, adapt & self-organise themselves, and by closely observing them we can identify specific pattern also known as emergent behaviour or emergent phenomena. The emergent behaviour can be described as non-trivial, global behaviour which cannot be understood by simply analysing the behaviour of individual elements. This emergent behaviour can be either a desirable consequence or an undesirable consequence. For instance, the structure and behaviour of a single neuron can be represented by a simple integration of input signals in the form of trains of electrical pulses or spikes. However, if one considers millions of neurons, a complex neural system emerges with non-trivial connections between its parts. Emergent behaviour of the collective behaviour of neurons is, for instance, intelligence, a desirable phenomenon, and epilepsy, as an undesirable counterpart.

2.3 Modelling of complex systems

As discussed earlier, complex systems are hard to model as it is very difficult to provide a mathematical equation that represents the entire system. So the solution is to dissect the system until it becomes simple, this is known as the bottom up approach. One among the popular bottom up modelling approaches is the agent based modelling approach. What is an agent?, well there is no universal agreement on the term ‘agent’, some modellers consider agents to be any individual component where its behaviour can range from primitive reactive decision rules to complex adaptive artificial intelligence, while other insist that the agents must be adaptive [29]. In simple terms agents are the building blocks of a complex systems that make their decisions based on a set of local rules without any information of the global system. Agents are characterised by

- Attributes.
- Behavioural Rules.
- Memory.
- Resources.
- Decision making sophistication.
- Rules to modify behavioural rules.

Agents interact with other agents in what is known as an environment. The environment may itself change dynamically according to the actions of the agents, these changes occur passively, rather than in the active fashion, i.e. the state of the environment evolves dynamically, but only in response to the actions of the agents, rather than as a result of particular adaptive behaviour or goal-seeking [23].
2.4 Why agent based modelling

Agent based modelling or individual based modelling has become a powerful simulation modelling technique that has an increasing number of applications in various fields such as complexity science, systems science, systems dynamics, computer science, management science and the social sciences. Agent based modelling and simulation is becoming increasingly useful in real world business situations for investigating behaviour in complex and non-linear systems for the evaluation of long term operational implications of strategy and policy decisions. Agent based modelling offer a lot of advantages over other modelling methods such as non-spatial modelling, cellular automaton, etc. The advantages of agent based modelling were captured in three statements in [18], they are

- **ABM captures the emergent behaviour**: Emergent behaviour is an important aspect of complex systems. The emergent behaviour is hard to predict and may be counter intuitive, thus ABM offers insights on the how the interactions of the agents lead to a particular global phenomena.

- **ABM provides a natural description the system**: In many cases ABM is the most apt way of describing a system of behavioural entities. For instance, it is more natural to describe how shoppers move in a supermarket rather than to derive an equation that governs the dynamics of the density of shoppers.

- **ABM is flexible**: ABM is modular; agents can be added or removed from the model. It also provides the opportunity to fine tune the complexity of the system on different levels such as behaviour, rules of interaction, degree of rationality and learning capabilities.

![Figure 2.1: Agent based systems](image-url)
2.5 Developments in DR since the smart grid

Since the smart grid is aimed at addressing an impending crisis situation, a variety of pilot projects have been launched around the world to take advantage of the information technology provided by the smart grid and build applications that would lead to load forecasting and demand response, etc. The EU and the U.S. are aggressively promoting smart grids with a major amount of the budget going into infrastructure development for a sustainable future. Notable economist Jeremy Rifkin, in his interview throws light on the perceived rate of deterioration of the ice caps and the results of recent studies which highlight the error pointing out that the earlier predictions were way off-course. He talks about the energy crisis, climate change and economic meltdown feeding off each other and accelerating the crisis and world in very bad predicament in 20 years.

Albadi et.al. in their work give a clear overview of demand response, the various methods used for demand response, the benefits of demand response and the costs of demand response [15]. Their work is presented in figure 2.2 which gives us an idea about the composition of a demand response program. Schisler et.al. discuss about the technology developed by EnerNOC which has been employed as a demand response solution by curtailing customer appliances on an hourly basis to strengthen the ancillary power markets through monetized benefits [44]. Plug-in Hybrid electric vehicles (PHEV) is in the early adopters phase and it is only a matter of time it becomes a popular choice and reaches the early majority phase. Once PHEV’s are plugged into the grid, they can easily overload the current infrastructure as they are high power consumers and they will be a part of the residential consumer’s energy needs. Mallette et.al. discuss the idea of a financial incentive based system where the PHEV’s are charged during the non-peak hours supported by case studies and results [30].

Romanos et.al. describe a thermal model predictive controller which is used for predicting indoor temperatures during pre-cooling phase which is the DSM followed to reduce peak demand [41]. The model takes into account the user preference on thermal comfort. Xiong et.al. in their work use a multi-agent market approach to demand response [48]. They use two types of pricing strategies, a uniform pricing strategy and a pay-as-bid strategy. In their model, each generator submits their bid prices and quantity of power that they would like to sell a day ahead based on a Q-learning approach. Then an Independent System Operator (ISO) decides which generators are selected to supply the demand. ISO chooses the cheapest generator first, this continues till the demand is met. In the uniform price auction, all the generators are paid at the market clearing price which is the highest accepted price by ISO where as in pay-as-bid strategy, each generator is paid at the quoted price. Yang et.al. in their work provides a counter example on how reduced demand might lead to increased prices by highlighting the difficulties in the power market compared to a regular market [49]. The main argument provided in this paper is the geographic location of the load and the network condition dictates the price of a resource, even though the demand might be low, the resource is available at different prices at different locations as network congestion and distribution losses also have to be considered.
Now moving on to the current happenings, The Netherlands has the first smart city in Europe, the "Amsterdam Smart City" project along with a variety of pilot projects
such as "Power Matching City". The "Power Matching City" project implemented in Hoegkerk is a living smart grid lab, where distributed sources are installed in homes and market based models are used to select economical energy use, i.e. choose to take electricity from the grid or use the energy produced form distributed energy sources installed at home, based on cost [17]. The results have shown that the project is working and has seen the reduction of electricity consumption form the grid, but it has also shown an increase in gas usage and the money spent by the consumer is still about the same [28]. Although this is only the initial phase of the power matching project, the project also hints about appliances connected to the grid and buying / selling of power in the future.

Grid connected appliances will be a part of tomorrow, some of the leading appliance manufacturers have built prototypes of intelligent appliances which have advanced learning capabilities to reduce peak loads as discussed in [41, 17, 6, 39]. Most of the pilot projects today contain just one agent interacting with smart grid contributing to demand response. In the future, hoards of smart appliances are going to be connected to the grid. The "Power Matching City" project is true smart grid initiative taking into account both demand side management and sustainable energy production. The customer acceptance of this project and implementation on a large scale is still a bit foggy. The initial cost involved for the customer is very high and the projects doesn’t really address the buyback period for the consumers. Given this situation, one of the directions to proceed is smart energy management of appliances. Now the focus shift to how the appliances interact with one another and how they share the resources when they are in abundance scarce.

One of the most effective ways to have demand response is for every consumer to participate, irreverent of the amount of contribution, as the saying goes, tiny droplets make an ocean. The effect of a major population contributing to demand response will pave the way for the rest to join them and change the life style. When a huge majority participates, the individual contribution required goes down which in turn makes it an attractive option to change the lifestyle provided that there are financial benefits and incentives. More on the business front is discussed in the chapter 6.

2.6 Conclusions

From this it is clear that the scientific community has taken note of the advantages of smart grids and have started to build on top of the basic framework. The applications developed for smart grids are still in the nascent stages, as it gains more popularity and the cloud over the privacy issues clear the general public will no longer be consumers but prosumers. In the next chapter we see how the principles of economics can be used as a solution to resource distribution in an electricity grid.
3.1 Introduction

Economics is the branch of social science that deals with the production, consumption and distribution of valuable resources or services. Economics can be broadly classified into microeconomics and macroeconomics. As the name suggests, microeconomics deals with how individual agents make their decisions whereas macroeconomics studies the system on a larger scale such as performance, structure, behaviour etc. Economic models are generally used for modelling complex systems, and these concepts have been applied in the field of technical sciences over the years to model complex behaviours. By using economic models, we hope to achieve what’s called the economic equilibrium, for instance, market equilibrium refers to the situation where a market price is established through competition where the supply of a product or service meets the demand. In this chapter, we will understand the basic laws of economics such as law of supply, law of demand and look at the different markets and price formations. Then we explore the different mechanism used to achieve the market mechanism.

3.2 Demand and supply

Law of Demand:

The law of demand states that when the supply is constant, an increase in demand leads to an increase in the equilibrium price, whereas if the demand decreases, there is a decrease in the equilibrium price. This is illustrated in the figure 3.1, where the blue line indicates supply and the red line indicates demand. When the supply remains constant and demand changes, we see a corresponding change in price.

![Figure 3.1: Law of Demand](image)
Law of Supply:

Law of supply stated that when the demand is constant and the supply changes, there is a change in the equilibrium price. If there is an increasing supply against a constant demand, it leads to a reduced equilibrium price of the good or service, while a decrease in supply against a constant demand leads to an increased equilibrium price. This is illustrated in figure 3.2, where the demand curve remains constant and the decrease in supply leads to an increased equilibrium price.

![Figure 3.2: Law of Supply](image)

Equilibrium Price:

Economic equilibrium is reached when the supply and demand are met, which translated to the meeting of the supply and demand curves. This is illustrated in figure 3.3.

![Figure 3.3: Equilibrium Price](image)
3.3 Market structure and price formulation

In principle there are three types of market structures, namely;

- Perfect Competition
- Imperfect Competition
  - Monopolistic Competition
  - Oligopoly
- Monopoly

Perfect competition is a situation in where both the producers and consumers are too numerous to have any control over the prices; a situation in which everyone is a price taker. A price taker is a person or a firm that has no power to influence the market price [45]. In such a situation where the market is under perfect competition, the demand and supply decisions of the consumers and producers are transmitted to each other through the price. Thus the price of the commodity solely depends on the demand and supply which has to be accepted by both producers and consumers.

Monopoly is an extreme case of market power, where there is only a single firm dealing with that particular commodity or the exclusive possession or control of the supply of certain commodity. In many countries the electricity market falls under this category. Monopoly also exists in other sectors such as information technology; Apple Corporation’s App store policy, Microsoft’s windows applications etc. When either of the market players have market power over prices, they can influence a price increase leading to increased profits at the expense of others. Microeconomic approaches tries to achieve perfect competition amongst the different producers in the market, where as monopoly always has price above the market price [45].

