Control Architecture and Utility Maximization for a Smart Grid based Energy Community

Master's Thesis

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Control Architecture and Utility Maximization for a Smart Grid based Energy Community

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Abstract

This thesis presents a control architecture and utility maximization mechanisms for a smart grid based energy community. The particular focus is upon a central server-based, utility-oriented energy community which is composed of producer-consumer (prosumer) households each having a home gateway, an energy management system, smart meters, production units and appliances. To find out how such an energy community could be optimally managed from a central server, the type of intelligence required for the different nodes in the energy network has been identified. In addition, different control mechanisms that enable the energy community to make an optimal use of its energy resources are explored. Moreover, utility maximization mechanisms have been implemented on the aggregate energy profile of the energy community targeting three main objectives namely *maximizing the aggregate greenness*, *minimizing the aggregate energy cost* and *maximizing the prosumers' comfort*. *Maximizing the aggregate greenness* aims to maximize the level of consumption of renewable energy resources using a novel mechanism that reduces the difference between the supply of and demand for renewable energy resources. *Minimizing the aggregate energy cost* aims to reduce the peak to average ratio of the aggregate energy profile of the energy community using direct mechanisms for energy cost minimization and a novel appliance based pricing scheme. *Maximizing the prosumers' comfort* aims to preserve the schedule preference of prosumers. The mechanisms above are designed and implemented under a research setting of a renewable energy company that manages an energy community composed of central servers which control household, building and/or industrial prosumers.

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Preface

The following text has been included from the chapter of Psalm 23 in the Holy Bible in order to thank God Almighty.

Psalm 23

The LORD is my shepherd; I shall not want.
He maketh me to lie down in green pastures:
He leadeth me beside the still waters.
He restoreth my soul:
He leadeth me in the paths of righteousness for his names sake.
Yea, though I walk through the valley of the shadow of death,
I will fear no evil: For thou art with me;
Thy rod and thy staff they comfort me.
Thou preparest a table before me in the presence of mine enemies:
Thou anointest my head with oil; my cup runneth over.
Surely goodness and mercy shall follow me all the days of my life:
And I will dwell in the house of the LORD forever.

Acknowledgement

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Chapter 1

Introduction

1.1 Trends in the Electricity Power System

The traditional electricity system, which is based on the principle of uni-directional electric flow from large and centralized energy generation units driving electric power through various stages of transmission and distribution to consumers and storage units, is starting to exhibit a paradigm shift towards a new kind of electricity system that is based on the concept of bi-directional electric flow and that is composed of producer-consumer (prosumer) households which are capable of generating, storing and consuming electric power.

This paradigm shift is explained by [2] as being a change from a *generation – transmission – consumer* paradigm towards the advent of prosumers, which are homogenous consumer models that are intelligent by their ability to self-address their energy management objectives. It has also been projected in [3] that such a trend in the electricity power system reduces the number of stages that were present in the traditional electricity power system architecture on the path of electricity flow from generation units to consumers thus flattening the electricity system architecture. This rising trend is further emphasized by the distributed generation behavior of prosumers, which is being witnessed widely as it opens path to local generation capabilities that could potentially transform households into energy producers.

Considering the additional benefits of the integration of renewable energy resources into the power grid, which could potentially relieve the current high level of dependence on dwindling amount of non-renewable energy resources, it can be said that electricity consumers should prepare for an aging electricity grid to transform the electricity grid into a smarter one, to be able to unleash the huge benefits of the smart grid and the untapped benefits of renewable energy resources. With the current power grid system that is straining under outdated technology and increasing its demand for high-quality power [4], these changes seem inevitable. Moreover, as stated in [5], advancements in information technology and on-going research on power infrastructure and complex systems have made such futuristic objectives reachable, which could be the answer to some of the pressing energy challenges of today.

1.2 Terminology of the Smart Grid

According to the NIST (National Institute of Standards and Technology) roadmap document given in [6], smart grids consist of seven different domains. These are the *generation*, *transmission*, *distribution*, *customer*, *service provider*, *market*, and *operation domains*.

a) The *generation* domain consists of both renewable and non-renewable energy resources for the generation of electric power.

b) The *transmission* domain deals with the transfer of the generated electrical power from generation sources to distribution points through multiple sub-stations.

c) The *distribution* domain is responsible for transporting electricity from the transmission domain to the customer domain by means of electrical interfaces.

d) The *customer* domain consists of both renewable and non-renewable energy resources for the generation of electric power..

e) The *service provider* domain deals with the transfer of the generated electrical power from generation sources to distribution points through multiple sub-stations.

f) The *market* domain is responsible for transporting electricity from the transmission domain to the customer domain by means of electrical interfaces.

g) The *operation* domain ensures the smooth operation of the power system.

When compared to other types of grid developments like distributed generation (Micro grid) and the super grid, the smart grid is different in a number of aspects. The focus of distributed generation (Micro grid) is on transmitting electricity over short distances outside the traditional grid system by including solar panels, wind turbines and co-generation units which are locally distributed. The smart grid focuses instead on updating the conventional grid, from unidirectional transmission and distribution of electricity, to an integration of generation and distribution of resources like solar and wind power through advanced micro control properties of prosumer households, aggregators and/or central servers. The smart grid thus provides higher power efficiency and better quality [7].

The super grid, on the other hand, focuses on the advanced micro control properties of the smart grid, as well as the advanced macro control properties of an intercontinental wide area synchronous grid. In such a way, the super grid has many network properties that are similar to the internet, where the exchange of electricity in the super grid is comparable to the exchange of information on the internet. As pointed out in [8], compared to the more costly requirements of the super grid that include bulk power energy highways needed for secure and suitable access and huge renewable energy resources such as hydro, solar and wind power, smart grids presents a flexible and less expensive grid development solution.

1.3 Vision of the Smart Grid

As compared to the traditional electric grid which is structured to support one-way flow of electricity from centralized bulk generation facilities through a transmission and distribution network to consumers, the notion of the smart grid hinge on adding and integrating digital computing and communication technologies and services to the electric grid that enable bidirectional flow of energy and two-way communication and control capabilities [9]. Additionally, high penetration of renewable energy sources and their distributed generation, consumption and storage in included in the vision. Moreover, the development and the deployment of the smart grid are expected to have a big impact on the economy, by creating opportunities for new jobs and businesses.

1.4 Operations in the Smart Grid

The main components of smart grids operations domain include Monitoring, Control, Fault Management, Analysis, Reporting and Statistics, Calculations, Training, Records and Assets, Operation Planning, Maintenance and Construction, Extension Planning, and Customer Support [10]. As the main responsibility of these operations is to guarantee the smooth operation of the power system, *Control of Smart Grids Operation* is an important component since it is required to control critical load peaks created by consumers during peak hours of the day. Such load peaks require quick and available power reserves. What is also an important point to consider is that in the low voltage domain, the power grid needs to have voltage values stable at around 220 - 230 V at all times for safe operation of devices since the variability behavior of loads on the grid could cause damage on devices connected to the grid. Therefore the control of smart grids operations remains an important component of smart grids operations.

In reference [11], Kundur classifies the requirements for control of power systems as those that

1) *Meet the continually changing load demand of active and reactive power in view of the fact that electricity cannot be stored conveniently in sufficient quantities.*

2) *Supply energy at minimum costs and minimum ecological impact.*

3) *Ensure the quality of power at minimum standards with regard to:*

      (a) *Constancy of frequency*;

      (b) *Constancy of voltage*; and

      (c) *Level of reliability*.

Moreover, energy companies need a better control of loads and should be able to balance the flow of power. Similarly, customers need to have more control over their energy usage and to become more conscious of the patterns of their energy consumption. In addition, in reference [12], it is stated that a system like smart grids should be able to accommodate the flexible operation of power production and consumption units, a behavior

explained in [12] as a plug-and-play addition of sub-systems, and which often results in power variations without the need for the redesign of the controller. As stated in [13], for this to happen, a control architecture needs to be designed for the energy grid that accommodates load variations on the grid because of the varying consumption patterns and the natural variations in power production, for example from wind turbines and CHPs.

1.5 Benefits of the Smart Grid

The development of the smart grid is intended to support the following four main goals [14] pp. 488-491.

1) *Reduce aggregate energy usage and increase grid efficiency*;

2) *Enable increased use of renewable green sources of energy such as wind and solar*;

3) *Enhance the reliability and security of the electrical system*; and

4) *Provide the electrical infrastructure needed to support widespread use of electric vehicles*.

While aiming for those outlined goals; the smart grid development provides the following benefits to utility companies and prosumer households. First, the smart gird development *reduces peak power usage* by making use of Demand Response (DR) mechanism to curtail loads at peak load periods or by shifting peak hour usage to non-peak periods. Second, the smart grid development *enables large-scale use of renewable sources of energy* by supporting distributed power generation through bi-directional flow of electricity and aiding in the integration of clean, renewable energy derived from solar and wind power sources through the abatement of their inherent variable and intermittent power generation characteristics. Third, the smart grid development *enhances the reliability and security of the electrical system* by providing tools for customers to manage their energy use. Fourth, the smart grid development *provides the electrical infrastructure for electric transportation* by integrating the power grid system with the transportation system through monitoring and managing the charging and discharging of electric vehicles. This collaboration of the two sectors helps to avoid overload in the grid and to minimize overall energy cost for the community.

1.6 Terminology of an Energy Community

The term Energy Community often refers to a composition of various components that consists of residential households, service units, production units, sundries and small scale industries, with an emphasis on the electric power production, consumption and storage characteristics of the different components and the aggregate energy profile of the community. Community energy is a related terminology that covers a broad scope of energy projects scaling from individual domestic installations to community wide networks which generate power to meet the communitys energy demand.

With the advent of the concept of prosumers and the support of the smart grid, the mentioned components of the energy community are able to communicate bi-directionally to the power grid of the energy community. Thus, prosumers are able to import energy from the grid for consumption and for storage, and they are also able to generate their own energy for local consumption, storage or for export to the power grid. Therefore, such energy related and smart grid enabled expertise and practices forge links between the different components of the energy community.

Driven by the multifold benefits of community level energy projects, such expertise and practices are evolving continuously at the energy community level. The multifold benefits include building a sense of ownership and control over the communitys energy future, finding a sustainable energy solution to the community, generating electricity that is owned by the community, outsourcing the communitys energy resources, reducing electricity costs and thus energy costs of the community, and improving the overall energy efficiency in the energy community.

1.7   Challenges in an Energy Community

Supplying adequate, clean energy to a world that is rapidly industrializing at every level of the society is one of the greatest challenges of the 21st century [15]. The report from Energy Information Administration (EIA) of the U.S. Department of Energy (DOE) [9] projects that the worldwide energy consumption is expected to have increased by 54% by the year 2035 from what it was just around the beginning of the century in 2008. Such challenge of supplying adequate, clean energy is compounded by the problems of maintaining stable energy cost through an era of dwindling, non-renewable energy resources and reducing energy related pollution in an age when greenhouse gas emissions are often associated with significant changes on the global climate.

While an important component for solving the aforementioned problems is the integration and proper utilization of renewable energy resources, which are often generated from distributed producer-consumer (prosumer) households in a society, the challenge at an energy community level remains coordinating prosumer households and other components of a society into an energy community that employs a sustainable architectural design approach to incorporate demand response control mechanisms for various kinds of utility maximization strategies and integrates renewable resources into a smarter grid that enables bi-directional communication to and from such prosumer households thus facilitating distributed generation.

1.8   Structure of the Thesis

This thesis report is organized as follows. First, a section on the objective of the project discusses the aim of the project; the research questions posed in the project and expected contribution of the project work. Following that, a chapter on smart grids control architecture describes the architectural control requirements, the comparisons and the contrasts of different models with an explanation about the benefits of incorporating demand side

management and demand response control mechanisms into the smart grid. The third chapter focuses mainly on a design of a control architecture at an energy community level. It presents a system model of the energy community with its architectural components and specification on resource reservation. In the fourth chapter, an identification of resources which can be considered into the utility function for a smart grid based energy community has been performed which throws light on the following sections that base mainly on utility maximization functions. The following two chapters discuss utility maximization mechanisms and the consideration to grip the proper and essential utility components, and optimization mechanisms for such utility functions respectively.

Chapter 2

Objective

2.1 Hypothesis

As the cost of energy resources is ever increasing and the penetration of alternative energy resources is at its all-time highest in many societies, the problem of finding an efficient control mechanism for the specification, identification and utilization of available electrical energy resources at the energy community level is a very important societal problem to address in order to achieve an increased and comfortable use of alternative energy resources, an efficient scheduling of consumption, production and storage of energy resources and ultimately bring a reduction in energy cost for both energy companies and prosumer (producer-consumer) households.

2.2 Objective

The objective of this research aims to address this issue at the energy community level through identification and a design of control architecture and utility maximization mechanisms that directly aim at reducing peak energy demand and maximizing the usage of renewable energy resources, both of which contribute substantially to reducing the energy cost of the community.

2.3 Research Questions

In this project, two research questions have been addressed based on the quality of information that they cover and the amount of quantifiable data that they relate to, each of which gives a clearer overview of the requirements, specifications and solutions to the future smart grid based energy community.

The first research question relates to the smart grid based architectural intelligence requirements for an energy community. The research enquires what kind of intelligence is necessary for the different nodes in an energy community and how such an energy community could be managed using control architecture. The included research sub-questions

enquire how the distributed nodes in the energy community can be managed using the control architecture, how open source should the local network be to accommodate energy data from self-communicating nodes, what set of information should be captured or stored at each node and what types of intelligence are required at the various nodes that include smart appliances, households, and the community.

The second research question relates to the requirements of utility maximization in a smart grid based energy community. It enquires how an energy community can make optimal use of its resources, how the availability of real time data could be used to optimize the resource utilization of the system, what kind of strategy or algorithm is an efficient resource utilization strategy or algorithm, and how such a strategy or algorithm could benefit from the availability of data on the generation capacity and the demand of each appliance on a per minute basis.

2.4   Research Setting

The research work is conducted on a renewable energy company named Qurrent, which manages an energy community namely Q-munity that is composed of a central server (Q-Server) and prosumer (producer-consumer) households each with a home gateway, an energy management system (Q-box), smart meters and household appliances under a renewable energy company (Qurrent) that is based in Amsterdam, The Netherlands.

2.5   Scope of the Thesis

This thesis work is focused on presenting control architecture and utility maximization mechanisms within the scope of an energy community. As defined in the previous chapter, the energy community terminology is defined as a composition of various sectors that consists of residential households, service units, production units, sundries and small scale industries, with an emphasis on the electric power production, consumption and storage characteristics of the different sectors and the aggregate energy profile of the community. Moreover, the research setting is at Qurrent Renewable Energy Company, which conducts a smart grid based energy community management. The company currently administers more than forty prosumer households which are composed into one energy community.

2.6   Goal of the Thesis

The major goals of this work are presenting control architecture for an energy community level smart grid development and utility maximization mechanisms at the energy community level which help address the current issues related to energy cost reduction through maximizing energy efficiency and through increasing the identification and the level of usage of green energy resources. These goals generally conform to the general goals of the smart grid which are to ensure a cost and energy efficient, secure and safe electric power grid which has a transparent, sustainable and environmental-friendly system operation. Moreover, the thesis goals go beyond what could be achieved by the general

goals of the smart grid by providing better identification and utilization mechanisms for green energy resources and by proving better load management mechanisms both of which contribute to energy efficiency and reduction of overall energy cost.

2.7 Contributions of the Thesis

The major contributions of this thesis are presenting control architecture for an energy community level smart grid development and deployment and utility maximization mechanisms at the energy community level which helps to address the current issues related to energy cost reduction through maximizing energy efficiency and through increasing the identification and the level of usage of green energy resources. Since most energy communities are composed mainly of buildings and electric vehicles, and given the fact that such residential and transportation sectors consume a large part of the total energy use of many communities [15], adopting the novel mechanisms presented by this paper would help in alleviating the dependence on non-renewable energy resources such as oil and gas through a better communication infrastructure, more optimal control mechanisms and proper usage of available energy resources for smart grid based energy communities.

Chapter 3

Literature Review

3.1 Introduction

In this chapter, the literature review that was conducted in the research is presented. The literature study first starts with the concept of smart grid, and identifies recent developments in the field of smart grid based power systems. Then, the literature review covers important concepts in power systems management such as Demand Side Management, and implementations such as Demand Response Programs. Furthermore, the difference between such programs has been identified and presented along with a discussion on why such programs are important. The literature study also includes recent developments in the field of power systems which enable demand side management without interfering with privacy issues of the prosumer. Finally, the results achieved in the literature study are presented.

3.2 The Smart Grid Framework

The NIST Smart Grids Architectural Framework presents the smart grid electricity and information architectural framework as an integration of end-to-end, advanced communication infrastructure for the electric power system that provides consumers with near real-time information on their energy consumption [6]. The proposed smart grid system simultaneously draws energy from multiple sources including thermal, wind, oil, solar and hydro sources [16]. Power is directly transmitted through the utility grid, whereas data is routed through a communication line using the internet. Moreover, the architectural framework provides a pricing scheme that reflects changes in energy supply and demand to avoid power demand peaks in energy usage based on the operation of smart appliances and devices.

The communication data gives the total power transmitted across the grid for specific points in time, along with the corresponding voltage and frequency. The smart grids interoperability panel in reference [10] further identifies intelligence in the overall framework in terms of characteristics such as:

* lower duration and frequency of power outages

* lower generation requirements with reduced inefficiencies in energy delivery and use
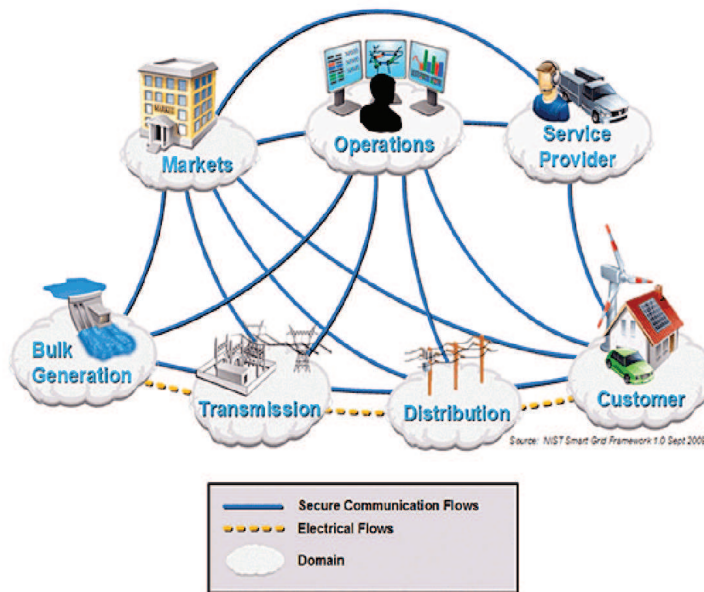
Figure 3.1: NIST Smart Grids Conceptual Model

* efficient charging of electric vehicles

* integrated renewable wind and solar resources

* effective distributed generation and storage

Focusing on the end user services in the customer domain, as an example, in reference [17], architectures for smart end-user services in the power grid have been presented with respect to actors and components of smart grids as shown in Fig. 2.

Inside the prosumer household, the energy management box hosts local intelligence and is connected to a number of smart devices such as a smart digital meter, a smart washing machine and a PHEV charging station [18]. To achieve optimal energy efficiency, the home energy box is connected through a communication network to external service providers that may offer additional intelligence.