The situation when firms face a declining demand but are not monopolies is called imperfect competition. Majority of the firms in the real world are under imperfect competition. Imperfect competition can be divided into two types, monopolistic competition and oligopoly. Monopolistic competition is the competitive of the two where a lot of firms compete and there is room for more firms to enter. When the operating firms are making higher profits, the entry of new firms drive the individual profits down and to a normal level under perfect competition. Examples of monopolistic competition are taxi companies, restaurants, small retailers, etc. Oligopoly is a condition where there are only a few firms that are dealing with a certain commodity. The chance of a new firm entering the market is slim. In oligopoly, the firms have greater control over the market than in monopolistic competition and have an interdependent relationship with other firms. The actions of one firm affects its rivals, for instance, a firms action to reduce price can lead to a rather big market share forcing the competition to respond.
3.4 Economic models

There are several models that are used to orchestrate the sale of goods and services. Economic models can be broadly classified into price based and non-price based which is illustrated in figure 3.4. Non-price based mechanisms such as game theory are founded in the concept of individual optimizations and a selfish behaviour and in cooperative methods, all the modes have the knowledge of a global utility function and usually characterize resource exchange until a marginal rate of substitution is achieved for all agents after which there is no motivation for 0-cooperation[36]. Price based mechanism revolve around the factor price, price forms a common baseline for comparison among diverse agents. It encapsulates the quality, quantity and urgency of the agents. The price based mechanisms maybe classified into two, namely commodity markets and auctions.

![Economic Models Diagram](image)

Figure 3.4: Economic Models

3.4.1 Auction models

Auction can be further classified into one-to-many auctions and many-to-many auctions. In one-to-many auction there is a single agent who initiates an auction for a resource and several other agents bid for the resources where as in many-to-many auctions, there are several agents who initiate separate auctions where other agents can bid for resources.

3.4.1.1 One-to-Many Auctions

English Auction:

An English auction is a typical open auction where the auctioneer announces the resource and the minimum selling price of the resource and the bidders bid against each other in a sequential manner. The buyers decide on the price and quantity based on their requirements, and increase their bids based on their capacity and urgency. The predominant character of an open bidding, i.e. bidding in small increments, is a strategy
adopted by many in this type of auction. As the price increases the competition for the resource reduces and finally a winner is obtained. An English auction takes a longer time to complete as it is a cyclic process of bidding or as it’s commonly known as bidding in rounds and this type of auction is beneficial to the bidders.

**Dutch Auction:**

The Dutch auction is also a sequential auction in which the seller starts with a higher price and continuously lowers the price until a participant shows interest in the price. It is more efficient when compared to the English auction, since logically speaking; only a single bid is required to obtain a winner. The Dutch auction, similar to the English auction also has a minimum price or reserve price beyond which the auction stops. This type of auction is faster and favours the selling party more, as the first bidder to accept the price bids the win, which creates an environment where the bidders have to buy the resources at their maximum possible budget otherwise they stand a chance to lose the auction.

**First Price Auction:**

The first price auction is a sealed auction, where the bidders simultaneously submit bids for a resource. The submitted bids are the processed and the highest bidder gets the resource. The First price auction has traits similar to the Dutch auction, as the bidders are not aware of the competition; the bidders adopt a similar strategy of paying the maximum according to their evaluation of the market price of the resource.

**Vickery Auction:**

Vickery auction also known as the second price auction is similar to the first price auction, the bidders submit the sealed bids containing their evaluation of the market price of the resource. The winning bidder is the highest bidder, but the price paid for the resource is the price offered by the highest losing bidder. If there is no second highest bidder, then the price paid is the average of the reserve price and the highest offered price.

**3.4.1.2 Many-to-Many Auction:**

**Double Auction:**

Double auctions are commonly known as two sided auctions as they permit multiple buyers and sellers to submit their bids at their desired price. Then the auctioneer sets a clearance price, where the sellers whose ask price is below the clearance price and the bidders whose offer price is more than the clearance price make a sale at this clearance price. Double auctions have two variants, namely, continuous double auction and periodic double auction.
Continuous Double Auction (CDA)

In continuous double auction the offers are bids are simultaneously submitted and a match is made as soon as there is a suitable match. In continuous double auctions individual clearance price is set for each seller which from here on will be referred to as the transaction price. This type of a pricing policy is known as discriminatory pricing policy.

Periodic Double Auction:

Where as in periodic double auctions, the bids are collected over a predefined period of time and the matches are made. This type of an auction is also called as sealed bid, Uniform price double auction as the other agents are not aware of each other’s bids and this type of auction has a common clearance or transaction price and hence it is referred to as uniform price double auction.

Proportional Share Protocol (PSP)

The proportional share protocol mechanism is similar to the CDA. This type of scheduling is based on weights of the different tasks or in the auction terms, its bid price. The amount of resources allocated to a task depends on its bid price in relation to the sum of bid prices of all tasks executing on that server [38].

3.4.2 Commodity markets

In commodity market models, the sellers of the resource or service stipulate their ask price and charge the buyers/users according to the amount of resources that they consume. The commonly adopted pricing policies of such markets can be either flat or variable depending on the resource supply and demand. In general the ask prices are in such a way that the supply and demand remain in equilibrium. In the flat pricing policy, the price remains constant irrespective of the quality of the service and it is not dependant on the supply or demand [40].

3.5 Demand response, a problem of resource allocation

Economic models have been developed to study the behaviour and reasoning behind the allocation of limited resources. Demand response when looked at as a problem of distribution of limited resources offer an interesting aspect to modelling the electrical system. In fact the term "Grid Economics" has been coined some time ago due to the popularity of the concept and a lot of research has already taken place in grid economics in the context of computer grids. Most computers at any given time do not use their resources optimally, and thus began the concept of grid computing where the resources of the idle computers such as processing power, data storage, etc., were shared with other computers connected over a network. Economic frameworks offer a way to observe the
effectiveness of various resource allocation mechanisms and policies to help us understand how the individual choices contribute to the total behaviour of the system.

3.6 Conclusions

We now have a basic understanding of how demand and supply leads to a price formation and which players control the price in different markets. This chapter also highlights the microeconomic approach, the different economic models and a special look in to the different auction mechanisms. We can now visualize electricity as a valuable and scarce commodity and how economic approaches can help in distribution of this scarce resource which forms an active way of demand response and demand side management. In the following chapter we will analyse the user requirements and design a system which will help evaluate our model.
4.1 Introduction

The introduction of smart grid enables us to use the flexibility of communication between the end user and the grid operators. Smart meters allow the extraction of real-time energy consumption data which could be vital in shaping the lifestyle of the end users, from being just a consumer to becoming a prosumer. In this chapter we look into the user requirements, first we begin by identifying the players in demand response and then introduce key concepts that will aid in meeting the requirements. Then we begin identifying the versatility of a household in terms of the appliances and their character which make them different and what role they play in our model. We conclude this chapter with the help of use cases depicting the idea of this thesis.

4.2 System requirements

As systems evolve and become more intelligent and logical, we shouldn’t overlook the fact that the machines are still machines and they are built to serve a purpose. So it is important for us to understand what the expectations and requirements of the end users are. There are two players that are involved in demand response, first, the grid operator who oversees the operation of the grid and second, the energy subscriber who consumes the energy. From the perspective of the grid operator the requirements are;

- Reduce peak demand.
- Better load forecasting.
- Better resource utilization.

From the perspective of the consumer,

- Ease of use.
- System that learns and adapts.
- Takes into account the user priority.
- Flexible.
- Autonomous.
- Aid in reducing energy costs.
In order to reduce peak demand, the options are either to increase the supply or reduce the demand. Since installing new infrastructure to add additional capacity is an expensive option, the grid operators prefer to reduce the demand. From chapter 2 we have seen the initiatives from the energy suppliers and grid operators; they favour price based and incentive programs to motivate the users to participate in demand response programs. From these programs the grid operators try to achieve a predictable maximum demand for which they can plan a course of action. But most of these programs are not dynamic nor do they provide the users with active data to get maximum involvement form the user. Whereas the user expect something more subtle, a system which runs in the background, which need little supervisor, adapts to the varying user needs.

4.3 Attribute and environment identification

The design of a software model begins with understanding the environment and the parameters which drive the environment. The focus of this work being the energy management and distribution inside a household, we first have to understand how the wind blows in this environment. A household is a haven of diverse electrical and electronic appliances, all created for the comfort of mankind. A typical household may hold from 10 up to 60 different appliances interacting with the grid and having its own characteristics and usage pattern. The usage pattern is mainly driven by the householder whose willingness to change their daily rituals are slim. The aim of the design of these software agents is aid the behavioural modifications of the householder through economic benefits and automation for a collective cause.

The attributes of household appliances are identified as follows,

- **Maximum Rated Power:** Maximum rated power or rated power is an indication of the upper limit of power setting till which the device can be operated safely. Operating a device beyond this specified may damage the device. Usually the maximum rated power is lower than the actual maximum power a particular device can handle, it is intently specified lower as it provides an additional blanket of safety. The maximum rated power specified in watts also signifies that the maximum power that a device will consume when operated according to the manufacturer’s specification at any given point in time. This factor helps in identifying the impact that a single device can have on the grid.

- **Operating Power:** Apart from the maximum rated power, devices can operate at other power settings. Most of the appliances come with a flexible operating power options such as microwaves, blenders, music systems etc. For instance a microwave may come with a defined range of power setting varying in steps such as 200W, 400W, 600W and 800W, whereas other devices such as the stereo systems allows greater flexibility.

- **Duration of Operation:** Duration of operation is the time for which the device has been active and consuming power from the grid. A household can have three types of devices under this category.
4.3. ATTRIBUTE AND ENVIRONMENT IDENTIFICATION

- **Fixed Duration:** A fixed duration device is one which operates for a fixed period of time for every operation and does not provide the user with the flexibility to change it. Example of such a device is a coffee maker.

- **Variable Duration:** A variable duration device is one which offers the user the flexibility to alter the duration of operation. This may be achieved either by providing the users with predefined time setting such as washing machines, ovens, etc., or giving the users the complete control to the duration of operation such as blenders, shavers, etc.

- **Continuous Operation:** A household also plays host to continuous power consumers. Such devices continuously consume power from the grid at either a predefined rate or at a varying rate. Devices such as fire alarms, smoke detectors and electric clocks, consume a constant amount of power whereas appliances such as refrigerators and freezers have cycles of increased power consumption during the compression process, and consume reduced power when performing actions such as circulation etc. When looking at this category with a magnifying glass, we can also include devices which are on stand-by as in principle they consume power. Since the amount consumed is small they can be omitted from this category.

- **Frequency of Operation:** Frequency of operation is again user centric. Every household has its own pattern of operation and frequency of operation. This mainly is dependent on the inhabitant’s routine and the no. of inhabitants. Some global characteristics (for majority of the households) can be observed for certain devices which slide into the base of daily rituals, such as electric tooth brushes, shavers and washing machines which have more or less a constant frequency of use either in a day or in a week. This attribute helps us identify how much an individual device contributes to the daily/ weekly energy consumption.

- **Time of Operation:** Similar to the frequency, the time of use or operation follows a predictable pattern and remains constant. Examples of such devices include tooth brushes, shavers, washing machines, coffee makers. The utility companies have a variable tariff for electricity and this factor determines the consequence of consumption. For instance, in the Netherlands, households can subscribe for dual tariff energy plans. The price of energy during the day is higher than at night, operating high power devices such as washing machines and dish washers which also have longer duration of operation during the low tariff may lead to a significant saving in the long run. And with the emerging concept of real-time pricing, this could prove a vital component from both the consumer and producer perspectives.

- **User Priority:** This attribute although does not exist in the present world as we have a continuous supply and the user can consumer without any restrictions. But as the wheel turns the destination gets closer, i.e. as time changes, this may not be always be possible and we may have to prioritize our consumption habits and device. This attribute helps us incorporate the "need" and "urgency" factor into the software agents.
<table>
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<th>S.No</th>
<th>Appliance</th>
<th>Power Rating (W)</th>
<th>Model</th>
<th>Duration of Usage (min)</th>
<th>Frequency of usage (times per day)</th>
<th>User Priority</th>
<th>Billed (watt-hour)</th>
<th>Billed per day (watt-hour)/week</th>
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<td>2/7</td>
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<td>6/7</td>
<td>2/7</td>
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Table 4.1: Appliance Details
A survey of the most commonly used devices in a household was conducted. The data on the most commonly used devices were gathered from a report prepared for Senter Novem [20] about electrical equipment in Dutch households from 1980-2005 and also provides different scenarios about the consumption in the future (2010-2020). After selecting the appliance a survey on their specifications were done by gathering the specs from the respective manufacturer’s website. The data gathered is presented in table 4.1. The data provided in the table will be used for simulation purposes in this thesis. The table represents 20 most commonly found in a Dutch household, along with a recent model of that particular appliance in the market provided along with its model number and power specifications. The table also contains details such as minimum duration of operation in minutes, frequency of operation per day, user priority, power consumption per operation, and power consumption per day. The billed per use denotes how much the user will be charged, it is a conversion of the device usage to watt hour which is the unit of billing. This table is prepared with the activities performed by householders in a week as a reference.

4.4 Use case modelling

The next step of the design process is to understand how the different attributes of the agents and the environment will fit into the model. The aim here is to design a model that incorporates the economic market mechanism using auctions, which address the needs of the users. This is done with the help of use cases modelling. A use case is a procedural definition of functional requirements of a system. The use cases hide the complexities in the process and give a non-technical overview of the system from the user’s perspective. Before we begin with the use case, we give a rough translation of the requirements into a model.

The main requirement form the grid operators is that they have a need a method to reduce peak demand. So we introduce a limit to the consumption on the user side, we term it bandwidth which is explained in detail in section 5.2.2 in the next chapter. By the introduction of this bandwidth, the grid operator can be assured that the end user cannot consume more than the maximum allotted bandwidth which proves to be a method to control the demand. This also helps in better load forecasting, as the grid operator knows the amount of allocated bandwidth to each house hold. From the user side, we try to optimally use the allotted bandwidth by implementing an economic market mechanism through auctions. The functionality of the system is described with the help of a use case diagram and the use cases.

4.4.1 System description

With the help of use cases, a simple model of the system is depicted in 4.1 which is known as the use case diagram. The use case diagram gives a visual representation of the system, the actors, interactions, dependencies etc.

Actors:
There are two primary actors in the systems

- Consumer - any householder who has access to devices at home.
- Grid Operator - a person who oversees the smooth operation of the electrical grid.

### 4.4.2 Description of the use cases

**Allocate Budget:** Allocation of budget is done by the consumer, who determines the target amount one wishes to spend for a particular device over a period of time and number of operations.

**Operate Device:** Operation of a device is performed by the consumer when the device is turned on by the user. This leads to a series of functions performed by the system as described by the use cases.

**Calculate Bid:** When the operation of device is performed the first function to follow is the calculation of bid. The calculation of the bid takes into account several factors such as the power required by the device, the duration of operation, device priority, the available budget and then finally determines a bid price for the resource.

**Make Request:** After calculation of a bid price, a request is made to the system with the requirements such as required power, duration and price.

**Acquire resource:** After the system allocates the required resource after finding a suitable offer, the device will obtain the allocated resources and perform its operation.
Allocate Bandwidth: The bandwidth allocation is done by the grid operator. The grid operator decides the bandwidth allotted to each household based on the current situation of the grid. When the load on the grid is less, more bandwidth is allocated and when there is a heavy load on the grid less bandwidth is allocated.

Calculate Ask Price: Once the bandwidth is allocated, based on the utilization of the bandwidth an ask price is calculated for the remaining resources.

Make Offer: Once the price calculation is done, an offer is made to the system specifying the ask price and the amount of resource.

Grant Resource: Once a suitable request and offer has been found the requested bandwidth is now allocated to the requesting appliance.

4.5 Conclusions

Identification of the attributes of the agents and the environment helps us to understand and predict how the system will behave under different circumstances. An important aspect of design is understanding the functional requirements of the system and with the help of use cases modelling we inch a step closer to designing our software system.
5.1 Introduction

In this chapter we propose a design which combines the various aspects discussed in the previous chapters into a software model which will help us simulate the system under various conditions and observe the behaviour. A lot of researchers around the world have developed concepts and models that help us to study different systems by using simulations which in turn help us redesign and reengineer these concepts and translate them to real world applications. Economic models have been used to in many fields to model complex systems especially in the field of resource distribution. The chapter begins with description of the software architecture.

5.2 Software architecture

The implementation of the market mechanism consists of three prime players as shown in figure 5.1, namely:

- Consumers
- Producers
- Matchmaker

![Figure 5.1: Components of an auction mechanism](image)

5.2.1 Consumer agents

The consumer agents are the equivalent of bidders in an auction and are the electrical appliances in our model. The consumer agents will have the attributes discussed
in section 4.3 such as maximum rated power, duration of operation, frequency of operation, time of operation and user priority. The attribute frequency of operation will help make the decision of setting maximum prices spent on bidding when budget is introduced into the system. The attribute time of operation will help us implement a rolling user priority which will help us to accommodate and simulate the requirements of the ever changing human mind. From the energy usage pattern we identify that some of the high priority devices are only operated during a certain time of the day and subsequently certain medium priority devices are operated for the rest of the day. When the numbers of medium priority devices are high, the competition for resources will become fierce and there might be a need to prioritise among the medium or low priority devices. By using the time of use attribute we can model an evolving or rolling priority.

5.2.2 Producer agents

In a household scenario, we model a single producer as there is usually a single source of power. As the popularity of distributed generation and micro-grids emerge multiple producer agents can be included. In our framework we only consider one producer, which controls the availability of resources. In the electrical network, we usually talk about power consumed and not how much we consume simultaneously. Talking in the jargon of the internet, we usually only consider the download and we never look at the electrical grid in terms of bandwidth which dictates how much energy we can consume simultaneously as illustrated in figure 5.2. In our implementation we consider electrical bandwidth. There are certain advantages and disadvantages towards this approach, with the diversity in rated power and duration of operation, reducing the bandwidth below a critical may render certain devices inoperable. Let’s take an example, the rated power a lamp is 60W and that of a coffee maker is 2650W. We consider the scenario where a householder enjoys a cup of coffee (assuming it takes 1 min to make the coffee) when he reads a book under the lamp for an hour. The the billed usage can be calculated as

\[
\text{Billed usage (Coffee Maker)} = \frac{2650}{60} \times 1 = 44 \text{ Wh (aprox)}
\]

\[
\text{Billed usage (Lamp)} = \frac{60}{60} \times 60 = 60 \text{ Whr}
\]

Total billed = 44.16 + 60 = 104.16 Whr

The above can be interpreted as a device of rating 100W is operated for an hour. If our aim is to consume 100W in an hour we can ensure that by providing a bandwidth of 100W, but in this case we will not be able to operate the coffee machine as it requires a minimum of 2650W, even though it is billed lower than the lamp. We require a minimum bandwidth of 2710W to operate both the devices simultaneously.
This might be a problem when approached from the consumer perspective as a consumer would like to operate the devices available at will. But looking at it from the perspective of the producer and DR, the main agenda is the reduction of peak demand, this proves to an asset. By reducing the bandwidth available to a household we can ensure that during peak hours the power consumed by households does not go beyond a certain level. This forms as an innovative demand response strategy and an effective & and reliable way of load forecasting.

5.2.3 Matchmaker

In an auction, there is usually an auctioneer who mediates the auctions. In our framework the matchmaker performs the job of the middleman between the consumers and the producer. This agent performs the tasks of maintaining the requests from the producer and consumers alike and also performs the matching. The matchmaking mechanism is simple, it maintains a queue of the resource requests till its validity period sorted with the highest at the top of the queue and matches it to the with the producer requests as and when the requests occur.

5.3 Components of the software agents

Apart of their characteristic attributes, all the agents have a certain attribute in common (illustrated in figure 5.3),

**Communications Manager:** The communications provides the functionality of establishing communication between the matchmaker and other agents and vice versa through messages. This is present in all the agents.
**Resource Manager:** The resource manager computes the resource required for an operation according to the characteristic of the individual agents. In the producer side, the resource manager takes care of computation of available resource and allocation of resources. This attribute is common to the consumer and producer.

**Price Manager:** The price manager computes the price for the resources based on the requirements and the adopted pricing policies. This is present in the producer and consumer.