Based on the conceptual architectural framework from NIST, and by encapsulating some of the service requirements into producer-consumer (prosumer), reference [19] presents a more distributed and multi-layered prosumer model that implements various control and interaction functions so as to realize distributed intelligence in the energy service. The main advantage of the prosumer based architecture was argued that the basic agents which are prosumers are of the same type, which makes the proposal of a high level network of homogenous agents possible. Moreover, the prosumer acquires functionality of sensing, monitoring and energy optimization, which supports energy efficiency efforts. This prosumer based model is presented in the following figure.

Another dimension into the architectural model presented by the NIST framework is to simplify the smart grid architectural model with an ICT perspective. The Interna-
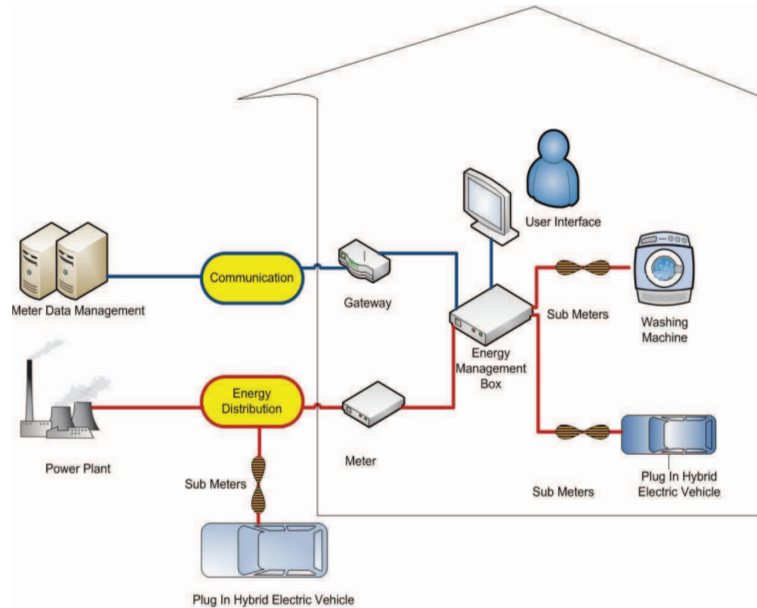
Figure 3.2: Smart Grid End User Services
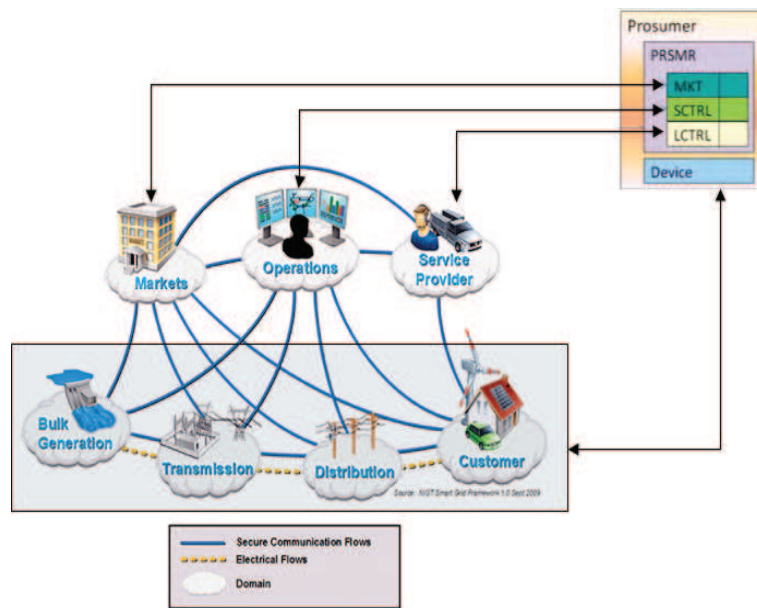
Figure 3.3: NIST Model Evolving to Prosumer Model

tional Telecommunication Union takes such a view point in reference [20] and presents a simplified yet ICT-focused architecture consisting of five domains, in contrast to the seven domains categorized by NIST:

* Grid domain which includes the Bulk Generation, Distribution and Transmission domains;

* Smart Metering (AMI) domain;

* Customer domain which contains smart appliances, electric vehicles, premises networks (Home/ Building/ Industrial Area Network);

* Communication Network domain; and

* Service Provider domain which includes Markets, Operators and Service Providers domains.

3.3 Demand Side Management

Demand Side Management (DSM) is a set of interconnected and flexible programs which allow customers to shift their electricity demand away from power consumption peak periods, reduce the overall energy consumption, and thus improve the efficiency of the energy system, primarily focusing on energy consumption [21]. As presented in reference [22], DSM ranges from improving energy efficiency using smart energy tariffs with incentives for certain consumption patterns, to sophisticated real-time control of distributed energy resources. Moreover, DSM includes programs implemented by utility companies to control the energy consumption at the customer side of the meter [23].

Demand Side Management incorporates activities between the utility, customers and sometimes even third party energy companies to implement efficient energy utilization. As outlined in reference [2], such utilization benefits the customer, the utility and society from the point of view of:

Customer Benefits	Societal Benefits	Utility Benefits
Satisfy electricity demands	Reduce environmental degradation	Lower cost of service
Reduce or stabilize costs	Conserve resources	Improve operating efficiency and flexibility
Improve value of service	Protect global environment	Reduce capital needs
Maintain or Improve lifestyle and productivity	Maximize customer welfare	Improve customer service

Table 3.1: Benefits of Demand Side Management

Therefore, the task of a demand side manager is to define the load shape according to the load that has been researched by the utility. The objectives for the various load types are defined in reference [24] as:

Figure 3.4: **Peak Clipping:** involves reducing power consumption load during periods of peak demand.
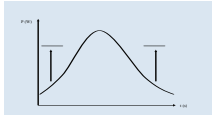
Figure 3.5: **Valley Filling:** involves improving power consumption load factor through building power consumption load in off-peak periods.
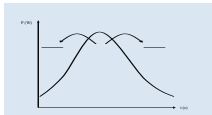
Figure 3.6: **Load Shifting:** is the reduction of power consumption load during peak demand periods and the building of power consumption load during off-peak hours.
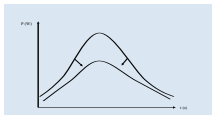
Figure 3.7: **Energy Efficiency:** is the reduction of load during most hours of the day.
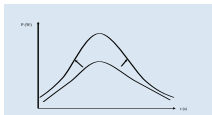
Figure 3.8: **Electrification:** is the building of power consumption load during all or most hours of the day in an equal manner.
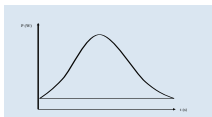
Figure 3.9: **Flexible Load Shape:** involves using programs that change the energy consumption of customers on a need-based manner based on agreement.

3.4 Demand Response

One of the mechanisms for control of power grid operation is Demand Response. In reference [25], Demand Response (DR) is defined as the change in electric usage by end-users from their normal consumption patterns in response to changes in the price of electricity over time. An alternative definition for Demand Response is the incentive payment designed to induce lower electricity use at times when wholesale market prices are high or when the overall system is unstable. Moreover, Demand Response controls the electricity demand by actively reducing the use of resources from the consumer side rather than increasing the electricity supply to meet the demand [26]. The ultimate goal of the demand response mechanism is that the peak power consumption is reduced to a level that the power utility can reduce the need for less efficient peaking power plants to feed the peak demand [27].

3.5 Why is Demand Response Important?

There are many reasons why Demand Response programs are important. Maintaining electricity demand and supply is a very critical problem that can be answered by the use of demand response programs that balance the right amount of demand to the available

amount of supply within the schedule duration. This is important because an imbalance between electricity supply and demand would harm the electric grid within seconds. Also, the size and complexity of the electric grid which takes years of construction, generation and transmission should be taken into consideration [28]. Such a system requires proper management of the system balance with in decision intervals that vary from years of planning to seconds of balancing supply and demand side fluctuations.

General classifications of Demand Response Programs, Benefits and Costs presented in [25] as:
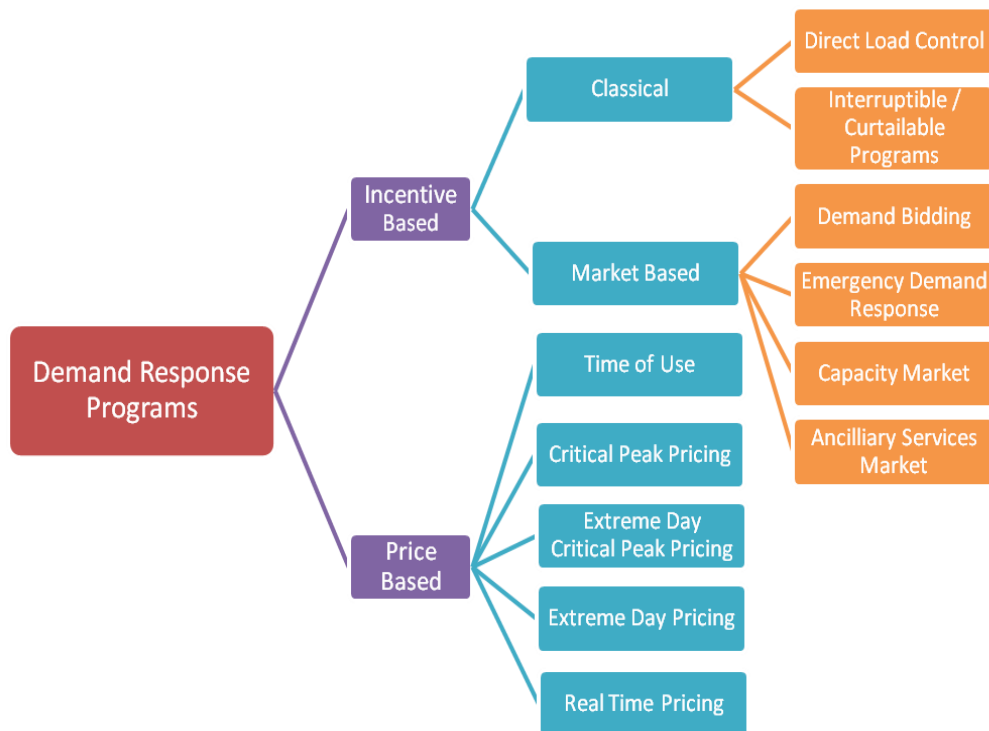
Figure 3.10: Demand Response Programs Classification

Demand Response programs are generally classified into Price Based programs and Incentive Based programs. Price Based programs provide prosumers with time varying price rates that reflect the cost of electricity in different time periods aiming to reduce peak demand electricity usage. Price Based programs are classified into real-time pricing (RTP), critical-peak pricing (CPP) and time-of-use pricing (TOU). On the other hand, Incentive Based programs pay prosumers that are willing to reduce their demand at requested peak demand durations as requested by the utility company. The following table shows the comparison and contrast between the two Demand Response programs.
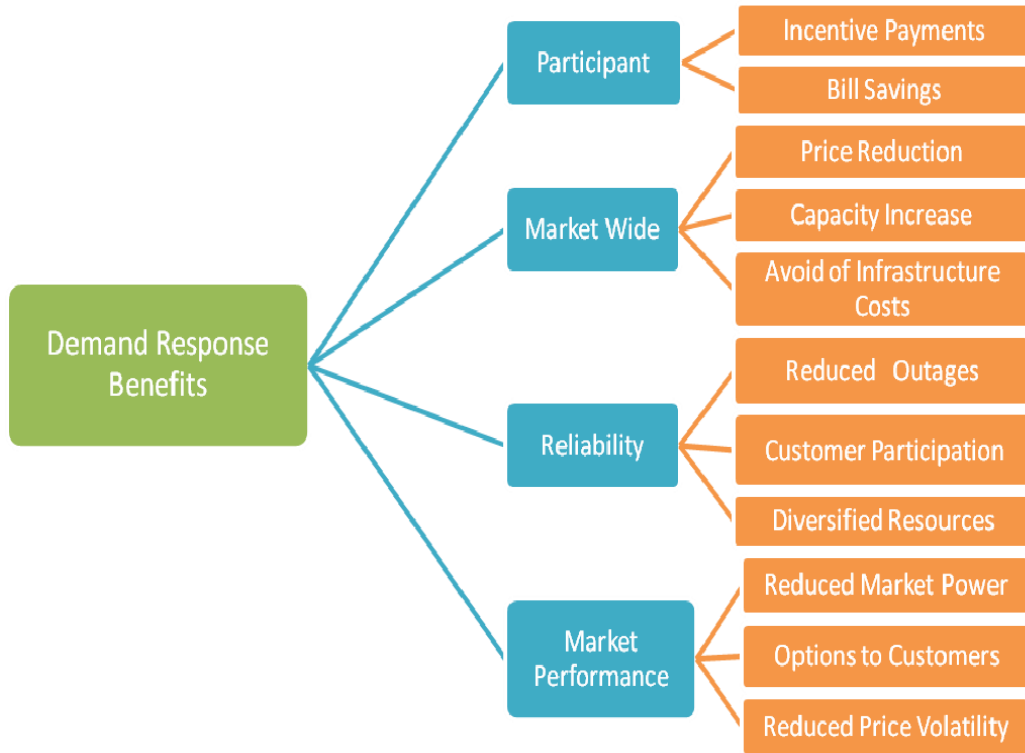
Figure 3.11: Demand Response Benefits Classification

With respect to the Demand Response (DR) architecture for the customer domain, some suggestions for such classification of demand response mechanisms have been proposed in reference [29]. In the paper, four different use cases were proposed based on common architectural element for electricity delivery without demand response, for direct load control of devices, for price based control of demand, and for price based control of demand with direct load control of appliance operation. However, the specification of how each of these techniques could be applied in an actual energy community has not been presented. For example, it has not been stated how price based control integrates with direct load control of devices. Also importantly, the question of how much amount of price based control should be applied before the utility company could shift to direct load control of appliances has not been answered.

Another classification of demand response mechanisms is presented in reference [30] which classified the programs based on the type of customers and the type of resources that they consume. For example, reactive and proactive resources are one such classification presented by the paper. Reactive resources include customers that receive demand response signals to reduce or shut down their demand or update rates to adjust their consumption voluntarily where as proactive resources refer to the customers who initiate a demand response action by sending bids to the utility to either reduce their demand in exchange for payments, or to negotiate a price for buying energy.

Demand Response Programs	
Price Based Programs	**Incentive Based Programs**
Time-of-Use (TOU): is a type of pricing that sets price rates with different unit prices for usage during different time blocks inside the 24 hour (daily) duration, according to average cost of power generation and consumption during those time periods.	**Direct Load Control (DLC)**: includes programs implemented by utility companies to shut down or cycle the operation of appliances for residential-type and small business type prosumers on short notice. **Interruptible/ Curtailable (I/C) Service**: provides a rate discount or bill credit for prosumers that abide to load curtailment or reduction during contingencies and provides penalties to prosumers that do not abide to curtailment policies, making it more applicable to industries large business prosumers.
Real-Time Pricing (RTP): is a type of pricing that sets price rates which fluctuates hourly reflecting changes in the wholesale price of electricity. Prosumers are typically notified of RTP prices on a day-ahead or hour-ahead basis.	**Demand Bidding/Buyback Program**: is offered to large prosumers of higher than 1MW power usage in which prosumers offer bids to curtail load based on aggregate electricity market prices or an equivalent. **Emergency Demand Response Program**: provides incentive payments to prosumers for load reductions during periods when reserve shortfalls arise.
Critical Peak Pricing (CPP): is a type of pricing that is hybrid of TOU and RTP by implementing Time of Use pricing but shifting the normal peak prices of TOU to a much higher CPP prices in the event that system reliability is at stake or supply prices are very high.	**Capacity Market Programs**: prosumers offer load curtailments as system capacity to replace conventional generation or delivery resources using a day-of notice of events to get payment incentives. **Ancillary Services Market Programs**: prosumers bid load curtailments in ISO/RTO markets as operating reserves aiming to get paid the market price for committing to be on standby if their load curtailments are needed.

Table 3.2: Demand Response Programs Price-based and Incentive-based Programs

Demand response service providers could also aggregate a group of customers and provide the utility with large demand reduction upon request. These aggregation entities have the capability to provide a demand reduction that is based on the location of the customers and in compliance with the individual constraints of the mutual agreements, without

much reliance on the network model [19].

As the penetration of demand response increases, however, incorporating the network model into the demand response analysis algorithm becomes important. This is necessary because it ensures the proper performance of the demand response process and achieves the targeted demand reduction. Reference [30] argues that the added value to the demand response algorithm can only be realized if the engine is developed as an integrated function of the Distribution Management System (DMS) at the network control center level. The paper further projected this argument by presenting a demand response architecture consisting of a demand response engine that receives meter data from the Meter Data Management System (MDMS), which in turn collects the data from individual customers or the aggregator(s) through different means of communication. Depending on the types of programs the customers are subscribed to, the output provided by the demand response engine may contain control commands for directly controllable loads, demand reduction signals for interruptible loads and/or updated electricity rates for voluntary demand reduction.

The demand response engine introduced in reference [30] is composed of a Demand Response Manager that generates demand response messages which include commands and requests to be transferred to the meters/load controllers, a Validation Module that validates whether or not the demand response event has been accomplished successfully, a Local Database that stores the system status (customer information and network model/connectivity) to be utilized by the demand response sub-modules and a Customer Ranking Engine that runs the demand response event attributes by the individual constraints and identifies the customers that match the demand response event.

The demand management system calculates the forecasted demand, thereby estimating the capacity margin for the future time intervals. The capacity margin is defined as the difference between the demand limit and the forecasted demand taking into account the reserve margin. A decrease in this capacity margin or a negative margin would cause the utility to trigger a demand response event. Essentially, the demand response engine sends three types of messages to the customer meters and/or load controllers: price signals, control messages and meter poll messages.

Normally, a control message would contain the start time and end time of the event, and depending on the type of the program may contain the required demand reduction level for the individual customer. For example, this could correspond to an operational shift control message that is aimed at peak energy demand reduction sought in this paper. Moreover, customers may have the option not to participate and forgo the payment with or without a penalty. As suggested in reference [30], in such cases, the utility might turn to load shedding as the last resort option.

Another issue related to the dynamics of energy demand load and the implementation of demand response programs is the response time it takes, termed ramp period by various literature on demand response programs, until the consumer demand is reduced to the requested levels. It is only after the ramp period, which can take from a few seconds to a few minutes for larger loads that the utility can verify whether or not the requested demand reduction actually took place. This can be performed by sending meter poll messages to provide meter readings at the start of the sustained response period.

3.6 Energy Disaggregation

As part of the identification of the operational schedule of prosumers, energy disaggregation was found an interesting concept to include in the literature study. Most of the problems regarding optimal scheduling, resource utilization and utility maximization in an energy community are based on appliance operation information. This is because of the fact that appliance level operational information provides an accurate data that allows the researcher and/or the utility company to identify user behavior and thus propose better mechanisms to schedule appliances and to decide how a resource is utilized in an energy community. However, because of privacy concerns that dwell in most components of an energy community, it is not an easy task to find power consumption behavior from appliances and production units inside prosumer households or other members of the energy community. For example, if such an appliance level data is provided to an aggregator or a central server, some users and members of the energy community could be sensitive of the fact that the controller might get access to detailed user specific information such as the time that they are at home, the time when they watch TV, the kind of TV channels that they are watching, for how long they take a shower, for how long they stay in the bathroom, or so. This could possibly open doors to other related security issues.