**Matchmaking Unit:** The matchmaking unit is responsible for matching the requests from the consumer and producer which are available in the respective queues. This is a component of the matchmaker.

**Offer Queue:** The request queue holds the all the requests from the producers sorted in the lowest ask price and they are available till their validity period. This is a component of the matchmaker.

**Request Queue:** The request queue contains all the resource request messages from the consumers. They are sorted in the descending order of offer price and are available till their validity period. This is a component of the matchmaker.

![Software Architecture Diagram](image-url)
5.4 Message specification

The consumer and producer agent communicate with the matchmaker by passing message packets. In our implementation of the system, since we have only one producer we assume that the matchmaker doubles as both the producer and consumer thus eliminating the need for message passing. When the framework is scaled for multiple agents, the producer and matchmaker can be separate.

5.4.1 Resource request message

The resource request message consists of the following data fields (figure 5.4)

- Consumer Id: The unique Id given to every appliance in the household.
- Request Id: This is a unique Id generated by the consumer to keep track of the
- Quantity: Each consumer has a characteristic of set power; this is an identification of how much resource is required.
- Duration: Specifies how long the requesting quantity is required.
- Unit Price: Indicates the amount the consumer agent is willing to pay for one unit of resource for one unit quantity of time.
- Validity: Specifies the time for which this request id valid.

![Figure 5.4: Request message format](image)

5.4.2 Response message

The Response message contains the information necessary to let the consumer agent know of the outcome of the bid (figure 5.5).

- Request Id: Indicates which request of the consumer this message is in reference to.
- Allotment: The allotment contains the information.
- Transaction Price: The price at which the sale was made.

![Figure 5.5: Response message format](image)
5.5 Market mechanism

In our economic framework we choose to implement the Continuous Double Auction (CDA) method to achieve our market mechanism. The CDA approach is well documented and widely used for modelling economic models for various applications. In the work done by Behnaz et-al [35, 38, 27] in the design of an economic framework for resource sharing in ad-hoc grids, we observe that the performance of CDA in terms of throughput, consumer/producer deadline satisfaction, consumer surplus, producer surplus and volatility in different network conditions fares better when compared to First Price Auction (FPA) and Vickrey Auction (VA) on an overall scale. CDA also offers several advantages, being a closed bid auction; there is considerable reduction of communication overhead for embedded electrical devices which would be the case for open cry auctions such as the English and Dutch auctions where the information has to be broadcast to all the agents and it is a severe limiting factor in the design of embedded systems. Another work by Zhu [46] also establishes the advantages of CDA for resource allocation in computational grid and the work by Perukrishnen et-al [32] also illustrate the usability of CDA for electrical resource allocation.

5.6 Pricing mechanisms

5.6.1 Perfect competition pricing strategy

A novel dynamic pricing and bidding strategy introduced in [13, 37, 34] proves to be an efficient mechanism to implement the pricing situation in a market under perfect competition. So the ideas from the paper are used as basis of the pricing formula for perfect competition market condition. The basis of the formula is that when demand increases and the resources are limited, the ask price goes up and when the resources are plenty and the demand is less, the ask price goes down. The new price is computed as the function of utilization of the resource and previous price as described in the following sets of equations For producers,

\[ p_a(t) = \max\{p_{\text{min}}, p_a(t - 1) + \Delta p_a\} \]

For consumers,

\[ p_b(t) = \min\{p_{\text{max}}, p_b(t - 1) + \Delta p_b\} \]

Where \( p(t) \) is the new price and \( p(t - 1) \) denotes the previous price. \( p_{\text{min}} \) is the minimum acceptable value for the producers and \( p_{\text{max}} \) is the maximum affordable price for the consumers which is given by

\[ p_{\text{max}} = \frac{\text{Budget}}{\text{ResourceQuantity}} \]

And ResourceQuantity is the quantity of the needed resource. The values of \( \Delta p_a \) and \( \Delta p_b \) are given by.

\[ \Delta p_a = (u_r(t) - u_{\text{th}R}) \ast \alpha \ast p_a(t - 1) \]
\[ \Delta p_b = (u_{\text{th}T} - u_t(t)) \ast \beta \ast p_b(t - 1) \]
5.7. INCORPORATING DEVICE PRIORITY

The characters $\alpha$ and $\beta$ indicates the rate at which the price change occurs either increase or decrease. Higher values of $\alpha$ and $\beta$ lead to a high transaction price transaction price in resource depleted condition and lower values in abundant resources conditions. The variables $u_{thT}$ and $u_{thR}$ are the threshold values denoting the lower limits of the task or resource utilization. Lower values of the utilization limits reflect in lazy agents whereas higher values indicate active agents. $u_r(t)$ and $u_t(t)$ indicate the previous levels of utilization.

5.6.2 Monopolistic pricing strategy

In addition to the situation of the market under perfect competition, we also explore another economic concept which is very common in the electricity market, Monopoly. Thus it becomes important to model a monopoly and observe the effects of a monopoly on the behaviour of agents. In a monopolistic market, the producer may set the price irrespective of the demand as there is no competition. The data from such experiments could be useful when modelling markets which require extreme control. In our monopolistic pricing model, the pricing strategy adopted by the producer tries to extract the buying capacity of the market and enjoy higher profits. In this pricing policy the producer increases the ask price by the average of the transaction price of a pre-defined time period.

5.7 Incorporating device priority

In a household scenario, there has to be a certain level of Quality of Service (QoS). The users have a certain level of priority constraints which has to be met. In our implementation we translate the device priority into an aggressive bidding strategy, i.e. devices with higher priority will adopt an aggressive pricing strategy while the devices with medium priority and lower priority will have a considerable milder pricing policy. This is done by providing higher values for $\beta$ which amplifies the next bid and thus clearly giving an advantage to devices with higher priority.

5.8 Budget

In real markets, the demand is dependent on buying capacity of the buyers. The objective of the economic framework is obtain an economic equilibrium where the price spend to buy a resource matches the price asked for the resource and vice versa. Thus providing budgets to the consumer agents we go a step closer and can control the demand and avoid impossible demand scenarios. It will also allow us to study the impact of budgets in addition to priority as a viable option to obtain the required Quality of Service (QoS). With the introduction of budgets, constraints are set to control how much agents can spend on a single transaction for a unit of the resource by the factor $p_{\text{max}}$. 
CHAPTER 5. SOFTWARE ARCHITECTURE

Requirements | Capacity of the software model
--- | ---
**Grid Operator**
Reduce peak demand | The concept of energy bandwidth address both these requirements. By limiting the bandwidth the grid operator effectively controls the maximum demand. By knowing what is the expected maximum demand happens to be a very good load forecasting technique
Better load forecasting | By implementing economic principles, we try to achieve a state where the supply equals demand.

**End User**
Ease of use | This software model practically embeds into the appliance and just blends into the user’s daily life. In order for the system to be triggered, the user has to just go about his usually business.
System that learns and adapts | We implement a history based learning mechanism providing the agents with basic capacity to understand the evolution of the system and act accordingly. We also infuse priority into the agents which allows the agents to adapt according to the user’s need.
Flexible | The software architecture is flexible, it allows in modifying the character of the different agents, allows changing priority, allows changing the bidding level of aggressive bidding by tuning the parameters.
Autonomous | The systems can be autonomous once triggered by the user. All the user has to do is to provide the appliance with a budget and the number of operations and trigger the device. Once the device is triggered, the device is capable of identifying the best time to operate.
User Priority | The user priority incorporated in the model, allows the agents to take into account the user preference and need and also provide the facility to change priority according to time.

Table 5.1: Summary of Requirements

5.9 Effectiveness of the software model

In this section we will assess how the proposed software model fares upto the requirements addressed in section 4.2. We will use a table to summarise the details that show the capacity of the software model to meet the requirements table 5.1
5.10 Prologue to technology

5.10.1 Free pastry?

Pastry is a generic, scalable and efficient substrate for peer-to-peer applications. Nodes in pastry form a decentralized, self-organizing and fault-tolerant overlay network within the Internet. Pastry provides an efficient request routing, load balancing, and deterministic object location in an application-independent manner. Free pastry is an open-source distribution of the pastry framework provided by Rice University. Free pastry written in Java provides an API which is suitable for this experiment as pastry provides the required underlying routing, node discovery and provides flexibility to add more or remove nodes in the experiment. A more detailed description of the design of pastry can be found in [42].

Since testing of the software on a single computer will be trivial and will not account for difficulties introduced by a distributed environment, we chose free pastry in this implement to provide the communications for the distributed environment. This allows us to monitor the possible sheers introduced by the distributed environment such as latency, synchronization, etc. The suitability of this framework for such applications against other competitors have already been studied and implementations have been done in the works [13, 16, 47]. Since the household electrical network does not comprise of extensive nodes, this middleware framework proves to be more than sufficient to test even the most extreme home networks and can be used which this project is scaled to higher system levels such as when modelling the power distribution of a neighbourhood or a city etc. More information on Free Pastry, its distributions, documentations and tutorials can be found at [5].

5.10.2 Java

Java is a widely used programming language invented by James Gosling & co. in the mid 90’s at Sun Microsystems. Java is a simple, object oriented, platform independent programming language much similar to C++ and is well known for its portability and use for internet and distributed computing applications. Java is robust, secure and modular which makes it easier to program, debug and scaling up in future. Java has a network centric approach and multithreaded nature which makes it an attractive choice for programmers around the world for networking applications. Any computer with a JVM (Java Virtual Machine) can execute a java program, and in present day scenario is present in almost all computers which have access to internet. So Java becomes an attractive language for this project and moreover the middleware is also implemented in java which makes it a straight choice. A guide to the java programming language and documentation can be found at [1].

5.11 Conclusions

In this chapter we have seen the design of the software architecture and the incorporation of the characteristics of the agents. We see electricity form a different perspective,
as bandwidth which gives an edge with modelling and system design for demand response applications. We also talk about the importance of QoS and provide two methods, an aggressive bidding strategy and higher budgets with single spending limits, and study if they are able to achieve the required QoS requirements.
Experimental Setup and Results

6.1 Introduction

The testing and evaluation of concepts is an important aspect of system design, so this chapter is dedicated to the testing and evaluation of the software framework and the pricing mechanism. The first set of experiments are to verify if the software produces expected results, in terms of the general economic behaviour discussed in chapter 3, and concur with the theory. This chapter begins with the description of the experimental setup then moves on to the assumptions used in the experiments, the various test conditions and finally ends with the discussion of the obtained results.

6.2 Experimental setup

LAN (Local Area Network) is chosen as the test network since it is a step closer to HAN (Home Area Network) and better than a simulation on a single computer environment. This allows us to study the influence of network latencies and external interferences which might be incurred in the real world application. For our first set of tests, we have 20 nodes, which act as consumers which are simulated on 2 computers and a match maker and bootstrap node on another computer. All the nodes are supplied with the address of the bootstrap node to boot into the pastry network. Once they have joined the network, they pass a message to any one of the members of the leaf node to obtain the matchmaker’s address. Ideally the matchmaker is booted into the pastry ring after the bootstrap node. When the matchmaker joins the ring, it immediately sends its address to the bootstrap node, and subsequently this message is passed on to other nodes as they boot into the pastry network.

The agents are modelled according to home appliances in terms of power consumed and the operation duration is fixed at a constant period of 30 min for all the agents. For the modelling of the agents we use the information from table 4.1. By having such agents in our system we will be able to study the behaviour of the system under ideal conditions to see how the framework fares in producing the theoretical results when implemented for electrical grids. Introducing agents with diverse characteristics with varied duration of operation as a first step might lead to volatility in the market mechanism and we will not be able to study the effect of these parameters fully. The utilization threshold parameters $u_{thT}$ and $u_{thR}$ discussed in section 5.6.1 are set to values of 0.9 and 0.5 respectively which would signify that the consumer agents will want higher task utilisation and the producer agent would like to maintain its utilization at the specified level. The $\beta$ and $\alpha$ values of the agents are set to 0.02 and 0.0004 respectively. The values are set very low to prevent an explosive increase in price.
The experimental setup includes the generation of bids as a function of device operation. Each bid represents the user’s request or desire to operate the device. For experimentation purposes we assume that the user operates every idle device every 15 minutes. The experiments are time scaled, with each minute of the simulation period accounting for 1 hour of a day. The complete simulation is run for a period of 30 minutes where the first and last couple of minutes are not used for computational purposes as time is needed for nodes to join and leave the system.

6.2.1 Assumptions
The following assumptions are made when testing the system.

- All nodes are connected to the system at the start of the simulation.
- All nodes are aware of the matchmaker’s address.
- The producer and consumers are honest with their pricing and offers.
- The average network latency is the same for all the nodes.

6.2.2 Pricing strategy
From the following set of experiments we hope to understand the impact of two market concepts, perfect competition (P) and monopoly (M). In perfect competition condition, the price of the commodity is not dictated by a single factor but is driven by the supply and demand where as in a monopoly, the pricing strategy can be either to make higher profits or have a stronger grasp on the market.

In the market under perfect competition the price is determined after each successful bid based on the remaining resources available to the producer. The producer has a bid expiration of 15 seconds of the simulation time after which a price update takes place based on the current utilization state of the resources. In the monopolistic pricing strategy, the primary objective being exploiting the buying capacity of the consumers for profits, the price change happens every simulation minute with the new price being the average transaction price of the previous minute.

6.2.3 Network conditions
Different network conditions are considered for the experiments as they play a key role in evaluating the performance of the system under different circumstances. The network condition allows us validate, evaluate and observer the behaviour of the system under different demand and supply conditions. For instance, when the supply is more the device utilization should be high since there is plenty of resource is available at our disposal and vice versa.
6.3 EVALUATION CRITERIA

**Resource Intensive Network (RIN):** A resource intensive network is one in which there is an abundance of resources. In this network condition, we assume that the available resources are 80% more than the required resources. In our experiments this scenario equates to a bandwidth of 40.2KW.

**Task Intensive Network (TIN):** In a task intensive network there are fewer resources and more tasks, and in such a condition we assume we have 30% of the required resources. In this scenario this would equate to a bandwidth of 6.6KW.

**Balanced Network Condition (BN):** In a balanced network condition, the available resources are sufficient to meet the demand. In such a scenario the available bandwidth equates to 22.2KW.

### 6.3 Evaluation criteria

To evaluate the two pricing strategies we run the experiments under different network conditions namely, resource intensive (RIN), task intensive (TIN) and balanced network (BN) on the following criteria,

**Device Utilization**

Device utilization may be defined as the ratio of number of tasks from various devices that are entertained to the no. of requests placed by the devices. By computing the device utilization, we hope to understand how successful a particular agent/device is in acquiring the resources. By analysing this parameter we can fine tune the learning methodology of our software agents to obtain the required share of resources to meet the QoS requirements.

**Resource Utilization**

Resource utilization helps us identify how effective our pricing formula is in distributing the resources. By computing this utilization, we can fine tune the producer pricing to tailored applications. The resource utilization is computed as the total bandwidth available to consumed bandwidth.

### 6.4 Experiment scenarios

#### 6.4.1 Without priority

The first set of experiments involve the validation of the basic framework. We evaluate the basic price variation in the market under perfect competition and monopoly on the basis of device utilization and resource utilization and verify if it confers with the laws of economics.
Price Variation

In this section, we study the price variation in producer price, consumer price and transaction price in various network conditions for the two pricing strategies. Figure 6.1 shows the producer price variation under perfect competition in different network conditions. We observe that under RIN condition the producer price is on the decline as surplus resources are available and the producer tries to stimulate demand by reducing the prices. In the TIN condition where the resource is scarce and the demand is high the producer tries to reduce demand by increasing the prices. In the BN condition we observe that the price variation is minimum as the supply is more or less equal to the demand.

Figure 6.1: Producer price variation under perfect competition in different network conditions

Figure 6.2: Consumer price variation under perfect competition in different network conditions
Figures 6.2 and 6.3 represent the Consumer price and transaction price variation under perfect competition under various network conditions. We observe that the consumer price follows the producer price and we compute the transaction price as the average of the producer and consumer prices, so the transaction price encapsulates both the consumer and producer price and form here on the transaction price variation will be used for reference for market under perfect competition.

Figure 6.3: Transaction price variation under perfect competition in different network conditions

Figure 6.4: Producer price variation in a monopolistic market under different network conditions
Figure 6.4 represents the producer price for the market in monopoly under various network conditions. We observe that the pricing for the RIN and BN condition overlap, this is due to the fact that there are enough resources available to the consumers, so they do not have to fiercely compete against each other leading to lower consumer prices which in turn becomes the producer price. In the TIN condition, due to the scarcity of resources, the agents have to compete against each other to obtain resources. The more failures an agent faces, the higher the price increment in his next bid. This leads to an increase transaction price and subsequently the producer price.

![Consumer Price Variation](image)

Figure 6.5: Consumer price variation in a monopolistic market under different network conditions

![Transaction Price Variation](image)

Figure 6.6: Transaction price variation in a monopolistic market under different network conditions
6.4. EXPERIMENT SCENARIOS

Evaluation of Utilization

The next order of business is to examine the various utilization values. From the consumer perspective device utilization is important and from the producer perspective network utilization is important.

Device Utilization

Every appliance at home satisfies a particular purpose, some might be important than others, some might be important at a given point in time. So we analyse the device utilization from the users perspective using the user’s perceived priority of appliances at home.

![Figure 6.7: Comparison of device utilization in perfect competition and monopoly under RIN network condition](image)

![Figure 6.8: Comparison of device utilization in perfect competition and monopoly under TIN network condition](image)
Figures 6.7, 6.8 and 6.9 show the effect of the two pricing strategies. The device utilization is better for perfect competition than monopoly under different network conditions.

### Resource Utilization

Resource utilization will give the effectiveness of the pricing formula in allotting the resources. Figure 6.10 shows the resource utilization of monopoly and market under perfect competition. We see a general trend that the utilization is higher in TIN condition as there is more demand than supply, so the resources are better utilized. The resource utilization in RIN and BN conditions are comparatively less than TIN since the supply is greater than demand.
6.4. EXPERIMENT SCENARIOS

6.4.2 With priority

From the graphs of device utilization we can observe that the user’s perceived priority levels for the devices do not perform well under TIN condition. In order to give the devices with higher priority some leverage, we incorporate the devices priority requirements in the learning strategy. This prioritized bidding strategy will ensure that the higher priority devices will perform better under task intensive condition as we set the value of $\beta$ is set to 0.1 for level 1 priority devices, 0.05 for level 2 priority devices and 0.02 for level 3 priority devices.

Price variation

![Transaction Price Variation](image)

Figure 6.11: Transaction price variation in a perfectly competitive market under different network conditions with prioritized bidding

With the increase in the $\beta$ value we observe higher spikes in the perfect competition method in TIN condition. The higher peaks signify the failure of a device to acquire devices. We can considerably observe more peaks than in the figures 6.3 and Figure 6.11: Transaction price variation in a perfectly competitive market under different network conditions with prioritized bidding.

We also observe that in the monopolistic approach the transaction price increases from 50 range in the experiment without prioritized bidding to the 100 range. This is because the agents are more aggressive in trying to obtain the resources thereby leading to higher transaction prices and subsequently higher producer prices.

Device Utilization

Figures 6.13, 6.14 and 6.15 show the device utilization of the different priority devices with competitive pricing and monopolistic pricing under different network conditions.
Figure 6.12: Transaction price variation in a monopolistic market under different network conditions with prioritized bidding

![Transaction Price Variation](image)

Figure 6.13: Comparison of device utilization in perfect competition and monopoly under RIN network condition with prioritized bidding

![Device Utilization (RIN)](image)

Table 6.1 shows the comparison of device utilization with and without the influence of priority. The priority influence is introduced by the factor $\beta$ in the learning process. The influence of $\beta$ shows an increase in device utilization for higher priority devices. It also introduces a drop in device utilization of low priority device.
6.4. EXPERIMENT SCENARIOS

Figure 6.14: Comparison of device utilization in perfect competition and monopoly under TIN network condition with prioritized bidding

Figure 6.15: Comparison of device utilization in perfect competition and monopoly under BN network condition with prioritized bidding

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<thead>
<tr>
<th>Bidding Strategy</th>
<th>Device Priority</th>
<th>RIN</th>
<th>TIN</th>
<th>BN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>M</td>
<td>P</td>
<td>M</td>
</tr>
<tr>
<td>Without Priority</td>
<td>1</td>
<td>97.60</td>
<td>75.57</td>
<td>25.98</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>93.87</td>
<td>72.39</td>
<td>36.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>100</td>
<td>76.78</td>
<td>20.73</td>
</tr>
<tr>
<td>With Priority</td>
<td>1</td>
<td>98.74</td>
<td>80.15</td>
<td>43.20</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>96.89</td>
<td>77.51</td>
<td>38.75</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>97.55</td>
<td>76.52</td>
<td>18.68</td>
</tr>
</tbody>
</table>

Table 6.1: Comparison of device utilization
CHAPTER 6. EXPERIMENTAL SETUP AND RESULTS

<table>
<thead>
<tr>
<th>Bidding Strategy</th>
<th>Pricing Strategy</th>
<th>Network Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RIN</td>
</tr>
<tr>
<td>Without Priority</td>
<td>P</td>
<td>36.11</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>33.15</td>
</tr>
<tr>
<td>With Priority</td>
<td>P</td>
<td>35.49</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>32.92</td>
</tr>
</tbody>
</table>

Table 6.2: Comparison of resource utilization

Resource Utilization

Figure 6.16 shows the visual representation of the resource utilization of the system under different network conditions with competitive pricing strategy and monopolistic pricing strategy. We see that the resource utilization for the perfect competition method is still better than the monopolistic method. Table 6.2 shows the difference in resource utilization caused by the introduction of higher values of $\beta$. The utilization increases in the task intensive condition in both the perfect competition and monopolistic methods, but there is a slight drop in the utilization values. We observed an increase in device utilization values in the TIN network condition and it corresponds to an increase in the resource utilization in the TIN condition.