To avoid such matters, energy disaggregation is used as a mechanism that aims at finding the specific energy usage information by decomposing the aggregate energy profile into subcomponents [31], [32], [33]. For this purpose, it is important to identify the energy profile pattern of every appliance so that they could be easily identified from the aggregate energy profile. Considering the fact that different kinds of appliances have different kinds of energy profile patterns, it might look an easier task to identify which kinds of appliances are operating from a given aggregate energy profile, using different pattern recognition techniques. However, through an extended literature review and according to reference [31], [32], [34], [33] and [35], it was identified that such a setup requires a very high frequency probing of the main supply of each component. And a comparison of that with a low frequency probe form each appliance according to reference [31] revealed that such a mechanism could only be correct with in an error margin.

3.7 Results

In this chapter, a literature study has been presentedthat has been conducted as part of the research. Included in the study were the requirements and specification of the smart grid conceptual framework. In the framework, it was possible to identify what kind of components need to be included in the smart grid based power system. However, a specification of control mechanisms and how such mechanisms could be integrated in an architecture is not included. Identifying this limitation provided a motivation to work on presenting control architecture for a smart grid based energy community. For this purpose, an extended literature study has been included which aimed at gathering more information on control mechanisms such as demand side management. These mechanisms help balance energy imbalances in a smart grid based energy community. The requirements for such mechanisms are the knowledge of supply side commitment and demand side operational

schedule. Therefore, advanced mechanisms such as energy disaggregation were included in the literature study to identify the possibilities of such control techniques while preserving demand side privacy.

Chapter 4

Control Architecture for a Smart Grid based Energy Community

4.1 Introduction

In this chapter, the control architectural components of a smart grid based energy community are presented. First, the electricity and information architectural framework components of the smart grid are identified. Then the smart grid based energy community has been modeled, and the system constituents have been presented. In addition, control mechanisms that are associated with the architectural framework such as demand response and regulation control mechanisms are modeled and presented. The results achieved in the chapter are presented in the results section at the end of the chapter.

4.2 Related Work

The reference architecture of the smart grid presented by ITU-T [20] is presented as follows. It illustrates the relationship between domains using conceptual data flow lines representing the flow of information and communication between domains. Furthermore, reference points are used to specify the interactions going on between the domains through the data and control lines at the specified points.

Service Provider Domain
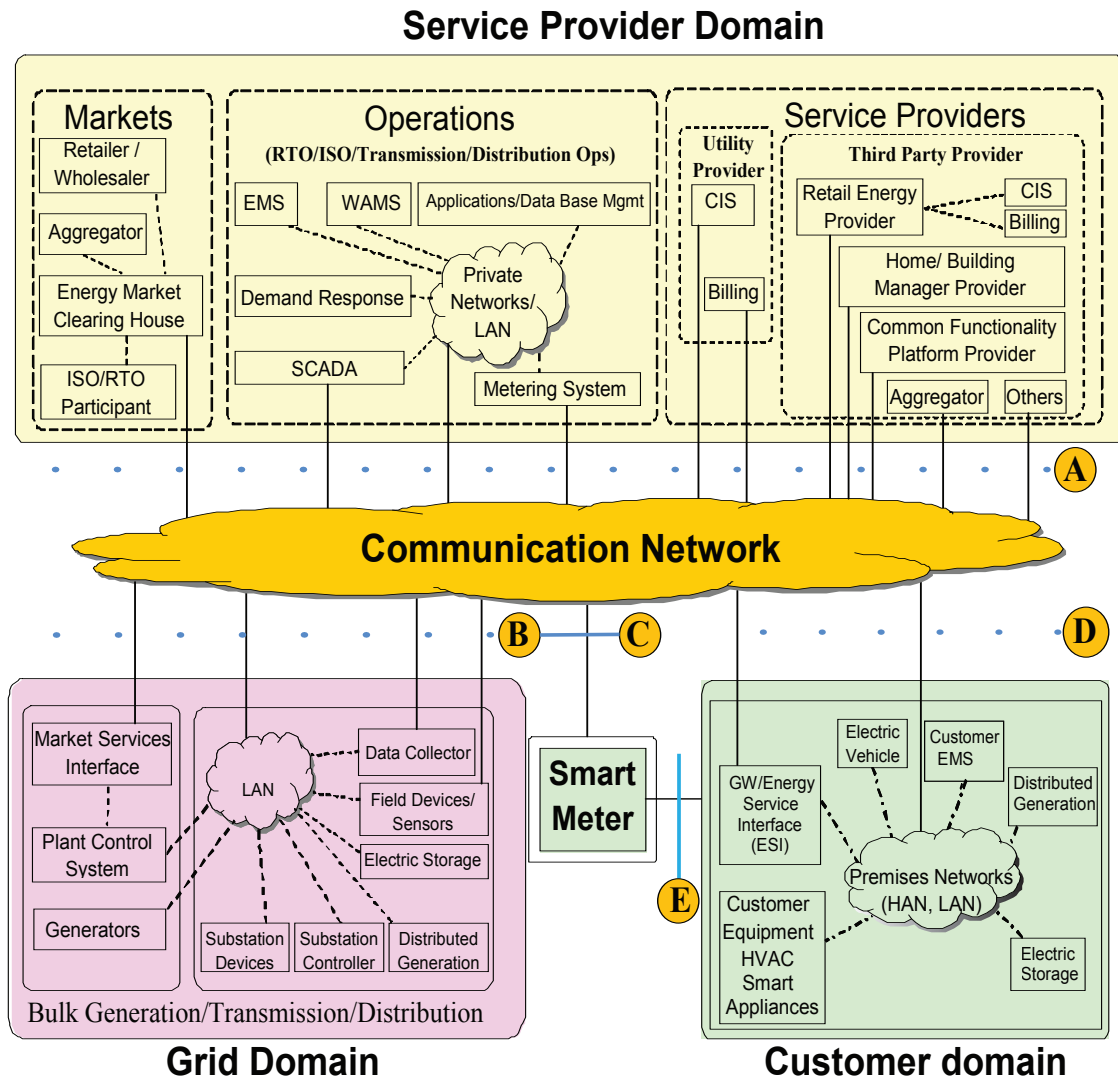
Figure 4.1: ITU-T Reference Architecture for the Smart Grid

* **Reference Point A**: Between Service Provider domain and Communication Network domain, it enables communications between services and applications in the Service Provider domain to actors in others domains to perform all Smart Grid functions illustrated above.

* **Reference Point B** : Between Grid domain and Communication Network: It enables the exchange of information and control signals between devices in Grid domain and the Service Provider domain.

* **Reference Point C** : Between Smart Metering domain and Communication Network:
  It enables the exchange of metering information and interactions through operators
  and service providers in the Service Provider domain towards customers in the Cus-
  tomer domain.

* **Reference Point D** : Between Customer domain and Communication Network do-
  main: It enables the interactions between operators and service providers in Service
  Provider domain and devices in Customer domain.

* **Reference Point E** : Between Smart Metering and Customer domain, it conducts
  services through ESI.

First the NIST framework, then the Prosumer architectural model, which has
evolved from the NIST framework, and finally the ITU-T document have been referred
in this paper to describe architectural frameworks for the smart grid. However, the different
models do not present a detailed control architecture that is tailored towards better identifi-
cation of renewable energy resources. The design of such architecture would help increase
the integration of renewable energy resources in the smart grid and thus increase their usage
in an energy community. Moreover, the proposed smart grid architectural models can still
benefit from better flexibility from the side of the prosumer by allowing the user to choose
from a wider duration of appliance operation time according to its need to either save money
or to use more renewable energy resources. This mechanism opens door to reducing power
peak from the aggregate energy profile of the energy community. This further allows reduc-
tion in the aggregate energy cost and increase of energy efficiency in the smart grid. These
important objectives are attained in this thesis paper by presenting novel renewable energy
resource identification and utilization mechanism that allows renewable integration into the
smart grid and provides utility maximization mechanisms that aim for aggregate energy cost
reduction.

4.3   Problem Formulation

The research problem mainly focuses on a smart grid based control architecture for
resource specification, identification and utilization of electrical energy resources in an en-
ergy community. Given is an energy community (Q-munity) that consists of a central server
(QServer), and a number of prosumer (producer-consumer) households. It is assumed that
each prosumer household consists of a home gateway, an energy management system (Q-
box), smart meters, smart appliances, and/or storage units. Given a specification on the
aggregate energy profile of the energy community with the maximum peak net power, the
minimum peak net power and the average net power, what is an efficient control architecture
for the smart grid based energy community which enables the specification, identification
and integration of renewable energy resources and provides more control options over the
peak to average ratio of the aggregate energy profile, over the difference in level of utiliza-
tion of renewable energy resources and over the energy cost and price for the central server
and prosumer households in the energy community.

Moreover, allocation of power bandwidth levels and resources by the central server to users that would like to operate appliances is included in the architectural model as a description of the operation of the system model. Power bandwidth level refers to an operating power level that a utility company could potentially provide to its prosumers. In such sense, the term is different from energy bandwidth level as it refers to the limit on instantaneous energy consumption, while the latter, as used commonly by energy companies, sets a time duration based energy consumption limit (for e.g., weekly, monthly, etc.). As an important architectural model parameter, the use of power bandwidth level allows the central server to set a proper control over the aggregate energy profile of the energy community by constraining that the instantaneous power does not go beyond a certain level, or by setting different prices for different power bandwidth levels. The advantage of power bandwidth as an important architectural model specification goes beyond what is possible with energy bandwidth constraint, since it can be applied at spontaneous moments like instants during peak hours of the day, rather than only during wider durations of time like what is currently possible with energy bandwidth levels.

4.4 Architectural Control Model Choice

The first step in specifying smart grid based control architecture is a proper modeling of the control requirements for the smart grid based system [36]. For this purpose, the system model would include a specification of the requirements of the control architecture and how different control mechanisms are integrated into the control architecture. The requirements of a control architecture for a smart grid based system are presented in reference [30] and [37] as *Demand Response Control* (the mechanism by which different control parameters are used for controlling smart energy devices and their usage), *Scalability* (the level of expandability in terms of the number of smart devices in the Home Area Network), *Security* (the provision of sufficient authentication and integration of new and existing smart devices), *Privacy* (the level of exposure of private information from the side of the consumer), *Flexibility* (the level of support for *plug and play* devices and related configurability options of the architecture), *Network Integration* (the level of adaptability to the existing IP Network), *Availability* and *Device and Network Management*.

One approach of presenting control architecture for managing smart grid based systems is using *hierarchical architectural models*. In reference [12], hierarchical control architecture was presented using the concept of model predictive control (MPC). The system is adapted to flexible systems one example of which is the smart-grid electric power production, storage and consumption. The architecture consists of a top-level *MPC controller*, second-level *aggregators* and lower-level *autonomous units*. The *MPC controller* is based on quadratic optimization to attain low algorithmic complexity and high scalability. The *aggregators* are controlled by an online algorithm that uses empirical predictive control. The *autonomous units* are designed to represent smart grid based electric power production, storage and consumption components. Although the hierarchical architecture model could represent the components of the smart grid in a proper and manageable manner, it has not been specified why an aggregator is an important component of the model, or whether the

model could perform efficiently in a two-tier architecture using a central server that replaces the aggregators. In addition, the presented predictive control approach to the smart grid control architecture did not use a way of identification of the resources connected to the grid in order to control access to resources and manage their optimal usage. For example, the need for a better identification of resources connected to the grid arises at times when it is necessary to identify the availability of green energy and/or non-green energy supplies.

In reference [13], Resource-Oriented Architecture (ROA) is implemented for smart grid based Home Area Network (HAN). ROA is a type of architecture that consists of clients and servers for requests and responses and focuses on resources as well as on the access to resources. In the paper, the architecture is implemented using Representational State Transfer (REST) services, which is an architecture design style with a set of design criteria that defines the request-response interaction between the server and clients according to the transfer of representations of resources.

In the paper, it was argued that in comparison to other architectures like Service-Oriented Architecture (SOA) which can give only a number of service interfaces, Resource-Oriented Architecture (ROA) requires the energy company to know which devices in the smart grid based network can receive what kind of message and what level of control is allowed before sending a control message. It is further pointed that in ROA, the energy company needs to make sure that these control commands or messages are granular enough to be deciphered by Home Area Network devices.

In comparison, for a smart grid based system, where emphasis is given to point-to-point integration of services, Service Oriented Architecture (SOA) is an architectural model solution that allows systems to provide a given resource to other systems that need to use the resource essentially *on-demand*. This enables a one-to-many integration with a high level of standardization. Moreover, in this work, SOA is chosen as the architecture for the smart grid based energy community since it is generally more flexible and more scalable than ROA and since it can handle complex data retrieval operations and updates.

A home area network energy distribution focuses predominantly on consumer household appliances. Such household appliances are generally networked inside different households using home gateway devices and are connected to the utility server using smart meter devices. The main difference between these two devices is that the home gateway is enhanced for information content distribution, while the smart meter is enhanced to enable two-way communication with the central server as part of the advanced meter infrastructure (AMI) [10]. However, as pointed out in reference [37], the home gateway can also support smart energy control of household appliances. With the presence of a smart meter and a Home Gateway device, there are two mechanisms to control the home network; either through the gateway device or through the smart meter. On the basis of the control flow, the architecture options for the home area network can be classified as centralized control and distributed control.

A centralized control architectural model takes direct control over energy-consuming household appliances using a central server that perform control on an individual household appliance basis by that uses advanced meter infrastructure to communicate with the smart meter and to send pricing and demand response control signals. As pointed out in reference [37], this allows the utility to have direct control of the energy consumption at each

individual node without being influenced by the gateway device.

What is also pointed out in reference [37] is that in a distributed control model, a home gateway rather than a smart meter is in control of the smart devices. Demand response signals from the utility are propagated only up to the home gateway which independently controls the devices. When comparing the centralized and distributed smart grid control architectures, centralized control architecture provides better advantages to the utility company where there is need to have direct control of the nodes in the home area network. As pointed out in reference [37], such architecture sends demand response control signals to and from a central server and appliances and production units via the use of smart meters. In such a way, smart meters are on the direct control flow path of the control architecture whereas home gateways are outside the control flow path of the control architecture.

When considering the existing control systems in the current electric power control organization, most of them are based on the concept of a centralized electric utility that does not benefit from observing emergent behavior phenomena at all frequencies in the overall system whenever relevant [19]. For example, if a number of households increase their usage frequency of a particular type of appliance in conjunction with certain environmental condition, such behavior may not be readily visible to the central server [38]. Such scenarios exhibiting evolving behavior could be more transparent in a more distributed architecture when compared to centralized architecture.

In a distributed architecture model, the home gateway has more control responsibilities on devices rather than the smart meter. In such a way, control parameters for demand response are communicated though the home gateway to the devices as indicated in reference [37].

Such distributed control architecture consisting of a network of prosumers and control requirements has been dealt with various literatures. For example, reference [19] modeled the electricity infrastructure as a network of intelligent agents using a control paradigm based on network control theory. The distributed control architecture was modeled as a multi-layered prosumer model that implements control and interaction between prosumers. The *device layer* corresponds to the electrical sources, transformers, etc. The *local control layer* corresponds to the hardware and software used for controlling stand-alone device actions. Examples of this are a generator governor or an EV battery charger. The *systems control* contains internal system control corresponding to EMS/DMS-like algorithms such as state estimation, contingency analysis and transfer capability and external system control which addresses interactions with the surrounding world, including self-identification, recognition, and agreement, assignment, and formation protocols. The *market layer* addresses the economics of production, storage, demand shift and comfort costs.

In addition to what has been suggested in reference [37], more communication mechanisms between the owner and the prosumer energy management system could make use of pre-defined commands such as *increase comfort*, *minimize energy cost*, *increase availability* or *maximize greenness*.

Concerning architectural model choices, different comparisons and contrasts for centralized and distributed control architectures have been identified. It has been noted that in terms of demand response control, centralized architectural model enables direct control of devices from the utility, which means that the utility also knows if demand response

requirements have been met. While in the distributed architectural model, the home gateway independently controls demand response requirements, and the utility, if there exists one, may not be able to predict if demand response requirements have been successful [37].

In addition, in terms of demand response control and with increasing network sizes, in a centralized architectural model, the utility could face difficulties managing demand response mechanisms while distributed architectural model has the advantage of scaling well with increasing network sizes. In terms of device and network management, and considering where the support, update, monitoring, configuration, error management and programming takes place, in a centralized architecture model, the utility is responsible for all device and network management that requires software and support. It can be said that this is a stricter requirement on the utility, since in a distributed architecture model, device and network management is the task of the individual home gateway. Such evaluation on device and network management also decides on the level of privacy of users, which is limited in the case of a centralized architecture model since the utility has direct access to individual power usage information one way or another. In a sharp contrast, distributed architecture model could enable the home gateway to limit the private information of the user. Flexibility is another evaluation criterion between a centralized architecture and a distributed architecture. In a centralized architectural model, the entire network is managed by the utility, thus making the network less flexible when compared to a distributed architecture model where the level of control on the home gateway level benefits the user with the freedom to override some or any of the existing policies.

Considering scalability, it is presented in reference [37] that a centralized architectural model requires the smart meter to directly interface to the home area network, which benefits the consumer by avoiding the requirements of additional devices although such an approach does not have the capability to scale to a large number of smart devices, making the implementation of demand response control difficult since control is made on the level of smart meters. In contrast, distributed architectural model enables the home gateway to control the home network, making the solution more scalable.

Another vivid contrast between the two architectural models is security, which is higher in case of a centralized architectural model since it is easier to establish a trust relation between a central server and smart devices, while it is lower in case of distributed architectural modes due to more internet connectivity options that could make the system vulnerable. The following table summarizes these comparisons and contrasts for centralized and distributed architectural model evaluations.

4.5   The Energy Community Model

The energy community model consists of the model for prosumer households (which consist of prosumer household appliances and production units, sensors and smart meters, the Qbox as an energy management system and a home gateway), the Qmunity server (which consist of data from several energy management systems or Qbox), the Qmunity system (which consist of prosumer households, an energy profiler, a scheduler, a price setter and display), management and authentication, and the Qmunity database that is used for

Architectural Model Evaluations	Centralized	Distributed
Demand Response Control	Utility Controlled	Home Gateway Controlled
Device and Network Management	Utility Controlled	Home Gateway Controlled
Flexibility	Utility Control (less flexible)	User Controlled (more flexible)
Home LAN Integration	Internet Connectivity Not Required	Internet Connectivity Required
Privacy	Utility has Direct Access	Limited Private Information
Scalability	Non-scalable	Scalable via Home Gateway
Security	Easier to Build Trust	Vulnerable through the Internet

Table 4.1: Architectural Model Evaluations

storing data for utility maximization and optimization mechanisms. The overall architecture is displayed as follows.

4.6 The Energy Community Architecture

Based on the architectural frameworks and specification referred in previous sections, the control architectural components that are important to define the control architecture are included in the proposed control architecture. Differently from other frameworks and specifications mentioned in the *Related Work* section, the focus of the proposed smart grid based energy community architecture is on the control architectural requirements, specification and development of such an architectural model. Moreover, important components that are used to facilitate and control renewable energy integration into the power grid, aggregate energy cost minimization and utility maximization in the energy community are included in the proposed architecture.

4.6.1 The Application Control Layer

The *Application Control Layer* is associated with the *management of electricity supply and electricity usage*, with *controlling the performance of the power distribution systems* and with *analyzing system operation*. These control functions are performed through *energy marketing*, *dynamic pricing*, *demand response mechanisms*, *information management* and *customer billing and management*.