From table 6.2 it is evident that we are able to engineer an increase in device utilization by increasing the value of $\beta$, a part of the learning methodology, for higher priority devices, which leads to higher device utilization. We also observe that the introduction of higher values of $\beta$ leads to a reduced resource utilization. This might lead to a few questions as to why there is a reduction in resource utilization when there is an increase in device utilization. The answer lies in the power consumed by these devices.
6.4. EXPERIMENT SCENARIOS

A household contains a host of appliance with different power requirement. The denial of one operation of a high power device could lead to the operation of several low power devices which may fall into any of the three priority category. The one high power device fails to obtain the resource it could lead to an increase in device utilization of several low power devices. Table 4.1 show that a device can consume power as high as 2700W and also shows that there are devices that consume as low as 2.9W.

6.4.3 Experiments with budget

In a real market scene, the need factor motivates people to purchase. An important factor which enables people to purchase is the power to purchase, i.e. the spending budget. In any market condition there is an exchange of valuables such as money for service or products for money, etc. In the previous experiments we noticed that the price of the resource shot up in the monopolistic pricing strategy with prioritized bidding. Budgets introduce a boundness into to the system, disabling the system from going beyond certain limits and keeping the system in check. We use budgets to introduce the boundness to the system and also to aid the user priority. In the following set of experiments we will study the influence of budgets and single spending limits on the device and resource utilization.

6.4.3.1 Experiments without prioritized bidding

Price Variation

Figures 6.17 and 6.18 shows the transaction price variation under perfect competition and monopoly under different network conditions. Each device was given a budget which is the product of expected number of operation, single unit spending limit and the power rating of the device. For device with higher priority a higher value of single unit spending limit is given. In this case 40, 35 and 30 are the single unit spending limit for level 1, 2 and 3 devices respectively.

![Transaction Price Variation](image)

Figure 6.17: Transaction price variation in a perfectly competitive market under different network conditions with budget
From the figure 6.17 we can notice three slopes on the raising transaction price signifying that the lower priority devices are out of the running as they cannot afford to purchase power at the given price. We can notice at time instant 10 minutes of the simulation the level three priority devices are out of the running and the medium or level 2 priority devices are out of the running at around time instant 18. The higher spending limit for higher priority devices ensure that the higher priority devices get a better share of resources during task intensive operations.

![Figure 6.18: Transaction price variation in a monopolistic market under different network conditions with budget](image)

Figure 6.18 shows a similar case for the monopolistic approach. Since the price increase does not go beyond 35, it keeps both the medium and high priority devices in play for most part of the simulation.

**Device Utilization**

The spending limits are proving to be a good limiting factor for low priority devices in TIN condition ensuring better QoS stats for the higher priority devices. However the single spending limit will not affect the system in BN and RIN conditions shown in figures 6.19 and 6.21.

Figure 6.20 shows the effect of the single unit spending limit, we see the self organization of the device utilization according to the user priority. We observed from the transaction price that the lower priority devices were out of the running, thus allowing higher priority devices to have better utilization. We see the priority 1 device utilization to be close to 48% in the perfect competition pricing strategy and around 38% in the monopolistic approach.
Figure 6.19: Comparison of device utilization in perfect competition and monopoly under RIN network condition with budget

Figure 6.20: Comparison of device utilization in perfect competition and monopoly under TIN network condition with budget

Figure 6.22 shows the resource utilization of the two pricing strategies under different network conditions. Compared to the system with no priority or spending constraints, we observe a reduction in resource utilization for the task intensive network condition for both the pricing strategies while the utilization levels remain the same for other network conditions.

6.4.3.2 Experiments with prioritized bidding

For the experiments with prioritized bidding we provide higher $\beta$ values to higher priority agents giving them an advantage among the other agents. In the previous section
we studied the effect of $\beta$, in this section we combine two parameters which is aimed at bring better QoS and study their combined effect.

**Price Variation**

Figures 6.23 and 6.24 show the transaction price variation under the perfect competition and monopolistic pricing strategies. A common observation we can make from
6.4. EXPERIMENT SCENARIOS

the graphs is that the introduction of different values of $\beta$ leads to a more fluctuating system or system with more peaks. With more aggressive bidding, the transaction price increases leading to higher producer prices in the monopolistic pricing strategy which is clear in figure 6.24.

Figure 6.23: Transaction price variation in a perfectly competitive market under different network conditions with budget and prioritized bidding

Figure 6.24: Transaction price variation in a monopolistic market under different network conditions with budget constraints and prioritized bidding
CHAPTER 6. EXPERIMENTAL SETUP AND RESULTS

Figure 6.25: Comparison of device utilization in perfect competition and monopoly under RIN network condition with budget and prioritized bidding

Figure 6.26: Comparison of device utilization in perfect competition and monopoly under TIN network condition with budget and prioritized bidding

Figures 6.25, 6.26 and 6.27 show the device utilization under the three network conditions. We observe a slight decrease in device utilization for device priority level 1 for RIN condition for market under perfect competition and a reduction in device utilization for level 3 priority devices in RIN condition for monopolistic pricing. The increasing price in the monopolistic market with a spending limit causes the reduced utilization of the lower priority devices.
In the TIN network condition, due to the increasing price observed in figure 6.24 lower priority devices are out of the running much quicker giving the higher priority devices more exclusive access to the resources in the monopolistic approach. We see better device utilization in both pricing strategies with higher values of $\beta$. The table 6.3 shows a comparison of the utilization values for the different network conditions under budget constraints with and without prioritized bidding.

Figure 6.27: Comparison of device utilization of perfect competition and monopoly under BN network condition with budget and prioritized bidding

Figure 6.28: Resource utilization for perfect competition and monopoly under different network conditions with budget and prioritized bidding
### Table 6.3: Comparison of device utilization with budget

<table>
<thead>
<tr>
<th>Bidding Strategy</th>
<th>Pricing Strategy</th>
<th>Network Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority</td>
<td>RIN P M</td>
<td>TIN P M</td>
</tr>
<tr>
<td>Without Priority</td>
<td>1 99.69 71.60 47.94 36.21</td>
<td>72.43 74.43</td>
</tr>
<tr>
<td>With Priority</td>
<td>1 89.71 80.15 53.91 63.74</td>
<td>83.46 79.05</td>
</tr>
</tbody>
</table>

### Table 6.4: Comparison of resource utilization with budget

<table>
<thead>
<tr>
<th>Bidding Strategy</th>
<th>Pricing Strategy</th>
<th>Network Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>RIN P</td>
<td>TIN P</td>
</tr>
<tr>
<td>Without Priority</td>
<td>1 36.26 76.78 58.14</td>
<td>2 32.55 77.59 59.65</td>
</tr>
<tr>
<td>With Priority</td>
<td>1 31.09 70.37 56.55</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.28 shows the resource utilization of the obtained by the two pricing strategies under different load conditions. We observe that there is a reduction in resource utilization in all network conditions compared to experiments without prioritized bidding. The table 6.4 shows the comparison of the resource utilization of the two pricing strategies with and without prioritized bidding. The table gives a clear indication that the increment of the value $\beta$ leads to an increase in device utilization of higher priority devices at the expense of the resource utilization.

### 6.5 Interpretation of the results

The acceptance of an idea lies in its simplicity and effectiveness, we see that the model is fairly simple and works in the background. It works along with the user to create an active method of demand response. Now the results from the experiments will allow us to assess the effectiveness of the model and help us evaluate the possibility of acceptance of the idea by the masses. In the previous chapter we have seen how the software model copes up with the requirements, while some of the functions of the model were obvious, some others have to be tested and evaluated. In this chapter, tests were designed to examine the capacity of the model to address the factors of device utilization which signifies how the user preferences incorporated in the model behaves and resource utilization. The results from the simulation show that when the resources are available all the devices get a fair share of the resources, when there is a scarcity of resources, we see that the incorporation of the priority enablers $\beta$ and the budgets give us the odds of 6.3:1.3:0.2 in favour of the higher priority devices.
We also observe that in the task intensive network condition we are able to achieve a resource utilization of up to 89%. When there are continuous power consuming devices, we can enable them to occupy the voids in the un-utilized bandwidth caused in a situation where the available bandwidth is not enough to accommodate the request of the demanding device. Now in the table 6.5 we have a recap of the requirements this time supported with the test results.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Capacity of the software model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>Reduce peak demand</td>
</tr>
<tr>
<td>Operator</td>
<td>Better load forecasting</td>
</tr>
<tr>
<td></td>
<td>We observe that the power consumed never go beyond the allotted bandwidth.</td>
</tr>
<tr>
<td>End</td>
<td>Better resource utilization</td>
</tr>
<tr>
<td></td>
<td>We are able to achieve a resource utilization of 89%.</td>
</tr>
<tr>
<td>End</td>
<td>System that learns and adapts</td>
</tr>
<tr>
<td></td>
<td>We see that the learning mechanism is able to sense the direction of the price change and adapt itself according to the market price.</td>
</tr>
<tr>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td></td>
<td>We see that the parameters of the model can be easily modified to achieve the required results, examples of such cases are the alteration of the priority, budgets, bidding strategy etc.</td>
</tr>
<tr>
<td>User</td>
<td>Autonomous</td>
</tr>
<tr>
<td></td>
<td>We also see that a device can operate only when its budget constraints are met, meaning that the device will operate when the market price falls in its range of play without any additional assistance from the user after the first trigger.</td>
</tr>
<tr>
<td>User Priority</td>
<td></td>
</tr>
<tr>
<td></td>
<td>We have incorporated the user priority using the learning mechanism and budgets and observe that the higher priority devices perform better than the rest.</td>
</tr>
</tbody>
</table>

Table 6.5: Recap of requirements supported by results

6.6 Application in real world

The results prove to be encouraging to find real world applications. As the theme of this thesis revolves around demand response, the main application is in the area of demand response. By implementing a home energy management system either in the form of intelligent devices or add-on smart switches we can achieve concepts described in this thesis. With the help of smart meters we can establish a link with the grid operators and obtain the bandwidth details to form an active form of demand response. If the infrastructure does not facilitate the usage of smart meters, we can still use this concept as a form of passive demand response which helps users keep track of their energy usage help them shape their lifestyle to a more eco friendly lifestyle. More insights on the applications and business opportunities are described in the business directions chapter.
This economic framework is also suitable for real time pricing applications which also a form of demand response strategy. When we consider the bandwidth of the household as the capacity of generation of power plant, we can determine the price of electricity based on the utilization of the generators. Generators usually operate at an optimal efficiency when at a certain load conditions. So we can use these economic principles to match the supply and demand by effectively varying the price in real time and using CDA approach to obtain the market mechanism and the perfect competition pricing strategy to obtain optimal utilization of the generators.

6.7 Conclusions

In this chapter we have successfully tested the economic framework designed for resource distribution in a household. We have tested and evaluated the two pricing strategies, one based on perfect competition where the price is determined by the demand and supply where no single entity can influence a price change and a monopolistic pricing policy where the producer can influence a price change. We have evaluated these two pricing formulas based on two factors, namely device utilization which signifies the percentage of successful operation of a device and resource utilization, which signifies how effective the formula is in effectively distributing the available resources. From the analysis of the above factors we have observed that the monopolistic strategy of pricing fares lower when compared to the perfect competition pricing strategy both in terms of achieving lower device utilization and lower resource utilization.

We have also seen that we are able to incorporate device priority using the learning mechanism and budgets as priority enablers. Higher values of $\beta$ makes the high priority agents more aggressive which in turn leads to an increased device utilization and higher bidding prices, reaching up to the price range of 100 in the monopolistic approach for task intensive condition. By introducing budget constraints we are able to limit the effect of $\beta$ on the bidding prices effectively bringing it within the range of 40 in both the monopolist and perfect competition approach in task intensive condition. The addition of budget gives more control over the behaviour of the system and combined with prioritized bidding, a desirable behaviour of device utilization can be achieved. We have also observed that in the case with budgets, the resource utilization of the monopolistic pricing policy is lower than that of the perfect competition pricing policy but does offer a more desirable behaviour in terms of higher device utilization with higher priority devices getting a utilization of 63.74% against 53.91% in the perfect competition approach. Thus it gives us an insight on choosing the appropriate pricing policy according to the users wish.
7.1 Introduction

Necessity is the mother of inventions; when a need arises man will find a way either to change the environment or adapt to it. Inventions are also a result of desire; over the years we have seen how man has changed the face of the planet. This embosses a simple fact of man’s nature; there is no end to desire. History is a black box which has recorded man’s violent nature, waging thousands of wars in order to control valuable resources such as gold, silver etc. What’s looming over the horizon is a battle for power, well power (P). The growing concerns over depleting natural resources is a "NO MENTION" to any educated person, as every part of the world is already started to feel the brunt it. This chapter is aimed at exploring how the ideas of this thesis can be used for real world applications and why such solutions are necessary.

7.2 Energy battle

A simple search on the internet reveals wealth of web sites dedicated towards spreading awareness about the energy shortages around the world. It is also interesting to note that most countries have taken some initiatives towards a sustainable future in the past decade, due to the OPEC oil embargo and the more recent 2008 oil crisis. These oil crises are driven by the transportation sector which is looking for a way out; and the proclaimed solution is hybrid and electric vehicles. This may ease up the pressure on the oil crisis, but it questions the effectiveness of the solutions as the production of batteries proves to be more harmful on the environment than emissions from vehicles. By turning to electric vehicles, an additional stress is laid on the existing electrical grid, which would require an overhaul of infrastructure in many cases to support plug-in electric vehicles (PEV) and plug-in hybrid electric vehicles (PHEV).

Switching to electrical transportation may be a greener option, but it still is a part of the growing energy crisis as most of the world’s electricity production is still from non-renewable resources. According to the statistics from 2009 [33], 82.8% of the world’s energy is produced form non-renewable resources as shown in figure 7.1. A lot of the countries are shifting to nuclear power; almost three quarter of France’s electricity is produced from Nuclear power. In developing countries there is strong opposition towards nuclear power as it poses significant risks caused by meltdowns such as the Chernobyl disaster and the more recent Fukushima disaster. The energy produced from renewable sources is steadily growing and in 2009 its contribution stood at 16% of world’s power production. The growth of energy demand is at 1.3% every year which is supported by a strong growth in renewable generation at 3% every year.
Although the growth of renewable energy production is encouraging; the fact still remains that it will be decades before renewable sources become the primary source of electricity generation. With the issues of global warming on the rise, Europe will be one among the worst affected regions due to the rise of the sea levels, especially the Netherlands due to its geography. With most of the indicators on global warming growing faster than predicted, the current plans of reduction in carbon emission will not be sufficient to contain the negative effects on the environment. The dawn of the computer era has changed communications standards and device control & automation enabling remote operation of machinery and real time data logging & analysis. The smart grid is the fusion of these various technologies and the first chapter of this thesis is devoted to smart grids; providing an introduction, composition and its impact on the world.

7.3 Market analysis

Green Energy is one of the hot topics on the market; there are start-ups popping everyday focusing on green energy and sustainability issues. There is a lot of investment going into the energy sector as there is a high demand for energy efficient products due to fading resources. The residential sector is a major player in energy consumption and the emphasis has now shifted to the residential sector focusing on home automation, smart home etc. This sector is expected to expand to 17 million homes by 2014 according to ABI research.

Looking at electricity consumption by sector in the European Union, we see that the major players are transportation, industry and households, which make up more than three quarter of the total consumption as shown in figure 7.2 [2]. The transportation and industrial sectors are governed by standards and regulations maintaining an optimal way energy consumption working along with the grid operators for load forecasting. Whereas in the household sector, only the appliances are governed standards which guarantees efficient operation, but the operation of the appliances is at the will of the users causing the demand from this sector to remain volatile and dynamic compared to other sectors. With the trend slowly changing to hybrid and electric cars, this sector is poised to outgrow the other major sectors. Such growth would introduce a major stress on the grid as well.
as the need to developed infrastructure to support the integration of these vehicles into the grid.

![Electricity consumption by sector](image)

**Figure 7.2: Energy consumption by sector**

### 7.4 Need for new energy perspectives

According to the research conducted by Accenture with over 9000 participants from over 22 countries in the November of 2009 [14], has revealed 4 major facts on a global scale, they are

- Concerns over energy related issues are high.
- Consumers are unwilling to undertake more significant changes on the demand side.
- Consumers favour supply-side efforts.
- Consumers demand greater government intervention in the energy market.

This study has revealed that the user’s primary concern in energy related issues is the rising energy costs, followed by climate change and pollution. End users have switched to energy efficient lighting and efficient appliance but are unwilling to invest in more complex and more efficient energy management system. One of the main reasons for this is the cost involved in buying a new energy management and home automation system. In the present market, they are considered a luxury. The market penetration of home automation in new homes in Europe is around 1.67% and is expected to grow to 7.18% in 2013 in spite of their hefty price tag. Because of the costs involved, the end-users look at supply side management to come up with more efficient and sustainable
CHAPTER 7. BUSINESS DIRECTIONS

generation. The relation between utility company and the customer is a bit rickety. They expect the government to regulate them in the use of renewable sources.

It is clear that cost involved in investing in a new energy management system is the main inhibitor to the growth of the home automation sector. So it is obvious that a cost effective energy management system is of high demand for demand side management. The willingness of consumers to adapt to new behaviour for energy conservation and ultimately cost saving is increasing. This forms the primary motivation for the development of a simple solution to enable the user to get an insight to the energy consumption and motivating them to save energy through incentives from the government, utility companies and housing corporations.

In the recent years a flurry of products focusing on enlightening consumers about their energy usage has hit the shelves. A combination of awareness of energy usage, efficient appliances, increasing energy costs and milder winters have led to reduced energy consumption in certain countries in Europe [4]. The increase in energy costs can be attributed to the fading resources, increase in demand and operational costs of the grid. The grid operators try to avoid blackouts by maintaining sufficient backup or reserve resources. The 2000-2001 electricity crisis of California State is a remainder of the effects of electricity shortages and how it adversely affects the economy. There has also been tremendous support from the grid operators towards demand side management; by providing incentives for customers willing to install smart meters, funding research into the study of real-time pricing to obtain better load balancing etc.

In order to have an impact on demand side management, a new perspective on energy consumption is required. The consumers are aware of the crisis, but do not have the required stimuli to make the necessary life style changes. The ideas form this thesis to introduce spending limits to get better grid stability could be a viable option for future research. The main focus of the thesis however is the resource allocation when under such constraints, and from the simulations, the results are motivating enough to call attention for more research. By proving autonomous systems which are capable of operating with minimal supervision; i.e. in terms of operating the devices when the energy is cheap proves to be a good stimulus for both the residential consumers and appliance manufacturers.

The ideas from this thesis also serve as a basis to curb any level of monopoly in oligopolistic electricity markets. For instance, in the Netherlands the electricity market is an oligopoly. There are a handful of companies that operate in the energy production and supply sectors. Customers have the freedom to choose the energy plan, duration and the company to supply power. But during their contract period, the load on that particular supplier does not translate into the price at which the customer is paying. Moreover the customers of a supply company do not have the freedom to shift to another supplier during the contract period forcing the customer to take the price offered by the producer for the contract period which falls in the waters of monopoly. What the smart
meter has brought to the table is a gateway to communicate between the supplier and consumer, which could mean that the consumer can buy the resource in real time before every use. This effectively transforms the electricity grid into an active market, where every producer based on its load condition and supply capacity tries to sell electricity and the consumers based on the offers from the producers have the freedom to choose between the different companies.