To perform these control functions, the *Application Control Layer* is responsible for initiating meter readings and processing the readings after they have been recorded from the meter. In managing energy demand, the Layer is responsible to effect the Demand Response operations. This is made possible by contacting the *Energy Control Layer* to determine energy price. The *Application Control Layer* also addresses information handling and storage, energy pricing, operation control, network functions, demand forecasting and energy usage management. Moreover, capacity planning and asset management are included under the *Application Control Layer* functions.

4.6.2   The Management Control Layer

The *Management Control Layer* covers system management functionalities that include application management, device management, and network management. Application management helps monitor if applications perform as desired by components of the energy community. Device management is concerned with data transmission and normalization. Network management is concerned with controlling network resources, their configuration and communication to ensure the network availability and performance.

4.6.3   The Security Control Layer

The main functions performed by the *Security Control Layer* include authentication, access control, data integrity and privacy functions. Authentication provides the mechanisms through which appliances, production units, consumption or production processes, and prosumers are identified if they are legit members of the energy community. Access Control guarantees that only those appliances, production units, consumption or production processes, or prosumers get the chance to use resources and services in the energy community. Data Integrity guarantees that the various actions, methods, measures, mechanisms, expectations, and outcomes stay consistent with in the energy community. Privacy Preserving aims for maintaining the rights and interests of members of the community to seclude some or all of their energy usage information while they still function as members of the energy community.

4.6.4   The Smart Meter Control Layer

The basic functions of a smart meter include the measurement of energy usage of appliances per prosumer level of an energy community. Control functions associated with the smart meter mainly include those operations that read and provide meter information from the smart meter to the control unit of the service provider, and that provide appliance level control functions from the service provider to the smart meter.

Based on these functionalities; a *Smart Meter Control Layer* shall include control mechanisms that

* guide how meter information is read from the smart meter,.

* monitor and take load control actions which help the management of energy consumption per prosumer level of the energy community,.

* protect the smart meter equipment and take actions on special events that require protective actions.

On special events that require protective actions, the control mechanism shall make use of the two way communication between the central server and prosumer households for exchanging meter data and information that are associated with the event. For example, if a meter turns down while it is on duty, that turn down event might cause voltage-current instability, which has then to be detected by the smart meter before causing any service outage, and proper control actions which include isolation of the particular meter and restoration of the system function back to normal should be taken by the control mechanism.

4.6.5 The Network Control Layer

The main responsibilities of the *Network Control Layer* include QoS management, Resilience and Recovery, reliable data transport, and resilience and recovery. The network layer provides a guarantee over QoS metrics like bandwidth, jitter and delay, and performs data differentiation from meters, appliances, production units or other members of the energy community, giving priority to one kind of information over the other based on its predefined level of importance. The *Network Control Layer* also manages network signaling across different compositions of the energy community. Moreover, the *Network Control Layer* is responsible to take care of and system disruptions due to human errors or software and hardware failures.

4.6.6 The Energy Control Layer

The *Energy Control Layer* performs functions to monitor and manage distributed energy resources and support services such as Plug-in Electric Vehicle (PEV) charging, and to manage energy capacity planning. It further provides the capability to monitor and control the aggregate energy load of the energy community.

4.6.7 The Renewable Integration Control Layer

The *Renewable Integration Control Layer* performs functions to monitor and manage green energy usage in an energy community through an identification, specification of the level of green energy supply and greenness demand in the energy community. It also deals with the control of aggregate greenness level in the energy profile of the energy community.

4.6.8 The Power Grid Control Layer

The power grid constitutes of the energy community constituents namely the bulk generation units, distributed generation units, storage units, substation units and transmission lines. Associated control functions are included under the *Power Grid Control Layer*. The layer aims to intelligently integrate both renewable and non renewable generated energy resources and distribute them in an efficient manner. In this paper, this integration is aimed to be in such a way that both types of resources, green or non green power resources, could

be identified for their individual amounts out of the total aggregate amount. Moreover, the control layer shall have communications between devices in the power grid and between these devices and other layers through secure delivery of control information.

4.6.9 The Prosumer Control Layer

Control functions related to prosumers are associated with the management of energy demand response. The prosumer in an energy community consists of the local energy generation and storage, the local energy consumption by appliances, the household/building/industrial energy management system and the client demand response functionality. To perform these functions, the *Prosumer Control Layer* is concerned with monitoring the energy usage of household, building or industrial prosumers, management of the prosumer energy generation and storage, the use of pricing information and the functionality of energy demand response to control such energy usage. In cases when there is power shortage or outage, the *Prosumer Control Layer* notifies the *Energy Control Layer* so that the service provider reacts to this message and reacts to it to provide the solution back to the prosumer.

4.6.10 Interaction of the Control Layers

The control layers of the proposed control architecture for a smart grid based energy community are orthogonal to each other. Each control layer performs distinct control functions. However, through control lines that enable the flow of control information from one layer to another, the control layers communicate to perform a number of control tasks at once. The distinct control layer interactions are presented below.

The *Application Control Layer* mainly interacts with *Prosumer Control Layer*, *Power Grid Control Layer*, *Smart Meter Control Layer*, *Energy Control Layer*, *Management Control Layer* and *Security Control Layer*. On the other hand, the *Management Control Layer* interacts with all other control layers.

The *Smart Meter Control Layer* needs to interact with other control layers from the proposed smart grid control architecture to perform the aforementioned load control actions, aiming for a proper management of energy usage per prosumer level of the energy community. First, the *Smart Meter Control Layer* needs to interact with the Prosumer layer to perform energy consumption reading through an energy service interface. Second, the *Smart Meter Control Layer* needs to interact with Network layer which enables information transfer and communication with upper control layers. Then, an interaction with the Application layer enables the service provider to make an aggregate of the energy community reading and use that information to set unit energy prices and prosumer billing information across the energy community.

Although the *Network Control Layer* communicates with most of the other control layers in the control architecture, it mainly communicates with the *Power Grid Control Layer* and *Energy Control Layer*.

The *Energy Control Layer* interacts with the *Prosumer Control Layer* and the *Application Control Layer* through the Network Control Layer. It interacts with the *Demand Response Function* in the *Prosumer Control Layer* to achieve necessary energy load re-

ductions. It also interacts with the Load Monitor and Control Functionalities in the *Power Grid Control Layer* to manage the power distribution in response to changing load of PEV charging.

The *Renewable Integration Control Layer* interacts with the *Prosumer Control Layer* and the *Power Grid Control Layer* to monitor and manage green energy usage in an energy community through an identification, specification of the level of green energy supply and greenness demand in the energy community. It also deals with the *Energy Control Layer* to control of aggregate greenness level in the energy profile of the energy community.

The *Power Grid Control Layer* interacts with *Application* and *Energy Control Layers* through the *Network Control Layer*, and interacts withthe *End-User Control Layer* for energy transmission. It also interacts the *Energy Control Layer* so that distributed energy sources are online, and their generation is fed to the grid as required. The *Power Grid Control Layer* is also responsible to execute necessary protection, recovery, and control operations in power grid generation, transmission, or distribution station by interacting with the *Application Control Layer* or by automatic sensing capability.

The *Prosumer Control Layer* interacts with a number of other layers as part of the control architecture proposed for the energy community based on the smart grid. To perform demand response client control functions, the *Prosumer Control Layer* interacts with Demand Response application in the *Application Control Layer* which performs prosumer subscription under the service provider and allows the transfer of dynamic pricing information. The *Prosumer Control Layer* also interacts with the *Energy Control Layer* for distribution capacity management and twoway energy transmission. Moreover, the *Prosumer Control Layer* interacts with the *Security Layer* to authenticate prosumers and authorize their operations and their information.
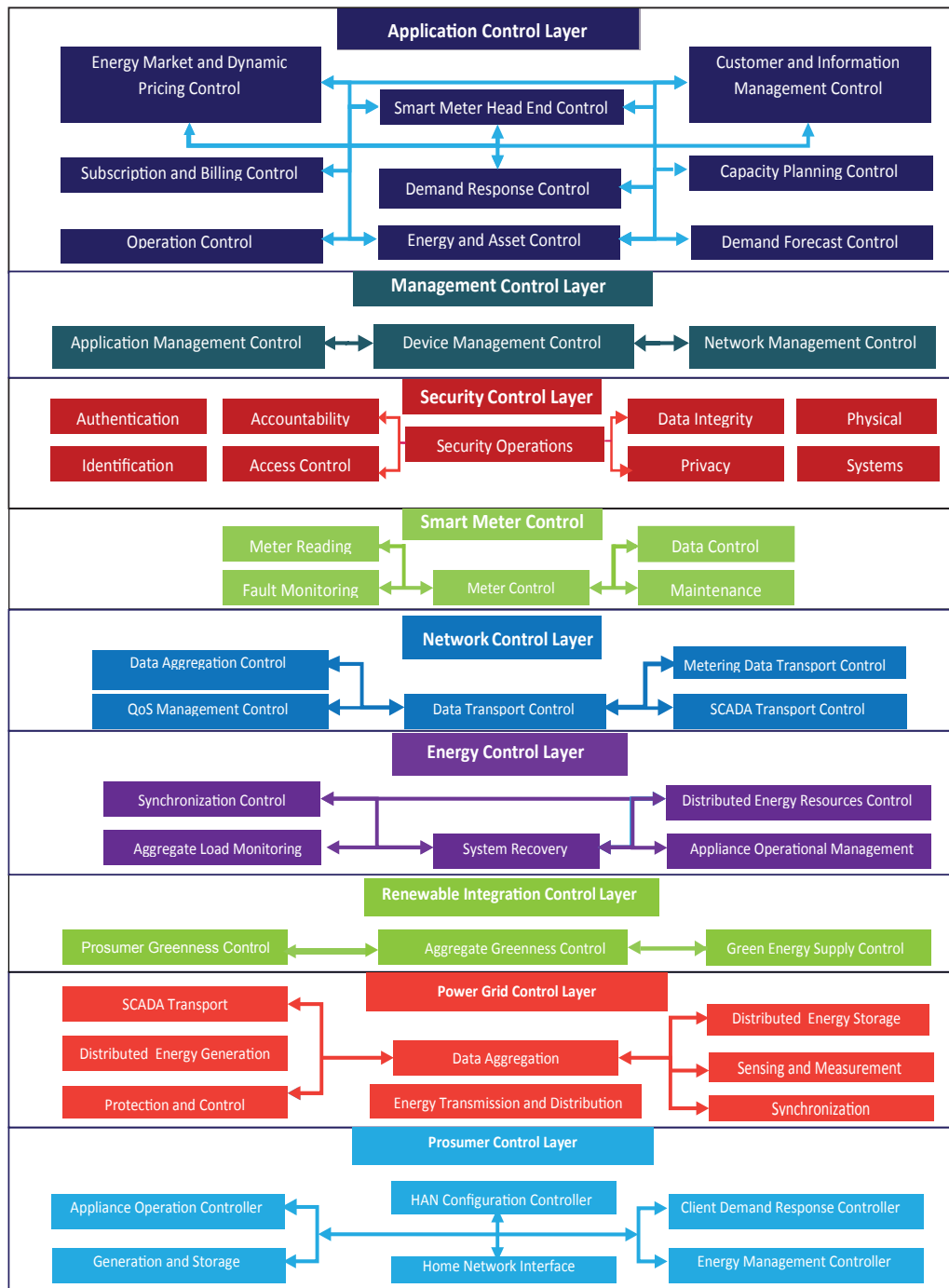
Figure 4.2: Logical Architecture of an Energy Community and its Constituents

4.7 Architectural Model Constituents

The Control Architecture consists of the central server (Q-Server) and the prosumer households represented by the symbol .

4.7.1 The Central Server (Q-Server)

The central server (Q-Server) consists of the Communications Manager, the Resource Manager, the Price Manager, the Resource Allocator, the Aggregate Profiler/ Load Forecaster and the Control Unit as main System Model constituents.

The Communications Manager specifies the mechanisms for communication between the Central Server (Q-Server) and Prosumer Households, and among the different system level constituents of the Central Server (Q-Server). It also keeps control of the flow of requests which is represented by the Production Request Queue and the Consumption Request Queue. For example, if an energy producing household provides a request to supply its produced energy resource to the grid, first it sends Resource Production Request Message to the Central Server (Q-Server) which then assigns this message to the appropriate queue (either the production request queue or the consumption request queue) by looking at the resource type and resource amount specification on the message.

The Resource Manager specifies the type and the amount of the aggregate energy resource that should be made available in the energy community at each operating time step, computes the level of production and consumption of energy resources in the energy community, accordingly computes the available amount and/or type of the required energy resource for prosumer household appliances during each operating time and avails this information to the other system model constituents.

The Control Unit specifies the different control mechanisms such as scheduling based, price based and incentive based techniques that are implemented in the energy community, implements the scheduling based control technique, such as scheduling the operating time and frequency of prosumer household appliances, and oversees the implementation of the other control mechanisms that include price based techniques and resource utilization techniques. With the use of the information from the Resource Manager about the available amount and type of the required energy resources and the information from the Resource Allocator about, the Control Unit can then decide how much of and which type of energy resource it should export from an external grid to which the energy community system could be connected so that the overall system is kept in balance.

The Price Manager specifies the different price policies that could be used in the energy community, computes and sets energy production price and energy consumption price in the energy community according to the specified price policies and energy resource availability as specified by the Resources Manager for each amount and type of energy resource.

The Resource Allocator performs the task of allocating the correct amount and the right type of energy resources by contacting the Communication Manager about the production requests and consumption requests that have been buffered and using the information

from the Resource Manager about the available amount and type of the required energy resources so that the overall energy grid is kept in balance as specified by the Control Unit.

The Aggregate Profiler/ Load Forecaster makes an aggregate energy profile of the energy community by making use of the level of consumption and level of production of energy resources information from the Resource Manager and the information from the Communications Manager about the number of requests in the Production Request Queue and the Consumption Request Queue to use it for machine learning intelligence for the purpose of load forecasting.

4.7.2 A Prosumer Household

The prosumer household primarily consists of appliances and production units which are connected through smart meters, sensors, a home gateway, and an energy management system to the central server (Q-Server).

The Smart Meter records electrical energy consumption and communicates that information to the utility for monitoring and billing purposes thus enabling two-way communication between the smart meter and the central system.

The Home Gateway acts as a communication gateway between the central server and the smart meter, thus transferring the data sent from central system to the smart meter and vice versa.

The Energy Management System (EMS), which could refer to a Supervisory Control and Data Acquisition (SCADA) unit or a Q-Box, performs the task of monitoring, controlling, and optimizing the performance of the generation and/or consumption of energy resources. The subconstituents of the EMS are the Communication Unit, the Price Setter/Display unit, the Household Profiler unit, and the Scheduler/Keep-alive unit.

The Price Setter/Display sets and displays prices for various types and amounts of energy resources.

The Household Profiler computes an aggregate of the household energy profile and/or the appliance based energy profile.

The Scheduler/ Keep Alive schedules household appliances and sends keep alive message to the central server for every appliance that is producing, consuming or storing energy within each time step interval.

Prosumer Household Appliances include smart plugged household devices that consume electrical energy.

Prosumer Household Production Units include smart plugged household devices that generate electrical energy.

4.7.3 The Control Unit

As mentioned in the previous sections of this report, the smart grid exhibits the flexibility of power consumption and production units, since it is essentially composed of prosumer households which could often experience plug and play addition of appliances and production units. Therefore, the control unit of the central server system model is an essential component of the control architecture of the energy community to stabilize the aggregate
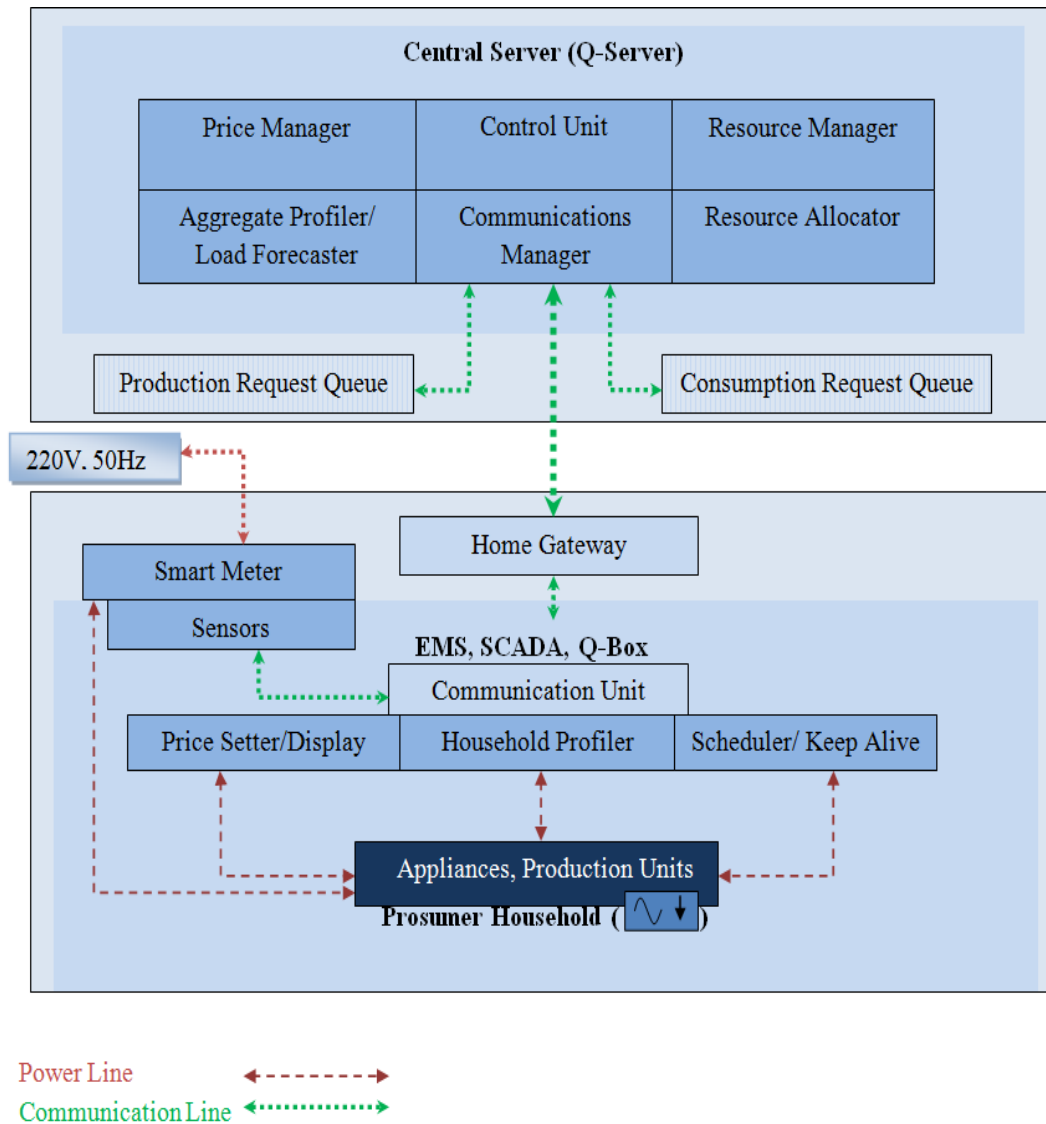
Figure 4.3: Physical Architecture of an Energy Community and its Constituents

energy profile and keep it within acceptable bounds. The following parts describe this controller/scheduler unit in a further detail using the explanation of how a given type and amount of resource is produced, distributed and consumed in the energy community and how the different components of the controller/scheduler unit could be integrated into a control architecture for an energy community. Given a certain type and amount of energy resource Er having lower bound Er and upper bound r as constraints, the problem setup is presented as:

The overall controller-scheduler follows an external energy resource balance E_b that keeps the aggregate sum E_{agg}, external compensation E_{ext} and the disturbance E_{dist} energy
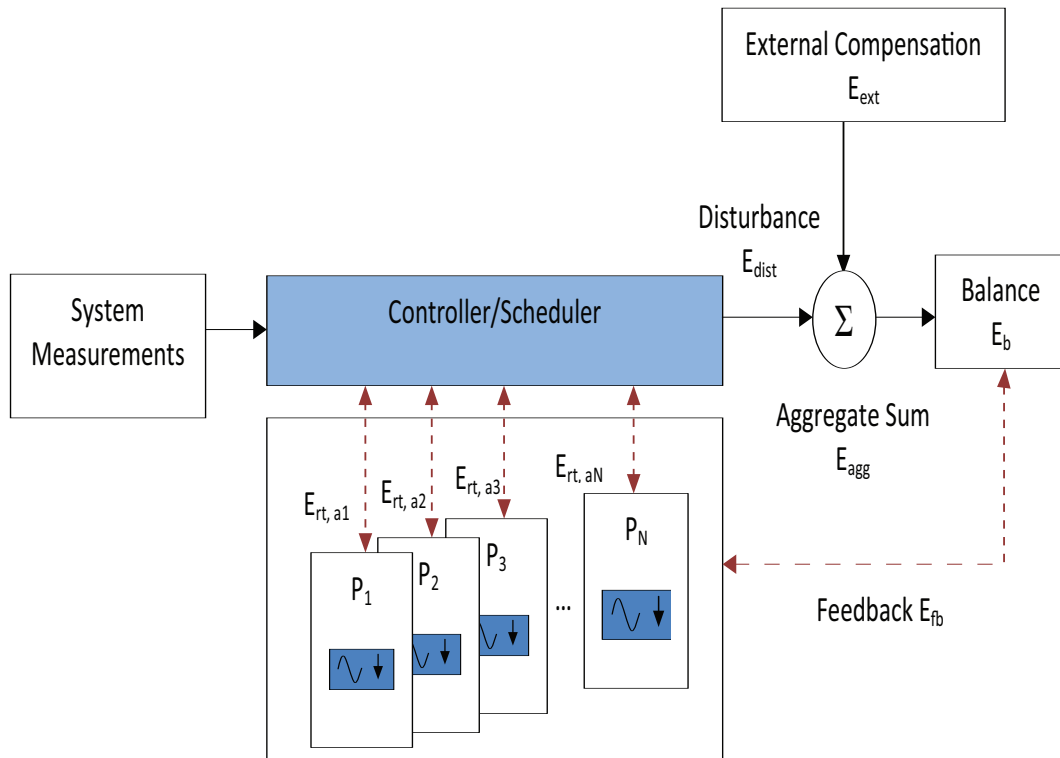
Figure 4.4: Controller-Scheduler of the Central Server System Model

resources in balance. The prosumers are modeled as intelligent prosumers in that they can decide when and how much of a given energy resource E_r type should they produce or consume.

4.7.4 Demand Response and Regulation Control Integration

One aim of control architecture for a smart grid based energy community is keeping the balance of the demand and supply of energy resources in an energy community [39]. This task includes ensuring that there are appropriate amounts of each type of energy resources in the community and the proper procurement of those identified resources by users that need those specific types and amounts of energy resources [40]. Among those control mechanism that serve for this purpose are *demand response* and *regulation control*. As described in previous sections, *demand response* is a mechanism that aims at controlling the energy consumption of residential and commercial prosumers at various times of the day with an objective of keeping the balance of demand and supply of energy resources in an energy community.

Keeping the balance of demand and supply of energy resources also includes *regulation control*. *Regulation control* is a mechanism that is triggered in surplus consumption

or surplus production circumstances in the energy community. At the energy community level, this mechanism includes processes such as an energy import-export processes from/to an external grid or from supply side generation reserves called ancillary services.

The integration of the aforementioned *demand response control* and *regulation control* mechanisms into control architecture is proposed in this paper. The control unit of the proposed architecture therefore includes a *demand response* engine and a *regulation control* engine that perform the demand response and regulation control tasks outlined above. Moreover, the control unit employs a *balance reference* engine which is used to generate and keep track of the balance reference signal. The main purpose of the control unit is therefore to capture the dynamics of the aggregate consumption and production of energy in the energy community on a day-ahead basis, and minimizing those dynamics or variations through the use of demand response signals and regulation control signals.

Let X_t^{brf}, X_t^{dr} and X_t^{rc} represent the reference signal, the demand response control signal and the regulation control signal respectively. The variables X_{t+1}^{brf}, X_{t+1}^{dr} and X_{t+1}^{rc} represent the values of X_t^{brf}, X_t^{dr} and X_t^{rc} at the following time step. e_t represents the error signal that tracks the overall system imbalance because of the application of demand response and regulation control mechanisms related to the system balance reference. f_{dr} and f_{rc} represent the corresponding functions for demand response and regulation control inside the control unit. Moreover, the resource manager performs a process of aggregating energy resources in the community and communicating with the control unit so that the control unit can make decisions of how much demand response measures should be taken and/or how much regulation control measures should be taken according to the balance reference. In the event that there are much variations with respect to the balance reference, which is set at a value W_t^{brf} equivalent to the reference bias import or export power from/to the external grid, import or export decisions from/to the external grid would be taken by the control unit.

The following control state space defines the relationship between the Resource Manager and the Control Unit.

$$e_t = X_t^{rc} + X_t^{dr} - X_t^{brf} \tag{4.1}$$

$$X_{t+1}^{brf} = X_t^{brf} + W_t^{brf} \tag{4.2}$$

$$X_{t+1}^{rc} = f_{rg}(X_t^{rc}, U_t^{dr}, W_t^{dr}, t) \tag{4.3}$$

$$(U_t^{rc}, U_t^{dr}) = f_{agg}(X_t^{brf}, X_t^{rc}, X_t^{dr}, t) \tag{4.4}$$

Given the Saturation Function with level α and the Delta Function $\delta(x)$ as

$$Sat_{\alpha_{max}(x)} = \left\{ \begin{matrix} -(\alpha) if x < -(\alpha), \\ x if x \leq (\alpha), \\ (\alpha) if x > -(\alpha) \end{matrix} \right\} \tag{4.5}$$

$$\delta(x) = \left\{ \begin{matrix} 1 if x = 0, \\ 0 otherwise \end{matrix} \right\} \tag{4.6}$$
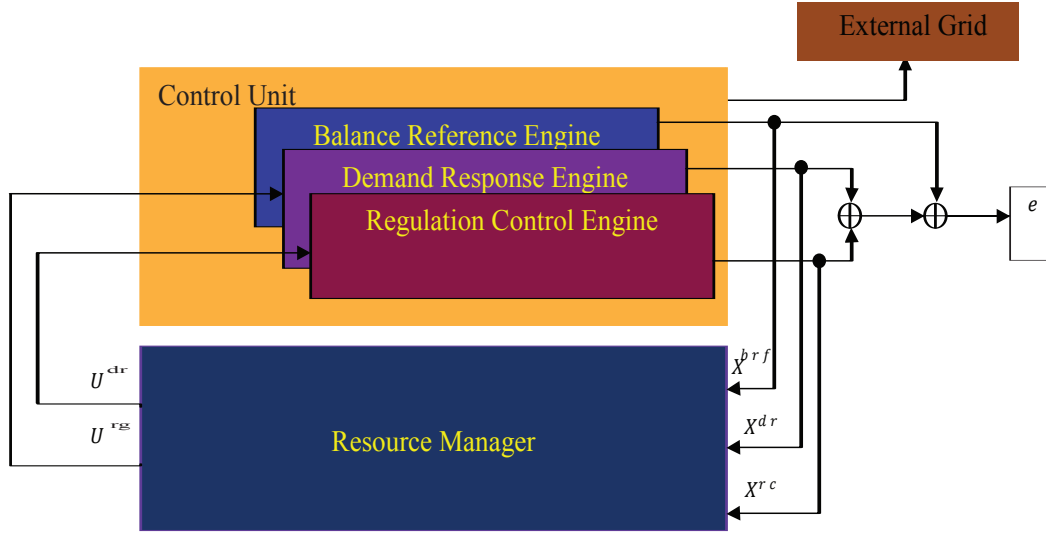
Figure 4.5: Control Unit and Resource Manager Interaction

And the following parameters for the model specification defined as Maximum of regulation control and demand response = $\alpha_{max}{}^{rc}$, $\alpha_{max}{}^{dr}$ Ramp time rate constant for regulation and demand response = $\alpha_{rmp}{}^{rc}$, $\alpha_{rmp}{}^{dr}$ Input control update rates for regulation control and demand response = T_{rc}, T_{dr}

The control state space is modeled accordingly as:

$$X_{t+1}^{brf} = X_t^{brf} + W_t^{brf} \tag{4.7}$$

$$X_{t+1}^{rc} = Sat_{\alpha_{max}^{rc}}(X_t^{rc} + \delta(t \, mod \, T_{rc}))Sat_{\alpha_{rmp}^{rc}}(U_t^{rc})) \tag{4.8}$$

$$X_{t+1}^{dr} = Sat_{\alpha_{max}^{dr}}(X_t^{dr} + \delta(t \, mod \, T_{dr}))Sat_{\alpha_{rmp}^{dr}}(U_t^{dr})) \tag{4.9}$$

The Control Signal is modeled as

(t mod T_{rc}) $U_t{}^{rc} \neq 0$ only if it is a multiple of T_{rc}. (t mod T_{dr}) $U_t{}^{dr} \neq 0$ only if it is a multiple of T_{dr}.

Thus, using T_{dr} and T_{rc}, it is possible to control the rate with which the Demand Response and the Regulation Service operate. This control unit operation is demonstrated in the control architecture as follows.

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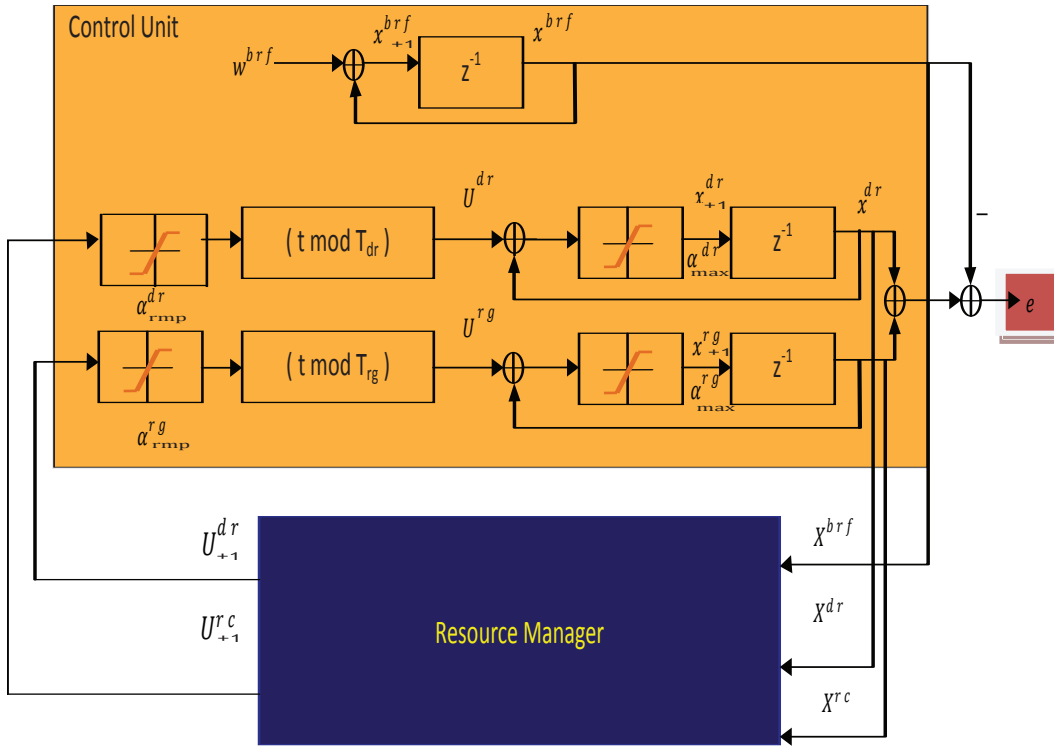
Figure 4.6: Control Unit and Resource Manager Operation

4.7.5 Results

In this chapter, the control architectural requirements, specification and modeling have been performed for a smart grid based energy community. The chapter started with a discussion on the comparison and contrast of centralized and distributed control approaches. It was identified that for issues that relate to better demand response control options, better device and network management and security, centralized control could outperform distributed control mechanisms in a smart grid based energy community.

Following that, demand side management techniques were discussed which included demand response and regulation control mechanisms. Demand response mechanisms were classified into price based techniques and incentive based techniques. The differences between the two techniques were outlined with additional information regarding how these techniques could be implemented in a smart grid based energy community. Moreover, the benefits of such demand side management techniques were presented by illustrating their effects on the power profile of the energy community. These effects include peak clipping, valley filling, load shifting, energy efficiency, electrification, and load shape flexibility.

The control architecture for the smart grid based energy community was presented in a layered architecture that consists of eight major layers. These layers are the application control layer, the management control layer, the security control layer, the smart meter

control layer, the network control layer, the energy control layer, the power grid control layer, and the prosumer control layer. The control related responsibilities of each of the control layers were presented. In addition, the control components of each of the layers were included in the architecture along with the control lines that help communicate control information from one layer to another.

Another approach of presenting the control architecture of the smart grid based energy community followed in this paper is using the architectural model constituents. With that approach, the control path and communications between the devices inside the central server and prosumer households has been modeled. In addition, the control unit inside the central server has been designed so that it can accommodate system imbalances using demand response and regulation control mechanisms.

Chapter 5

Utility Maximization for a Smart Grid based Energy Community

5.1 Resource based Utility Classification

Among the most anticipated benefits of the smart grid is that it optimizes the utilization of energy resources which enhances the capacity and efficiency of electric power networks and that it averts the construction of back-up or peak load power plants [6] p. 26. Optimization of resource utilization requires the maximization of the various energy resources in an energy community in a manner that leads the energy community towards the *benefit of all* scenario, where the cost of energy generation, distribution and consumption is reduced and the corresponding amount of payment is minimized. The term utility, in terms of smart electric grids, includes the different benefits that the modern power grid provides which could be similar to the utility benefits that the normal power grid provides (e.g. stable and uninterruptible power, unrestricted access time, etc.) or utility benefits that are made possible uniquely by the modern power grid (e.g. quality of power defined by the users preference for greenness) [41].

On the proposed system model for a smart grid based energy community, resource based utility maximization has been targeted. The main requirement for attaining this target is the proper identification and classification of energy resources in the smart grid. The following identification and classification of resources has been identified for that purpose. In general, the energy community has been classified into the supplier side and the consumer side.

On the supplier side, the energy community resource classification for each time step includes the type of energy resource, the cost of power, and the availability of power. The type of energy resource explains whether the specified energy resource is derived from green power source (e.g. derived from solar photovoltaic, wind, etc.) or non-green power source (e.g. derived from oil). The cost of power explains the money spent for different kinds of utilized and unutilized resources. The price of produced power explains the selling price for unit produced power (e.g. time-of-use price, critical-peak price, extreme-day price, extreme-day critical-peak pricing, or real-time price). The quantity of power explains the amount of power (e.g. the total amount of power, the amount of uninterruptible power, etc.).

The availability of power, and the operation time explain the access time of the specified energy resource and the response time of the energy source.

On the consumer side, the classification includes the type of energy resource, the price of power consumption, the amount of power, the availability of power and the operation time of appliances. The type of energy resource explains whether the energy resource is green (e.g. derived from solar photovoltaic, wind, etc.) or non-green (e.g. derived from oil). The price of power consumption explains the selling price for unit produced power (e.g. time-of-use price, critical-peak price, extreme-day price, extreme-day critical-peak pricing, or real-time price). The quantity of power explains the amount of power (e.g. the total amount of power, the amount of uninterruptible power, etc.), the availability of power and the time of operation that specifies the access time of a given resource and the response time for a given resource request.

Based on the classification of energy resources in smart grids, different sub categories have been identified and control parameters have been devised that allow the research of peak to average ratio reduction, energy cost reduction and power quality maximization in the energy community. In order to properly address the peak to average power reduction research problem, both the upper peak and the lower peak of the aggregate power are specified over all time steps in the specified duration; the average aggregate power (P_{av}) is specified as the mean of all time step aggregate power values in the energy community; whereas the power bandwidth is specified as the maximum available power in the energy community at each time step, which is the combined form for resources derived from both local generation and from external energy sources. Moreover, the ratio of peak aggregate power with respect to the average aggregate power (R_{pa}) and the aggregate power bandwidth (R_{pb}), and corresponding changes in the ratio of peak power to average power (R_{rpa}) have been identified.

The quality of energy resources in an energy community is defined in terms of the type of the energy resource that is generated, distributed or consumed in the energy community. In this project, the amount of generated green energy of production units and the greenness desire in power consumption of households for their appliances is used as the main indicator of power quality in the energy community. Other identified power quality factors such as EMC, delay, reliability, stability and continuous operation have not been dealt with here as many literature have covered those aspects already [42], [4], [43] and [44].

Another important parameter that determines the quality of power generation, distribution and consumption in an energy community is the concept of power bandwidth. Power bandwidth, in the context of power quality is defined as the amount of power that is available for use in an energy community at each time step, which is either generated in the energy community or imported from an external grid. This concept of power bandwidth, when used as a power quality parameter, defines for each user, the maximum amount of power that a user can produce and export to the power grid or import and consume from the power grid.

Regarding the cost of energy resources in the energy community, various aspects that directly or indirectly affect the cost of energy resources have been studied which include the effect of the level of energy utilization on the energy cost of the energy community (the level of utilization of energy resources and the level of utilization of green energy resources),

the change in aggregate peak power (the change in energy cost due to unit change in peak aggregate power), and the type of power source (the associated unit cost of an grey energy resource and green energy resource in the energy community).

Moreover, the amount of payment alloted for the use of energy resources has been considered in this project as a resource utility measure. To identify this concept further, the production price and the consumption price for energy resources in the energy community has been studied in detail along with the corresponding changes. Thus, the time unit step based price for unit consumed energy resource, unit consumed green energy resource, unit produced energy resource, unit produced green energy resource, and the corresponding time unit based changes in the parameters have been identified.

5.2   Resource based Utility Model

The resource based utility model is presented as follows. For each household h appliance $a \in A_h$, using the energy consumption in period $t \in \tau$ is *sched_Power_Appliance[h][a]* and it is possible to model the utility that household h gets from this utilization by representing it as *U[h][a](sched_Power_Appliance[h][a])*. In general, it may seem correct to consider that the utility of appliances depends on the amount of power that is consumed by the appliance. However, to make a clear distinction, the utility model proposed in this paper considers a *class based* classification on appliances that considers that the utility of an operation of an appliance depends on the derived class of the appliance, and not simply on the amount of power that an appliance consumes. On such consideration, the following classification is used by the utility model to identify the utility of operation of appliances. β and α are thermal characteristics of appliances with the environment. For example, β can be positive for a heater or negative for a cooler and T[h][a] represents the starting operating temperature of the appliance.

Appliance Classification	Appliance Example	Utility Function U[h][a] ($sched\_Power\_Appliance[h][a]$) =
Class 1	Lighting, Electronic Appliances	$\sum_{\forall t} U[h][a](sched\_Power[h][a][t],t)$
Class 2	Washing Machine, Drying Machine	$U[h][a](\sum_{\forall t} sched\_Power[h][a])$
Class 3	Refrigerator, Heating, Ventilation and Air Conditioning	$\sum_{\forall t} U[h][a](T[h][a] + \beta \sum_{t=1}^{\tau}(1-\alpha)^{t-\tau} sched\_Power[h][\alpha][\tau])$

Table 4: Appliance based utility function classification

5.3   Resource Based Scheduling Problem

Once classification of energy resources has been performed and a resource based utility model has been defined, the research problem that includes the set up of the utility maxi-

mization problem through scheduling of appliances is stated below interms of a reduction of peak demand, maximization of aggregate greenness and energy cost reduction of an energy community, following which the different solutions arrived at are presented.

An energy community is assumed to have a number of prosumer (producer-consumer) households each having household appliances, production units and storage units. These components of the energy community are described with parameters that specify the rated power of an appliance (A_{rp}), the consumed power by an appliance (A_{cp}), the flexible duration of an appliance, the generated power (A_{gp}) by a production unit, and the stored power (A_{sp}) by a storage unit at each time step (t), using control parameters that specify: the operating power of appliances (A_{op}), the rate of operation of an appliance (A_{ro}) and the amount of flexibility in operation time (T_{of}). The resource based scheduling problem aims to find a mechanism for scheduling the time of operation of appliances, the rate of operation of appliances and maximize the level of utilization of renewable energy resource in the energy community using a combination of demand response control techniques such as price based techniques and direct load control programs. Further objectives of the resource based scheduling problem are finding out a mechanism of bringing an optimal or comparatively higher reduction in the peak to average ratio of the aggregate power of the energy community, increasing the level of utilization of renewable energy resource of power consumed in the energy community, and reducing the overall energy cost for both the energy company and prosumer households.

5.4   Utility Maximization Mechanisms

There are a number of components of an energy community that can be regarded as the utility for the energy community. The type, the availability, the amount, the time of operation and the cost of energy generation, transmission, distribution and consumption, and the amount of payment that a prosumer household pays or gets paid for a specific energy unit could all be regarded as utility for the different actors and participants of the energy community.

One of the most important issues regarding energy resources when they are considered as utility in the smart grid is maximizing their level of utilization. More importantly at the energy community level of smart grids, where the expansion of the power grid infrastructure is very important to accommodate various types of energy resources that include renewable energy resources and micro grids, utility maximization is a way in which the various types of energy resources are put into use aiming a situation where every participant is expected to get the most out of its participation. Moreover, in such a scenario, the price of energy production and energy consumption should be set at a point which clearly reflects the level of availability of energy resources, their utilization and their cost variation to keep the overall energy generation and consumption at balance throughout the community.

In general, energy resources can be classified as *green energy resources* which are derived from green energy sources like solar photovoltaic or wind, *grey energy resources* which are derived from a combination of green energy sources and non-green energy sources like oil or gas. The form of energy that is derived both from green energy

sources and non-green energy sources is widely available, however it can still be better differentiated based on the level of production and utilization of each of the resources, derived from green and/or non-green sources. On the other hand, prosumer households that procure green energy resources could better specify the extent to which they need to use green energy resources, referred hereafter as *greenness*. In this regard, the current power grid needs a mechanism to differentiate energy resources into their energy source types by adding additional utility parameters: *generated green energy resources* that specifies the amount of generated green energy from the side of the producer and *greenness* that specifies the extent of the need to use green energy resources from the consumer side.

Another important aspect that is considered as the utility for an energy community is the *availability* of energy resources. In a given duration of time, the *availability* of energy resources defines whether or not the different types of energy resources can be generated and made available for consumption use. This important concept of *availability* of energy resources could be further extended to include the dual concept of the duration of time the resource is supplied from the producer side and the duration of time the resource is being used at the consumer side. In such a manner, *availability* of energy resources also defines whether or not the given type and amount of resource could be provided and made in to use during the time that it is needed. This is important since there is noticeable difference in energy cost for base load generation as compared to the energy cost for the additional type and/or amount of energy resource that is made available to meet additional energy demand above the base load generation during the duration of time that an energy resource is required.

Also related to the issue of *availability* of energy resources at the energy community level of smart grids is the *flexibility* of consumption, storage and production units in prosumer households in terms of their duration of operation. For example, *flexibility* of operation of household appliances describes the level of flexibility of the duration of operation of these appliances in an effort to drive their time of operation away from peak load hours, and/or in general to meet the various demand side objectives such as peak clipping, valley filling and/or load shifting aforementioned in this report.

In this project, the *operation time* of appliances which indicates the prosumer households preference for the operation time of its appliances and the *duration of operation flexibility* of appliances which indicates the flexibility of the prosumer household in time duration with in which its appliances can be operated before or after its actual *operation time* have been considered. For example, if the *operation time* of an appliance is from 3a.m. to 5a.m., its *duration of operation flexibility* could be from 1a.m. to 7a.m. These ways help the prosumer household to make better use of its knowledge of preferred schedule of operation of its appliances and thus take a better control and management over the time of operation of its appliances.

The cost of energy resources is another utility component of a smart grid based energy community. The unit cost of an energy resource depends on a number of aspects that include the availability of resources and how much a particular energy resource has been utilized at a given duration of time in the energy community. In this project, a cost function has been defined that indicates the hourly cost of generation and distribution of electricity by energy sources in the energy community. The energy cost function is made to

account for peak hour energy load demands during the day. Furthermore, the cost function has been made to reflect a two peak daily energy demand profile that corresponds to the morning peak and the evening peak as has been referred from [45] and [46].

The amount of payment that a prosumer household pays or gets paid for a specific unit of energy is another utility component in an energy community. Utility maximization programs should take concern of the effect of pricing in prosumer households so that prices can be used as a measure to minimize the amount of money spent on energy resources in the energy community. In this project, a dynamic pricing mechanism is implemented that is based on a day-ahead schedule and a critical peak pricing scheme where critical peak periods and corresponding event prices are defined in advance thus aiming at peak load reduction. In such a manner, customer specific information and individual base line load information is not required at the utility side. Moreover, the effect of peak load reduction is complementary to the other utility maximization objectives aforementioned.

As a unique contribution to the field, a prosumer household *appliance based pricing scheme* is proposed in this project which assumes that prosumer households could be willing to provide their appliance power usage information to the utility for a mutual benefit from this appliance based pricing scheme. In cases where prosumer households are not willing to provide their appliance power usage information, the utility company could make use of techniques such as energy disaggregation as specified in the *energy disaggregation* section and referred in reference [31]. This helps the utility company identify what kind appliances are under operation at each time step by just looking at the aggregate energy profile.

The pricing scheme takes the results of research performed by this project into account, which considered the different load levels of various appliances [39] and found out that it is only a few prosumer household appliances that contribute to peak load demands at different hours of operation. This has also been referred from reference [47] which provided the power consumption of an average household in the Netherlands in various scenarios in (kWh / hhyr) and the twenty most common household electric appliances in average in the Netherlands for various scenario's overviewed from 1980-2005 and estimated for 2010-2020. Thus, a pricing scheme that sets different prices for different appliances according to their load demand characteristics could maximize the energy resource utilization in the energy community by prioritizing specific kinds of appliance operations over others for the prosumer household during different times of the day.

5.5 System Model

Given in the system model are a scheduling period $\tau = 1, 2, ..., T$ that represents corresponding time steps inside the scheduled duration, the operating power for each appliance $a \in A_h$ in each household $h \in H$, $operating\_Power_{h,a}$ and the stand by power for each appliance $a \in A_h$ in each household $h \in H$, $standby\_Power_{h,a}$. The energy consumption initial scheduling vector for each appliance $a \in A_h$ in each prosumer household $h \in H$ is defined as:

$$is\_Operating_{h,a} = is\_Operating^1_{h,a}, ..., is\_Operating^\tau_{h,a} \qquad (5.1)$$

where Boolean $is\_Operating_{h,a}^t$ represents the status whether or not appliance a operates at time step t.

Each household $h \in H$ provides two durations of time represented by $(\alpha_{h,a}, \beta_{h,a})$ for its preferred time of operation, when it most desires to operate its appliance, and $(\gamma_{h,a}, \delta_{h,a})$ for its flexible duration of operation, through which time it can shift its appliances duration of operation, respectively. Thus, the time duration for its preferred time of operation is described with the beginning time of operation $\alpha_{h,a} \in T$ and the ending time of operation $\beta \in T$ where $\alpha_{h,a} < \beta_{h,a}$ to indicate start time of preferred operation should be before end time of preferred operation.

Similarly, the time duration for its flexible duration of operation is described with the starting time after which the appliance can be shifted to operate $\gamma_{h,a} \in T$ and with the ending time before which the operating time of the appliance needs to be finished $\delta \in T$. Moreover, $\gamma_{h,a} < \delta_{h,a}$ to indicate start time of flexibility duration of appliances needs to be before the end time of flexibility duration of appliances. In addition, $\gamma_{h,a} < \alpha_{h,a} < \beta_{h,a} < \delta_{h,a}$ to indicate that the flexibility duration is larger than the preferred time of operation.

The energy consumption final scheduling vector for each appliance $a \in A_h$ in each prosumer household $h \in H$,

$$sched\_Final_{h,a} = [sched\_Final_{h,a}^1, sched\_Final_{h,a}^2, ..., sched\_Final_{h,a}^\tau] \qquad (5.2)$$

where $sched\_Final_{h,a}^t$ represents a Boolean for the scheduled status whether or not appliance a is operating at each time step t.

Moreover, the final schedule should be the same in duration as the initial schedule:

$$\sum_{t=\gamma_{h,a}}^{\delta_{h,a}} sched\_Final_{h,a} = \sum_{t=\alpha_{h,a}}^{\beta_{h,a}} is\_Operating_{h,a} \qquad (5.3a)$$

and

$$\sum_{t=1}^{\gamma_{h,a}} sched\_Final_{h,a} = 0 \quad and \quad \sum_{t=\delta_{h,a}}^{T} sched\_Final_{h,a} = 0 \qquad (5.3b)$$

This constraint also applies to the scheduled power so that the scheduled operating power should be equal to the initial schedule operating power:

$$\sum_{t=\gamma_{h,a}}^{\delta_{h,a}} (sched\_Final_{h,a} * operating\_Power_{h,a} + (1 - sched\_Final_{h,a}) * standby\_Power_{h,a}) =$$

$$\sum_{t=\alpha_{h,a}}^{\beta_{h,a}} (is\_Operating_{h,a} * operating\_Power_{h,a} + (1 - is\_Operating_{h,a}) * operating\_Power_{h,a})$$

$$(5.4)$$

5.6 System Model Parameters

The system model parameter definition starts with specifying the *operating power*, the *standby power* and the *generated power* for each smart appliance and production unit per time step respectively. Then, the sum over all time duration for these parameters is calculated. Moreover, the desired level of prosumer consumption *greenness* from prosumers and the level of *greenness of generated power* by producers are defined. Moreover, the *cost parameter*, the *upper peak power ratio*, *lower peak power ratio* and *difference in aggregate power bound* are defined.

* $operating\_Power[h][a][t]_{\substack{\forall h \in H \\ \forall a \in A_h \\ \forall t \in T}}$, $standby\_Power[h][a][t]_{\substack{\forall h \in H \\ \forall a \in A_h \\ \forall t \in T}}$, $generated\_Power[h][a][t]_{\substack{\forall h \in H \\ \forall a \in A_h \\ \forall t \in T}}$

* $greenness[h][a][t]_{\substack{\forall h \in H \\ \forall a \in A_h \\ \forall t \in T}}$, $greenness\_Generated\_Power[h][p][t]_{\substack{\forall h \in H \\ \forall a \in A_h \\ \forall t \in T}}$

* $cost\_parameter[t]_{\forall t \in T}$, $price\_parameter[a][t]_{\forall a \in A_h \forall t \in T}$

* $upper\_peak\_ratio, lower\_peak\_ratio$

Following these definitions, the *initial power per time step*, the *sum of the initial power per time step*, and the *produced power per time step* in the energy community are calculated as follows.

* $init\_power\_per\_time\_step[t] = \sum_{\substack{\forall h \in H \\ \forall a \in A_h}}(init\_power[h][a][t])$

* $sum_init\_power\_per\_time\_step[t] = \sum_{\forall t \in T}(init\_power\_per\_time\_step[t])$

* $prod\_power\_per\_time\_step[t] = \sum_{\substack{\forall h \in H \\ \forall a \in A_h}}(generated\_Power[h][a][t])$

Based on the calculations above, the following equations show how *initial power* is computed per each appliance and time step and how *aggregate green power* is computed from operating status parameter of appliances, *produced power per time step* and *greenness of generated power*.

$$\begin{aligned} init\_power[h][a][t] = (operating\_Power[h][a][t] * is\_Appliance\_Operating[h][a][t] \\ + standby\_Power[h][a][t] * (1 - is\_Appliance\_Operating[h][a][t])) \end{aligned} \quad (5.5)$$

$$\begin{aligned} init\_power\_appliance[h][a] = \sum_{t \in T}(operating\_Power[h][a][t] * is\_Appliance\_Operating[h][a][t] \\ + standby\_Power[h][a][t] * (1 - is\_Appliance\_Operating[h][a][t])) \end{aligned} \quad (5.6)$$

$$aggregate\_green\_Generated\_Power[t] = \prod_{\forall t \in T} (prod\_power\_per\_time\_step,$$
$$(\sum_{\substack{h \in H \\ a \in A_h}}) greenness\_Generated\_Power[h][a][t]) \qquad (5.7)$$

$$upper\_aggregate\_power\_bound \leq upper\_peak\_ratio * max_{\forall t \in T} init\_power\_per\_time\_step[t] \qquad (5.8)$$

$$lower\_aggregate\_power\_bound \leq lower\_peak\_ratio * min_{\forall t \in T} init\_power\_per\_time\_step[t] \qquad (5.9)$$

$$diff\_aggregate\_power\_bound \leq upper\_aggregate\_power\_bound - lower\_aggregate\_power\_bound \qquad (5.10)$$

An important parameter is *price_parameter[a][t]* that is defined for each appliance at each time step to set different prices for different appliances and for different time steps respectively for two main reasons. 1) Differentiation on appliances irrespective of time steps helps to change the frequency of operation of certain appliances. For example, if a washing machine is priced higher and thus differently per unit energy consumption form another household appliance, the usage pattern of users could shift from using the washing machine less frequently, for example from three times a week to twice a week, an important behavioral shift which could be regarded as more efficient and less load incurring from the view point of the energy community. 2) Differentiation on time step in general helps to drive load away from peak demand hours. Therefore, a combination of these two techniques is twined in the price parameter for appliances. After the application of the scheduling and optimization algorithm, the *final schedule, final scheduled power per appliance per time step, scheduled power per time step, sum of scheduled power per time step* and *scheduled power per appliance* system parameters are defined.

$$\sum_{\forall t \in T} sched\_Final[h][a][t] == \sum_{\forall t \in T} is\_Appliance\_Operating[h][a][t]_{\forall h \in H, \forall a \in A_h} \qquad (5.11)$$

$$sched\_Prosumer[h][a][t] = 0 || sched\_Prosumer[h][a][t] = 1 \quad_{\substack{\forall h \in H, \\ \forall a \in A_h \forall t \in t}} \qquad (5.12)$$

$$sched\_power\_per\_time\_step[t] = \sum_{\substack{\forall h \in H \\ \forall a \in A_h}} sched\_power[h][a][t] \qquad (5.13)$$

$$sched\_power\_appliance[h][a] = \sum_{\forall h \in H} sched\_power[h][a][t] \qquad (5.14)$$

Using the above calculations, the final *schedule of operation of appliances* and *scheduled power consumption* of appliances are computed as follows.

$$
\begin{aligned}
sched\_Power[h][a][t] = {} & operating\_Power[h][a][t] * sched\_Final[h][a][t] + \\
& standby\_Power[h][a][t] * (1 - sched\_Final[h][a][t])
\end{aligned}
\tag{5.15}
$$

$$
sched\_Power\_Per\_Time\_Step[t] \leq upper\_aggregate\_power\_bound_{\forall t \in T}
\tag{5.16}
$$

$$
sched\_Power\_Per\_Time\_Step[t] \geq lower\_aggregate\_power\_bound_{\forall t \in T}
\tag{5.17}
$$

$$
\sum_{t \in T} sched\_power\_per\_time\_step[h][a][t] == \sum_{t \in T} init\_power\_per\_time\_step[h][a][t]
\tag{5.18}
$$

$$
sum_s ched\_power\_Per\_Time\_Step \leq sum_i nit\_power\_Per\_Time\_Step
\tag{5.19}
$$

$$
sum_s ched\_power\_Per\_Time\_Step = \sum_{\forall t \in T} (sched\_power\_per\_time\_step[t])
\tag{5.20}
$$

$$
sched\_green\_power\_per\_time\_step[t] = \sum_{\substack{h \in H \\ a \in A_h \ \prod_{\forall t \in T}}} (sched\_Power[h][a][t], Greenness[h][a][t])
\tag{5.21}
$$

$$
\begin{aligned}
sched\_power\_per\_time\_step[t] = {} & \sum_{t \in T} (operating\_Power[h][a][t]) + \\
& (standby\_Power[h][a][t] * (1 - sched\_Final[h][a][t]))
\end{aligned}
\tag{5.22}
$$

5.7 Maximizing Aggregate Greenness

In this project, a novel mechanism for differentiation of energy resources into their source types has been devised. Two parameters have been added to prosumer household production units and smart appliances to describe: 1) the level of greenness of generated power and 2) the desired greenness level of energy consumption, respectively. The system implementation considers the fact that the two parameters need to be synchronized or matched as closely as possible to guarantee an optimal maximum overall greenness of the energy community. The maximization algorithm is executed at the central server which

computes how much green power the scheduled prosumer household production units generate, how much green power the scheduled prosumer household appliances need to consume and therefore minimizes the difference between the two. The first utility maximization problem is *maximizing greenness*. To maximize greenness in the energy community, the following algorithm aims at minimizing the *difference aggregate greenness*:

$$minimize_{\forall t \in T}(diff\_aggregate\_Greenness) \tag{5.23}$$

where *difference aggregate greenness* is the absolute difference between the demand and supply of green power in the energy community as:

$$diff\_aggregate\_Greenness =$$
$$\sum_{t \in T} |(sched\_green\_power\_per\_time\_step[t] - aggregate\_green\_Generated\_Power[t])| \tag{5.24}$$

The maximizing greenness problem is formulated as a minimization objective between the demand of and supply for green energy resources as follows.

$$minimize_{\forall t \in T} \sum_{t \in T} \left(\frac{\Sigma_{\forall t \in T}\left(\begin{smallmatrix}(operating\_Power[h][a][t]*sched\_Final[h][a][t]),\\ (standby\_Power[h][a][t]*(1-sched\_Final[h][a][t]))\end{smallmatrix}\right), \Pi_{\forall t \in T}\left(\begin{smallmatrix}(\Sigma_{\forall t \in T,}\ greenness[h][a][t])\\ h \in H,\\ a \in A_h\end{smallmatrix}\right),}{\Pi_{\forall t \in T}(\Sigma_{\substack{h \in H\\ a \in A_h}}\ generated\_Power[h][a][t], \Sigma_{\substack{h \in H\\ a \in A_h}}\ greenness\_Generated\_Power[h][a][t])} \right) \tag{5.25}$$

Equation (5.26) presents the price of consumed energy *price_Unit_Consumed_Energy*[t]

$$price\_Unit\_Consumed\_Energy[t] = \sum_{\forall a \in A_h} \prod_{\substack{a \in A_h,\\ t \in T}} (unit\_Price[a][t] * \sum_{h \in H} sched\_Prosumer[h][a][t]) \tag{5.26}$$

Algorithm: Maximizing Greenness Utility Executed at the Central Server

1. Receive the desired level of prosumer greenness *Greenness*[*h*][*a*] from each appliance inside the prosumer household.

2. Receive the produced power per time step *prod_power_Per_Time_Step*[*t*] and the greenness of generated power, *greenness_Generated_Power*[*h*][*p*], from each production unit inside the prosumer.

3. Receive an initial schedule of operation of appliances *is_Operating*[*h*][*a*][*t*] from each prosumer household for its appliances at each time step.

4. *Solve* equation (5.25) using non-linear programming solver using the *Simplexmethod* that is described in reference [26] *Until* the parameter *diff_aggregate_Greenness* is minimized.

5. Send the scheduled operation of appliances *sched_Final*[*h*][*a*][*t*] to each prosumer household.

6. Receive from each prosumer its dispatch schedule operation of appliances *sched_Prosumer[h][a][t]*.

7. *Solve* equation (5.26) to compute a new price per unit of consumed energy *priceUnit_Consumed_Energy[t]* based on the scheduled operation of appliances *sched_Prosumer[h][a][t]*.

8. For each time step *t*, update price per unit of consumed energy *priceUnit_Consumed_Energy*[*t*] accordingly.

The maximizing greenness utility executed at the prosumer household provides the user with a flexibility of operation inside the in day time frame that is known as dispatch as shown in figure 5.1. This is important since it allows accommodating variations in near real time operation schedules of appliances. For some users that do not abide by the schedule from the central server, the central server could use pricing control as part of a demand response control mechanisms. Moreover, the household benefits from evaluating household optimization functions which enables the user to choose from one type of appliance operation over another during the in day schedule.

Algorithm: Maximizing Greenness Utility Executed at the Prosumer Household

1. Send the desired level of prosumer greenness *Greenness*[*h*][*a*] to the central server.

2. Send an initial schedule of operation of appliances *is_Operating*[*h*][*a*][*t*] for its appliances at each time step to the central server.

3. Receive the scheduled operation of appliances *sched_Final*[*h*][*a*][*t*] from the central server.

4. *Evaluate* household optimization function.

5. Send its actual scheduled operation of appliances *sched_Prosumer*[*h*][*a*][*t*] to the central server.

5.8   Minimizing Aggregate Energy Cost

In this project, a cost function has been defined that indicates the cost of energy generation, transmission and distribution at each time step in the energy community. The energy cost function reflects peak energy demand during the day by adjusting to higher energy cost values during peak energy demand times. As widely observed in energy communities, high energy demand during mornings and evenings is the main cause of peak energy demand observed during the day. It is expected that the energy community needs to address peak energy demand that goes beyond the community of energy generation capacity internally or communicate with an external grid, incurring higher energy costs during these dispatch times to account for energy consumption as referred from reference [45] and [46].

The second utility maximization problem that is executed at the central server and aims to minimize cost is defined as minimizing the cost variable,

$$minimize_{\forall t \in T}(cost\_variable) \tag{5.27}$$

Which depends on a unit cost parameter and the final schedule of appliances

$$cost\_variable = \sum_{\forall t \in T}(\prod_{t \in T}(unit\_cost\_parameter[t], timestep\_Load[t])) \tag{5.28}$$

$$timestep\_Load[t] = \sum_{\substack{h \in H, \\ a \in A_h}}(sched\_Final[h][a][t]) \tag{5.29}$$

The cost minimization formula is presented as:

$$minimize_{\forall t \in T} \sum_{t \in T}(\prod_{t \in T}(unit\_cost\_parameter[t], \sum_{\substack{h \in H, \\ \alpha \in A_h}}, sched\_Final[h][a][t])) \tag{5.30}$$

The cost function $c\_P_t s\_F_t$ is parameterized indicating the cost of generating and/or distributing electricity by the energy source at each time step $t \in T$. Moreover, the following assumptions have been made and the cost function is parameterized accordingly.

The cost functions are increasing when approaching the daily energy demand peak; and decreasing when going away from the daily energy demand peak, for each time step $t \in T$, and corresponding energy load L_t, the following inequality presented in holds:

$$C_t L_t' < C_t L_t'' \tag{5.31}$$

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The cost functions are changing quadratically as presented in (d) and thus convex meaning for an hour during the day $t \in T$, any real number $L_t', L_t'' \geq 0$ and any real number $0 < \in < 1$,

$$C_t(\in L_t' + (1- \in)L_t'') < \in C_t(L_t') + (1- \in)C_t(L_t'') \tag{5.32}$$

Equation (5.33) presents the price of consumed energy *price_Consumed_Energy*[t] :

$$\sum_{\substack{\forall a \in A_h \\ \forall t \in T}} (\prod_{\substack{\forall a \in A_h \\ \forall t \in T}} (unit\_price\_parameter[a][t], \sum_{h \in H} sched\_Prosumer[h][a][t])) \tag{5.33}$$

Algorithm: Cost Minimization Function Executed at the Central Server

1. Receive an initial schedule of operation of appliances *is_Operating*[h][a] from each prosumer household for its appliances at each time step.

2. Initialize a cost parameter *unit_cost_parameter*[t] that increases quadratically with the energy consumption load during the period of the day for each time step t.

3. **Calculate** the cost function as the sum for each time step t the multiple of the cost parameter at each time step *cost_parameter*[t] and the initial schedule of operation of appliances *is_Operating*[h][a][t].

4. **Solve** equation (5.30) using linear programming solver using the *Simplex* method [21]
   Until the cost function *cost_function* is minimized.

5. Send its actual scheduled operation of appliances *sched_Prosumer*[h][a][t] to the central server.

6. Receive from each prosumer its scheduled operation of appliances *sched_Prosumer*[h][a][t].

7. **Solve** equation (5.30) to compute a new price per unit of consumed energy *priceUnit_Consumed_Energy*[t] based on the scheduled operation of appliances *sched_Prosumer*[h][a][t].

8. Update price per unit of consumed energy *priceUnit_Consumed_Energy*[t] accordingly for each time step t.

Algorithm: Cost Minimization Function Executed at the Prosumer Household

1. Send an initial schedule of operation of appliances *is_Operating*[*h*][*a*][*t*] for its appliances at each time step to the central server.

2. Receive the scheduled operation of appliances *sched_Final*[*h*][*a*][*t*] from the central server.

3. **Evaluate** household optimization function.

4. Send its actual scheduled operation of appliances *sched_Prosumer*[*h*][*a*][*t*] to the central server.

Another mechanism to minimize the cost of energy resources is to drive load away from peak demand hours. The optimization algorithm implementation presented below aims at reducing the peak to average ratio of the aggregate energy profile of the energy community. The mechanism presented below reduces the difference between the upper and lower aggregate power bound.

$$minimize_{\forall t \in T}(upper\_aggregate\_power\_bound - lower\_aggregate\_power\_bound) \quad (5.34)$$

or equivalently,

$$minimize_{\forall t \in T} \sum_{t \in T} \frac{(upper\_peak\_ratio * max_{\forall t \in T} sched\_power\_per\_time\_step[t]) -}{(lower\_peak\_ratio * min_{\forall t \in T} sched\_power\_per\_time\_step[t])} \quad (5.35)$$

Equation (5.36) presents the price of consumed energy as:

$$priceUnit\_Consumed\_Energy[t] = \sum_{\forall a \in A_h} (\prod_{t \in T}$$
$$(price\_parameter[a][t], \sum_{h \in H} sched\_Prosumer[h][a][t])) \quad (5.36)$$

Algorithm: PAR Reduction Function Executed at the Central Server

1. Receive an initial schedule of operation of appliances *is_Operating*$[h][a]$ from each prosumer household for its appliances at each time step.

2. **Calculate** the initial power consumed by each appliance at each time step *init_power*$[h][a][t]$ as the sum of the multiple of operating power and initial schedule of operation of appliances (*operating_Power*$[h][a][t] * is\_Appliance\_Operating[h][a][t]$) and the multiple of the standby power and the non-operating status of appliances (*standby_Power*$[h][a][t] * (1 - is\_Appliance\_Operating[h][a][t])$)

3. **Calculate** the aggregate initial power consumed per time step *init_power_Per_Time_Step*$[t]$ as the time step sum of the initial power consumed by each appliance at each household *init_power*$[h][a][t]$ for each household and appliance.

4. Initialize an upper aggregate power bound variable *upper_aggregate_power_bound* using the multiple of a peak ratio *peak_ratio* below which the final scheduled aggregate power should stay and the aggregate initial power consumed per time step *init_power_Per_Time_Step*$[t]$.

5. **Solve** equation (5.35) *Until* the difference aggregate power bound variable *diff_aggregate_power_bound* is minimized.

6. Receive from each prosumer its scheduled operation of appliances *sched_Prosumer*$[h][a][t]$.

7. **Solve** equation (5.36) to compute a new price per unit of consumed energy *priceUnit_Consumed_Energy[t]* based on the scheduled operation of appliances *sched_Prosumer[h][a][t]*.

8. Update price per unit of consumed energy *priceUnit_Consumed_Energy*$[t]$ accordingly for each time step t.

Algorithm: PAR Reduction Function Executed at the Prosumer Household

1. Send an initial schedule of operation of appliances *is_Operating*$[h][a][t]$ for its appliances at each time step to the central server.

2. Receive the scheduled operation of appliances *sched_Final*$[h][a][t]$ from the central server.

3. **Evaluate** household optimization function.

4. Send its actual scheduled operation of appliances *sched_Prosumer*$[h][a][t]$ to the central server.

5.9   The Amount of Payment for an Energy Unit

For a smart grid based energy community, it is known that the amount of money that a prosumer household pays or gets paid for a specific energy unit directly relates to the associated pricing scheme. Utility maximization programs should therefore take proper pricing mechanisms that aim the *benefit of all* scenario. This project considers a central server based energy community where the central server takes its share of control over its prosumer households; therefore, more sophisticated and non-scalable price setting methodologies which require distributed control by prosumer households over their appliances have not been considered. This can be justified with game theoretic based control mechanism which is an example of such methodologies. It has been identified that game theoretic control mechanism is not scalable to the level of energy communities of larger sizes. Therefore, focus has been given on the using the central server as a primary control unit and considering the flexibility, quality, and cost minimization needs for the prosumer. Moreover, in this project, a pricing mechanism is implemented that is based on a dayahead schedule and a critical peak pricing scheme where critical peak periods and corresponding event prices are defined in advance thus aiming at peak load reduction. Figure 5.1 shows a specification of energy market pricing mechanism. It has been shown that a pricing mechanism is regarded as *dynamic* when its range of operation can be scheduled in the *day-ahead* and *in-day* market time horizon [1] pp. 9-10.

Figure 5.1: Time Frame and System Functions in Regulatory and in Competitive Markets, 1 [1]

As mentioned earlier, one of the unique contributions to the field, a prosumer household appliance based pricing scheme considers that prosumer households are willing to pro-
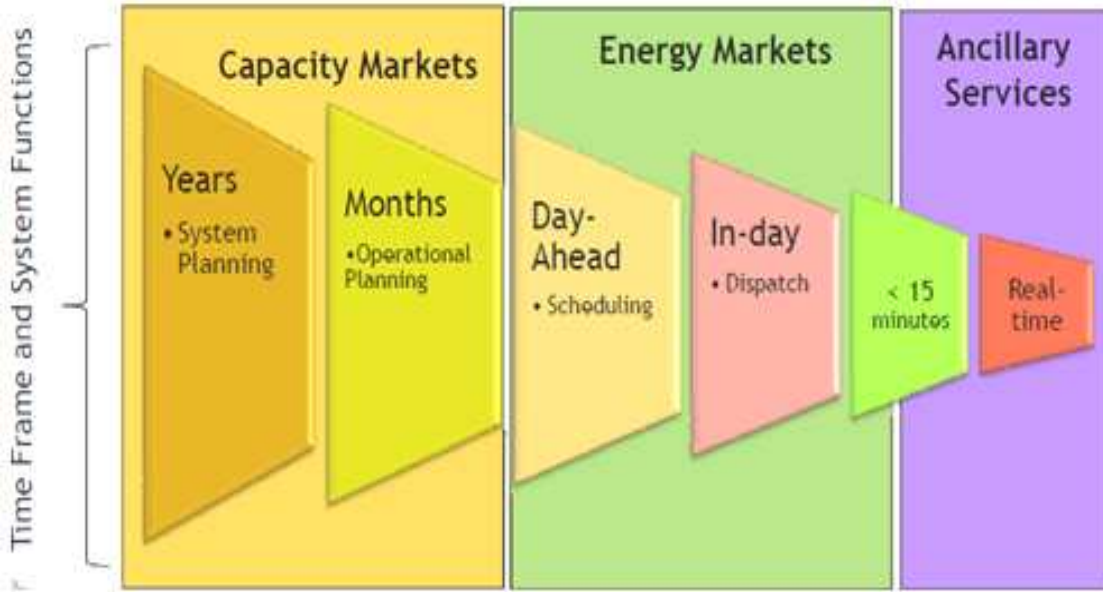
Figure 5.2: Time Frame and System Functions in Regulatory and in Competitive Markets, 2 [1]

vide their appliance usage information to the utility company if they get a mutual benefit from this appliance based pricing scheme. At those cases where prosumer households are not willing to provide their appliance power usage information, the utility company could make use of techniques such as energy disaggregation as specified in the section 4.3 and referred in reference [31]. This helps the utility company identify what kind appliances are under operation at which times of the day by just looking at the aggregate energy profile.

The pricing scheme sets different prices per unit of consumed energy at different durations of time for different appliances according to their load demand characteristics and could thus maximize the energy resource utilization in the energy community by prioritizing specific kinds of appliance operations over others during different times of the day.

The utility maximization function that aims payment reduction is expressed as follows.

$$minimize_{\forall t \in T}(payment)$$

where payment is defined from *unit price of consumed energy* and *final schedule of appliances* as:

$$payment = \sum_{t \in T}(\prod_{t \in T}(unit\_price\_Consumed\_Energy[t], \sum_{\substack{h \in H, \\ a \in A_h}} sched\_Final[h][a][t])) \quad (5.37)$$

$$unit\_price\_Consumed\_Energy[t] = \sum_{a \in A_h} (unit\_price\_parameter[a][t] * \sum_{h \in H} sched\_Final[h][a][t])$$

(5.38)

As shown above, the *unit_price_Consumed_Energy*[t] represents the time step based price of consumed energy, while payment represents the overall payment for the consumed energy in the community that is calculated based on the unit_price_parameter. In a single formula, equation (5.39), the appliance based pricing scheme with an aim to reduce payment is presented as:

$$minimize_{\forall t \in T} \sum_{t \in T} (\prod_{t \in T} (unit\_price\_Consumed\_Energy[t], \sum_{\substack{h \in H, \\ a \in A_h}} sched\_Final[h][a][t])) \quad (5.39)$$

Equation (5.40) presents the *price of consumed energy*[t] as

$$\sum_{\forall a \in A_h} (\prod (unit\_price\_parameter[a][t], \sum_{h \in H} sched\_Prosumer[h][a][t])) \quad (5.40)$$

This mechanism is implemented in an algorithm as follows.

Algorithm: Appliance Based Pricing Scheme Executed at the Central Server

1. Receive an initial schedule of operation of appliances *is_Operating[h][a][t]* from each prosumer household for its appliances at each time step.

2. Initialize a price parameter *unit_price_parameter[a][t]* that differentiates the price per unit of consumed energy for each appliance *a* over different time steps *t*.

3. **Calculate** the price of consumed energy function as the sum for each time step *t* the multiple of the price parameter for each appliance over each time step *t* $unit\_price\_parameter[a][t]$ and the initial schedule of operation of appliances $is\_Operating[h][a][t]$.

4. **Solve** equation (5.39) using non-linear programming solver using the *Simplex method* [21] *Until* the payment variable *payment* is minimized.

5. Send scheduled operation of appliances $sched\_Final[h][a][t]$ to each prosumer household.

6. Receive from each prosumer its scheduled operation of appliances $sched\_Prosumer[h][a][t]$.

7. **Solve** equation (5.40) to compute a new price per unit of consumed energy $unit\_Price\_Consumed\_Energy[t]$ based on the scheduled operation of appliances $sched\_Prosumer[h][a][t]$.

8. Update price per unit of consumed energy $priceUnit\_Consumed\_Energy[t]$ accordingly for each time step t.

Algorithm: Appliance Based Pricing Scheme Executed at the Prosumer Household

1. Send an initial schedule of operation of appliances $is\_Operating[h][a][t]$ for its appliances at each time step to the central server.

2. Receive the scheduled operation of appliances $sched\_Final[h][a][t]$ from the central server.

3. **Evaluate** household optimization function.

4. Send its actual scheduled operation of appliances $sched\_Prosumer[h][a][t]$ to the central server.

5.10 Utility Maximization Combination Function

The utility maximization combination function encompasses a number of objectives which are expressed with important parameters for the:

1. Aggregate energy cost of the energy community which depends on the amount of peak to average ratio reduction (PAR), the type of energy source and the amount of net power import/export from/to external grid,

2. Overall greenness of the energy community which depends on the aggregate/individual difference in green energy demand and supply,

3. Overall schedule preference/sensitivity parameter which depends on average flexibility of appliances in their time based operation.

There are two sides of the research problem. First, the amount of utility combination possible in terms of the targets needs to be identified. Second, the type of utility combination that helps attain the *benefit of all* situation needs to specified and implemented.

5.10.1 Utility Maximization The Combination Function

The utility maximization combination function is formulated as:

$$
\begin{aligned}
Cf(x) = & schedule\_Preference\_Index(\sigma) * flexibility\_Margin * (-1) + \\
& payment\_Sensitivity\_Index(\pi) * cost\_Minimization\_Function * (+1) + \\
& greenness\_Sensitivity\_Index(\gamma) * greenness\_Difference\_Minimization\_Function * (+1)
\end{aligned}
$$
$$(5.41)$$

There are two different ways with which the index variables for schedule preference, payment sensitivity and greenness sensitivity are decided. One way of deciding these parameters is using user specified parameters, which is through the energy management box on a day-ahead basis. Then it is possible to combine these individual user preferences into combination indexes by accounting with the quantity of power associated with each individual user. Another way is using sub-parameters that decide the effect of maximizing each of these parameters by noting the effect of each parameter on the aggregate community objective. For example, the type of energy resource specified by the level of greenness in the energy community affects the cost incurred in the energy community. And the cost sensitivity of energy community members affects the amount of reduction in peak to average ratio of the aggregate energy profile of the energy community. For the balanced combination, it is assumed that the effect of green energy seeking on aggregate cost reduction of the energy community is on a par with the effect of money saving on the aggregate cost reduction of the energy community, therefore given the name *balanced*.

Therefore, for the different scenarios, the utility maximization combination function indexes could take the following values: -

1. Money Saver, $\sigma = 0, \pi = 1, \gamma = 0$

2. Green Energy Seeker, $\sigma = 0, \pi = 0, \gamma = 1$

3. Schedule Preferrer, $\sigma = 1, \pi = 0, \gamma = 0$

Then it is important to look at the effect of these individual scenarios and combinations on aggregate energy cost and community utility objectives. Moreover, by using an optimal combination, it is possible to show from the results that 1) Energy cost is minimized, 2) Schedule preference is met, and 3) Greenness is maximized.

5.10.2 Shifted Duration

The *shifted duration* parameter shows how much the schedule preference of a user has been affected because the user has received a shift inside the duration of flexibility of operation. The difference between the time of preferred schedule and the time of final schedule results the size of the flexibility margin or flexibility duration.

$$ShiftedDuration for both Start and End = |Preferred\ schedule\ time - Actual\ schedule\ time| \tag{5.42}$$

given that preferred schedule start time and actual schedule start time are greater than flexibility duration start time and preferred schedule stop time and actual schedule stop time are less than flexibility duration stop time.

An important parameter is the difference between the starting value of *sched_Final* with that of *sched_Initial(is_Appliance_Operating)* and the ending value of *sched_Final* with that of *sched_Initial(is_Appliance_Operating)* for every appliance on time steps the appliance takes on different values, meaning when an appliance is scheduled to opearte on time steps that it was not initially scheduled to operate or vice versa. This can be found by counting the time steps when *sched_Final[h][a][t]* and *is_Appliance_Operating[h][a][t]* take on different values.

5.10.3 PAR factor and Cost Combination

The result of this research provides information on how much the energy cost is affected when there is a change in the energy demand peak in the energy community. For example, one percent of peak reduction may correspond to one percent of unit energy cost reduction.

$$CostFunction = \sum_{\forall t in T} unit\_cost\_parameter(t) * \sum_{\substack{\forall h in H \\ \forall a in A}} sched\_Final[h][a][t] \tag{5.43}$$

There is always this cost associated whenever an appliance is scheduled in some manner of operation. The question is how much energy cost could be reduced when peak is reduced; meaning how evident is the effect of peak reduction in the energy cost function. If the *unit_cost_parameter(t)* is not changing, peak reduction does not have an effect on cost. However, if peak reduction is performed on a varying *unit_cost_parameter(t)*, then peak reduction has an effect on cost reduction.

5.10.4 Balanced Energy Community Model

A different but more efficient mechanism to combine utility maximization function in this project makes use of an identification of the energy parameters for each member of the energy community for the communitys:

1. Level of greenness which describes the level of green energy needed,

2. Duration of time-shift which describes how much time shift could be introduced per operating appliance, and

3. Payment Sensitivity which describes how much money a user wishes to save per each appliance operation.

These values could also be input from the user as indexes considering that the sum of these values gives one, and also assuming that the user gives priority to these parameters more than any metrics which could also be introduced.

Then, it is also possible to identify which users prefer to go for only one of the parameters rather than willing to go for any two of these parameters. For example, a prosumer household that is identified as a schedule preferrer might go for only keeping his/her schedule and he/she might, at all times, need to get a response from the server as the earliest possible decision. Considering also other users which choose only one of these parameters (being green as the only option, or money saving as the only option), it becomes mandatory, from the point of view of fairness, that the combination function does one optimization for each of these kinds of users, while it goes for an index-based, three parameter leveled optimization for the remaining users. Such an implementation couples the benefit of fairness and reduces complexity since: 1) The input size that should be processed at once is lower than the total size of the community, and 2) Each of these single parameter optimization functions could be implemented in parallel, followed sequentially by the three parameter optimization.

Another combination approach could make use of the indexes in such a way that they are implemented as decision variables, and using an incremental search on the indexes, it is possible to find the best values of these indexes for any given combination of user needs or characteristics.

5.11 Optimized Energy Community Model

One combination approach that takes the individual preference of prosumer households into consideration is presented as follows. Prosumer households submit their payment needs through the use of indexes for greenness, for schedule preference and for money saving as $greennessIndex_t^h$, $schedulePreferenceIndex_t^h$ and $moneySavingIndex_t^h$. These are aggregated over all users to find indexes for the community such as $GreennessIndex_t^H$, $SchedulePreferenceIndex_t^H$ and $MoneySavingIndex_t^H$. In this aggregation, it is also considered that the household level of greenness, the household level of schedule preference and the household level of money saving are taken into consideration in such a manner that they

contribute to the aggregate indexes proportionally with their individual household energy demand.

From the Energy Community Model, the *household_Shift_Duration*, the *aggregate_Shift_Duration* and the *sum_Aggregate_Shift_Duration* are defined as:

$$household\_Shift\_Duration^h = \sum_{\forall a} \left| sched\_Final_t^{h,a} - is\_Appliance\_Operating_t^{h,a} \right|$$
(5.44a)

$$aggregate\_Shift\_Duration = \sum_{\forall H} household\_Shift\_Duration[household]$$
(5.44b)

$$sum\_Aggregate\_Shift\_Duration = \sum_{\forall t} shifted\_Duration$$
(5.44c)

Then, it is important to capture each of these indexes for the aggregate community. The following three captures are important.

1. Schedule Preference Capture

$$Schedule\_Preference\_Index_t^H = \sum_{\forall h} (schedule\_Preference\_Index_t^h * household\_Shift\_Duration_t^h)$$
(5.45)

2. Greenness Capture

$$GreennessIndex_t^H = \sum_{\forall t} (aggregate\_Green\_Generated\_Power_t^h - sum_{\forall h}(greennessIndex_t^h * \sum_{\forall a} sched\_Final_t^{h,a}))$$
(5.46)

3. Money Saving Capture

$$MoneySavingIndex_t^H = \sum_{\forall h} \sum_{\forall t} (unit\_price * (moneySavingIndex_t^h * \sum_{\forall a} sched\_Final_t^{h,a}))$$
(5.47)

5.11.1 Optimality Conditions

When combining the captured indexes, the concept of optimal utility mathematical model is used as follows. Let the desire of prosumers to procure a particular utility be represented by a utility function U (g, s) where g and s represent the for greenness and schedule preference utilities which are offered to prosumer households. The desire levels

or satisfaction levels depend on the payment that the user would like to spend on each utility component; thus, there are different levels of satisfaction. Given that the income of prosumers is limited by an income function I (g, s) (eq. 5.46), the optimization problem aims to find the value of g and s which meet the satisfaction levels of the utilities g and s while still abiding by the income function I (g, s). The relationships between the income function and the satisfaction functions are shows in figure 5.3.
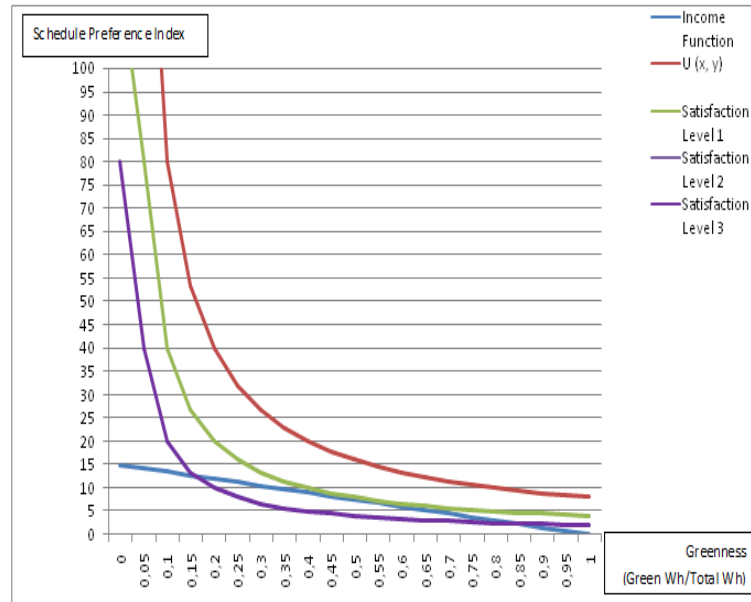
Figure 5.3: Utility based Optimization Functions Greenness vs Schedule Preference

The optimization starts with finding the maximum value of the derivative of the utility function U (g, s), V(g, s) while both g and s fit on the income function I (g, s). The optimization then calculates a Lagrange multiplier that allows such relationship. The mathematical model puts that for the equation (5.49) to hold, the ratio of the partial derivates of the derivative of the utility function with respect to both g and s should equal to the ratio of the corresponding prices of the utility variables as presented in equation (5.52). The concept of Lagrangian multipliers is further explained in the following section.

Max V(g,s)

Condition

$$I = p_g G + p_s S \tag{5.48}$$

Lagrange

$$L = V(g,s) + \lambda(I - p_g G + p_s S) \tag{5.49}$$

$$\frac{dV}{dg} - \lambda p_g = 0, \frac{dV}{ds} - \lambda p_s = 0, \frac{dV}{d\lambda} = 0 \qquad (5.50)$$

$$I = p_g G - p_s S \qquad (5.51)$$

$$\frac{dV}{dg} \Big/ \frac{dV}{ds} = p_g / p_s \qquad (5.52)$$

5.11.2 Lagrangian multipliers

The aggregation considers individual index variables of each household and appliance and decides an index vector using optimal utility mathematical model for the aggregate energy community. It is natural that there is a price for each individual utility function. For example, the price of being green is P_g, the price of preference for a users own schedule is P_s, and the price of money saving by a user is P_m which is negative in value since it benefits the user. Now to combine these individual utility functions in an optimal manner for the aggregate energy community, the constraints are either budget related which constrain that the expenditures cannot exceed the level of income, or expenditure related which constrain that expenditures should meet one of the indifference curves or satisfaction levels. Considering that there are n numbers of utility variables, the level of income that is spent on these utility variables is expressed as $I = P_1 X_1 + P_2 X_2 + + P_n X_n$. For utility maximization, marginal rate of substitution (MRS) should equal the ratio of prices, and thus marginal rate of substitution of utility X_j for utility X_i should equal to the ratio of price of utility i to utility j or P_i / P_j, where $1 \leq i, j \leq n$. This scenario signifies an optimal choice for a household.

5.11.3 Corner Solution

A decision to procure a single type of utility rather than a combination of utilities is termed as a corner solution. For an individual household that exhibits such kind of property, this is called the boundary optimal for that household. As shown in previous sections, tangency condition, which specifies that the utility function should be tangent to the indifference curve or satisfaction levels, does not necessarily hold for a corner solution, and therefore:

$$MU_1 / P_1 \leq MU_2 / P_2 \qquad (5.53)$$

And further substitutions are no longer possible. This scenario can be explained with much simpler examples from day to day life, taking a supermarket shopper for example. Given that there are choices for a shopper to purchase and consume chicken or beef,

if the shopper chooses to consume chicken only, these result in a corner solution where the tangency condition does not necessarily hold.

However, as it often happens, the demand level is not precisely known. This creates the optimal load demand pattern problem. Optimal load demand pattern is a dual problem of 1) *Economic Dispatch (ED)* and 2) *Unit Commitment (UC)* of production units and consumption units in the smart grid based energy community. There are two different classifications to this problem.

1. For Power Generators, the optimization objective using ED and UC is Minimization of Operating and Fuel costs.

2. For Power Loads, the optimization objective is dependent on the application which can be modeled as a utility function which bases on the concept of microeconomics such as the benefit function and the demand curve.

The solution of the Unit Commitment (UC) and Economic Dispatch (ED) problems includes:

1. Lagrangian Relaxation Techniques

2. Dynamic Programming

3. Mixed Integer Linear Programming (MILP)

To apply the Lagrangian, for every user, the value of λ for the Lagrange multiplier should be identified according to the budget constraint $I = P_1 X_1 + P_2 X_2 + + P_n X_n$ and the satisfaction levels. For this project, the budget constraint is considered to be equal to the aggregate household budget for electricity and the satisfaction levels are aggregated from overall specific needs of the household for those utilities. For example, for three utilities $greennessIndex_t^h$, $schedulePreferenceIndex_t^h$ and $moneySavingIndex_t^h$, f($greennessIndex_t^h$, $schedulePreferenceIndex_t^h$ and $moneySavingIndex_t^h$) may be equal to $0.4 * greennessIndex_t^h$, $0.3 * schedulePreferenceIndex_t^h$ and $0.3 * moneySavingIndex_t^h$.

After the corresponding prices of $greennessIndex_t^h$, $schedulePreferenceIndex_t^h$ and $moneySavingIndex_t^h$ are set, it is possible to identify what values of these parameters are optimal for the aggregate community. This implementation could start from every household, thus providing an optimal solution for the whole community. Thus, the implementation considers the satisfaction functions for an aggregate of a household and budget line for the energy community by first identifying the Lagrange Multipliers and the optimal values of each utility for each prosumer household in the energy community and then finding the corresponding values for the energy community, thus optimizing the combination.

Although this does not guarantee that each individual household in the community retains its optimal value, it can guarantee that the difference between the community optimal and the household optimal is the least minimum, meaning each household gets the best possible values according to its preference for each of the utility values. Parameters useful for optimization using Lagrange

1. Each prosumer household provides its values for

a) Its power consumption budget (daily)

b) Its preference over the utilities which derive the satisfaction function for the household.

c) Computes Lagrangian multiplier and optimal values corresponding to each amount of the utilities for the individual household.

2. The central server

a) Inputs values for the consumption budget (daily) of each household

b) Computes the aggregate consumption budget.

c) Inputs the preference values of individual households over each utility which derives the satisfaction function and the amount of power consumed or the amount of delay incurred according to each utility.

d) Computes the aggregate satisfaction function for the energy community.

e) Computes Lagrangian multiplier and optimal values corresponding to each amount of the utilities for the energy community.

5.12 Results

In this chapter, utility maximization mechanisms for a smart grid based energy community have been presented. The chapter first starts with modeling the utility function based on resource classifications in an energy community. Then, the problem formulation follows which presented the resource based scheduling and optimization problem in detail. Following that, utility maximization mechanisms that are formulated in this paper are presented.

The formulated utility maximization techniques include a function that maximizes aggregate greenness of the energy community and a function that minimizes aggregate cost reduction in the energy community. The two distinct objectives have been formulated keeping in mind the availability of energy resources, the unit cost of energy resources, and the schedule preference of prosumer households.

Following that, the implementation of the utility maximization functions was presented. The implementation considered the greenness desire of prosumer households, the schedule preference of prosumer households and the money saving desire of prosumer households in the energy community. Based on these preferences, different combinational approaches have been presented. Moreover, an optimal combination approach that made use of the concept of Lagrangian multipliers mathematical model has been implemented. The optimal decision then identified what is an optimal amount of combination possible between the three utility components defined by the utility formulae using the aggregate income level of prosumer households and the aggregate preference indexes over the individual utility components.

Chapter 6

Results and Discussions

6.1 Simulation Setup

The simulation setup starts with modeling of the energy community that is composed of prosumer households, smart appliances and production units. The simulation is characterized by the number of time steps that are included in one time execution of the simulation, which also decides the duration of scheduling and optimization for the energy community. For example, in a day-ahead schedule which is also the preferred scheduling duration by this paper, the simulation is executed per minute resolution, therefore, fourteen hundred and forty timesteps have been included in one execution corresponding to 60*24 = 1440 minutes in a day-ahead schedule. The energy community is also characterized by the number of prosumer households, and the number of smart appliances and the number of production units in each prosumer household. The other parameters that characterize the energy community and are thus important for the simulation are described in depth by the previous sections. The simulation has been performed with Matlab, Java and a linear optimization tool CPLEX. The optimization tool CPLEX was used as part of the simulation environment from the IBM ILOG CPLEX Optimization Studio version 12.14 [48] which is an optimization studio built on the Open Source Software Eclipse [49]. CPLEX was used to model the energy community. Java was used as part of the Net Beans Integrated Development Environment 7.2 [50]. Java was an important component of the simulation since the optimization of the energy community modeled using CPLEX was compiled and executed from Java. This also provides the opportunity to include a number of energy community models for one time optimization. Moreover, Matlab was used for plotting graphs which display important results from the optimization.

6.2 Simulation Data

The utility maximization formulae were implemented at an aggregate community level and prosumer household appliance level. The data has been collected from an energy community which is under the management of Qurrent Renewable Energy Company. The company manages around forty prosumer households in one location around Amsterdam, the

Netherlands. Twenty prosumer households were considered in one sample group considering their similarity in spatial locality. Each of these prosumer households openly provides their prosumer characteristics to the central server: their time based energy generation, energy storage and energy consumption information.

6.3 Results

The initial schedule of operation and power generation/consumption of appliances or production units has been compared side by side with the final schedule of operation and power generation/consumption of appliances/production units. Important parameters that characterized the energy community were regarded as decision variables by the utility maximization formulae and thus optimized from their original values. Moreover, these optimized parameter values have been compared to their starting values in an analysis method through which the effects of the optimization were evaluated. For example, the effect of the greenness maximization implementation has been evaluated on how much effect it has brought in reducing the difference in amount of green energy production and level of demand for green energy consumption in the energy community.

The results obtained for the implementation of these formulae namely maximizing greenness in the energy community, minimizing the peak to average ratio of the aggregate energy profile of the energy community, and minimizing the energy cost in the energy community have been recorded and plotted in Matlab. In addition, in order to see the effect of combining two or more of these developed formulae, combination functions have been implemented and their results have been compared with the individual formula implementations. The Matlab plots in figure 6.1 show these results in detail.

The result of the implementation of the various utility maximization functions on an actual energy community is presented as follows. The energy community consists of ten prosumer households with appliances and production units that are scheduled on a day-ahead basis. Based on the objectives of each of the utility maximization functions, a consumption behavioral model is derived for the members of the energy community. In each of the cases, the utility maximization combination function is applied, considering that the components of the energy community behave as green energy seeker, money saver, schedule preferrer or exhibit a mixed behavior of these individual behaviors in the community. The level in which these behaviors are exhibited by individual households is expressed by the use of indexes such that the values of the three indexes that correspond to the three behaviors vary from 0 to 1. For example, if a prosumer household gives all of its priority to green energy usage and is not concerned about money saving nor keeping its appliance operation schedule, its individual indexes will take a value as *Greenness Sensitivity Index (* $\gamma = 1$*)*, *Payment Sensitivity Index (* $\pi = 0$*)* and *Schedule Preference Index (* $\sigma = 0$*)* .

The following Matlab plots show the results for the ten prosumer households that are administrated by Qurrent Renewable Energy Company and whose data has been collected from February 1st to May 31st, 2012. For the purpose of the one minute optimization in a day-ahead manner, the time duration consisted of 1440 time-steps which correspond to 60 minutes in an hour, multiplied by 24 hours per day equaling 1440 minutes in every single day.

The primary objective of the first combination function is maintaining the schedule preference of individual households while maintaining the different objectives of maximizing green energy usage and money saving in a best effort manner. Figure 6.2 shows the obtained results.

6.3.1   Schedule Preferrer Combination $(\gamma, \pi, \sigma) = (0, 0, 1)$

It was observed that for the *schedule preferrer combination function*, while the average power stayed at 2620.47Wt, the initial peak power which was recorded as 4429.53Wt has been reduced to 2989.53Wt corresponding to a change of 32.51%, while the initial standard deviation was reduced from a value of 906.38 to a final value of 883.92, corresponding to a change of - 2.5%.

6.3.2   Money Saving Combination $(\gamma, \pi, \sigma) = (0, 1, 0)$

For the money saving combination, it was observed from figure 6.3 that for the *money saver combination function*, while the average power stayed at 2620.47W, the initial peak power which was recorded as 4429.53W has been reduced to 3019.53W corresponding to a change of 31.83%, while the initial standard deviation was reduced from a value of 906.38 to a final value of 917.84, corresponding to a change of 1.25%.

6.3.3   Green Energy