7.5 Role of shifft

Shifft is a start-up company founded in 2009 and is a part of the Yes! Delft incubation program. Shifft is a company working with smart grid technologies to provide a new energy experience focusing on bringing awareness to the end consumers through interactive games to achieve load levelling. The aim of this thesis is to provide a comprehensive study on the various demand response techniques and to provide an insight into how technology plays a role in providing demand side management taking into account the user's considerations and to identify the business prospects from the innovations achieved.

7.6 Recommendations

From the research done in this thesis a suitable way to enter the market is by coordinating with the utility companies and the end users to provide demand side management solutions in the form of smart plugs or switches. The plugs/switches are to be encoded with the intelligence which would comprise of the attributes of device being used, the priority considerations, budget information and the logic of the pricing strategy. These smart plugs should be able to communicate with the smart meter through a suitable home area network comprising of wired or wireless technologies. The smart meter being capable of communicating with the grid operators will provide the bandwidth data and will act as the matchmaker. From the software and pricing logic, we have studied the effect of the two pricing policies and the effect of the priority enablers. A combination of both the pricing policies can be used which would offer the benefits of both the policies. When the resource left goes below a set value a pricing policy shift can be made from perfect competition to monopoly there by offering better device utilization when the resources are scarce and better resource utilization when plenty of resources are available.

7.7 Conclusions

The effect of monopoly in electrical grid operation lead to the crisis in California in 2000, the deregulation in electricity markets have several advantages, but at the same time the lack of coordination could lead to an inefficient system as a whole. For instance, one of the energy suppliers could be overloaded and might not be able to supply the consumer at the set price, so the producer can either buy electricity from other producers to supply its customers or choose to suspend supply temporarily to its customers. This is
the case in many developing countries that are coping with shortages and peak demand. By creating a common market for electricity, we can introduce a more competitive environment where all the participating suppliers can share their load and energy surplus alike leading to a more stable grid and providing the consumers with more flexible and economical options. This opens up a lot of opportunities for businesses; from building the infrastructure required for communication between the different market players to manufacturing intelligent devices capable of making sound choices to injecting intelligence to existing devices.
Summary, Contributions and Conclusions

8.1 Summary and conclusions

In this thesis an agent based economic framework for resource distribution in a household smart grid is presented. The main idea presented in this thesis is the introduction of energy consumption limitations to reduce peak demand and form an active method of demand response and load forecasting. We look at this consumption limitation as a problem of resource distribution and utilize an economic mode to distribute the scarce resource. The work of this thesis is summarised in chapters as follows.

In chapter 1, an introduction to smart grids were provided, covering from the current state of the electrical grid system, operation of a power grid, the components of smart grid, and the technology involved. In this chapter we also identified one of the problems that exists in the present grid system and presents itself as a challenge, i.e. Demand response. We explain the concept of demand response and demand side management giving an overview of the problem that plagues the electrical grid system.

In chapter 2, we give to some background complex systems. We see why the electrical grid system is a complex system and explore ways of modelling complex systems. We identified the bottom up approach of agent based modelling as the choice of modelling complex systems and provide the basics required for understanding agent based modelling. Then we look into the developments that have taken place after introduction of smart grid. We explore into the technology market to see the existing solutions to the problem of demand response and demand side management.

In chapter 3, we explore the economic models, brush up on the laws of economics and understand the basic working of the economic principles. Then we look into the different types of markets and the price formation in these different markets such as perfect competition, oligopoly, monopoly etc. Then we look into the different mechanisms that are used to achieve the market mechanism such as auction models and commodity markets. In this chapter we also discuss the advantages of CDA and refer to the previous works done utilising CDA for resource allocation in computational grids.

In chapter 4, we identify our target environment, a household and we analyse the different operating components of a household, i.e. the diversity of the appliances in a household, its characteristics, and the environment in which they interact. They we describe the parameters that make up the core part of the electrical model. Then we move on the modelling and describe the functionality with a use case.
In chapter 5, we design the software system. We discuss the details on how the market mechanisms are going to be achieved, the various components of the software model, the message specifications etc. In this chapter we introduce the concept of electrical bandwidth as a method of introducing power consumption limits. In this chapter we also introduce the pricing mechanism for the economic model. We model two pricing strategies, one that of a perfect competition and the second, a common in the electrical industry monopoly. We then move on the incorporation of the user priority into the model and discuss ways of incorporating user priority also explore how budgets could incorporate the user’s needs. The chapter concludes with an introduction to the technology used for building the software model.

In chapter 6, we discuss the experimental setup in which the experiments are to be executed. First we begin with the validation of the software model by studying the pricing behaviour and verifying if it confers to the laws of economics. Then we move on to study the impact of $\beta$ on the device utilization and resource utilization. From the experiments we find that the factor $\beta$ gives a upper hand to higher priority devices and increases the device utilization. Then we introduce the concept of budgets and the constraints that budgets impose on the individual agents. We then see how the single unit spending limit or unit spending limit acts as parameter that incorporates priority. And then finally we combine budgets and priority in learning and see how effective they are in achieving the target. We observe that the incorporating both the budget and priority based bidding strategy increases the device utilization in all network conditions, especially the task intensive network condition. We also observed that the introduction of budget constraints help limit the effect of $\beta$ to higher priority devices and help in achieving QoS.

Another important aspect of this chapter was the evaluation of the pricing mechanism; we modelled two pricing mechanisms, perfect competition and monopoly. From the set of experiments and the study of the price variation, task utilization and resource utilization we identify that the pricing mechanism performs better in most cases for device utilization and in all network conditions for resource utilization. However the modelling pricing formulas as monopolies can be used in places where extreme control over the distribution of resources is required. From the perspective of resource distribution of resources, the perfect competition model of pricing strategy trumps the monopolistic model by achieving higher resource utilization rates.

In chapter 7, we move on to the business and entrepreneurial things of the thesis. First we highlight the current situation in terms of the problems faced today due to the various energy crisis and again highlight the impending crisis situation. Then we emphasise that even though sustainable energy source is the future, it will be eons before a large enough source is developed to support life on earth entirely some renewable source. Then we take a look at what the market is demanding. We identify from the surveys that the people are willing enough to change but do not have the necessary motivation and aid to change their lifestyle for a greener future. We then discuss how the ides of this thesis could be used for various business scenarios.
8.2 Thesis contributions

The primary contributions of this thesis are summarised below.

- The idea of introducing consumption limit in a household as an efficient way of reducing peak load & reliable maximum load forecasting method.
- Introduction of the concept of energy bandwidth and employing an economic framework for resource distribution as an aid to end users to adapt to the constraint of consumption limit and form a method of demand side management.
- Modelling of the electrical environment, including the survey of different household electrical appliances and identification and classification of the characteristics of the electrical equipment.
- Adapting the concept of economic framework form computational grids to use in electrical grids, from re-design to development of the software framework.
- Modelling and implementation of different pricing strategies namely monopolistic pricing strategy and perfect competition pricing strategy for resource distribution.
- Testing of the pricing strategies under different load conditions and the effectiveness of the pricing formula in achieving resource utilization.
- Performance comparison of the different priority enablers in achieving the desired behaviour.

8.3 Future directions

From the insights and experiences gained from this thesis, the following could be viable and valuable research directions.

- Energy Bandwidth an active demand response method: In this thesis we introduce the concept of energy bandwidth, and on the basis of load shedding and other demand response techniques we speculate that this method would form an active demand response. A research into the effectiveness of energy bandwidth in attaining active demand response is open for research.

- Bandwidth Sharing: In our work, we introduced limitations to consumption of energy which introduce certain perils of quality of service. In reality we might have situation where the bandwidth allotted to a particular household might not be used and a neighbouring household might be in need of some power. So discovery of matchmakers in the vicinity or matchmakers willing to share energy could prove to be a more efficient way of consuming energy. Thus research into mechanisms for the discovery and self-organisation of the matchmakers is a good prospect.

- Global market place: In this thesis work, we begin at the bottom level of the system with resource distribution within a household. The concept of resource
distribution based on consumption limits can be expanded to a larger system level such as a neighbourhood, city or a state. In such cases more research into the environment and the characteristics of the agents have to be studied, analysed and modelled to implement on a larger scale.

- **Secure electrical grid communication**: With the inception of the smart grid and smart meters, the issues concerning privacy and security have gone haywire. Thus implementing economic models involving real currency poses a serious risk. In this thesis we have used virtual currency which may work fine, but as time passes, security measures will become imperative.

- **Viable communication platform**: In this thesis we introduce the idea of active demand response through varying the bandwidth available to a household. In order for this to be active, a communication a secure, reliable, scalable and real-time communication link has to be established.

- **CDA for real-time pricing**: In this thesis we used continuous double auctions due to its many advantages of both producer and consumer getting into the act, etc. Taking a step further from this thesis would be explore options of buying every unit energy consumed from home directly from a grid operator based on the current load on the system. This is the basis of real-time pricing.
Additional Results

Price Variation

Figure A.1: Producer price variation under perfect competition in different network conditions with prioritized bidding

Figure A.2: Consumer price variation under perfect competition in different network conditions with prioritized bidding
APPENDIX A. ADDITIONAL RESULTS

Figure A.3: Producer price variation in a monopolistic market under different network conditions with prioritized bidding

Figure A.4: Consumer price variation in a monopolistic market under different network conditions with prioritized bidding
Figure A.5: Producer price variation under perfect competition in different network conditions with budget

Figure A.6: Consumer price variation under perfect competition in different network conditions with budget
Figure A.7: Producer price variation in a monopolistic market under different network conditions with budget

Figure A.8: Consumer price variation in a monopolistic market under different network conditions with budget
Figure A.9: Producer price variation under perfect competition in different network conditions with budget and prioritized bidding

Figure A.10: Consumer price variation under perfect competition in different network conditions with budget and prioritized bidding
Figure A.11: Producer price variation in a monopolistic market under different network conditions with budget and prioritized bidding

Figure A.12: Consumer price variation in a monopolistic market under different network conditions with budget and prioritized bidding


[23] Adam Getchell, *Agent-based modeling*, Tech. report, Department of Physics, University of California, Davis.


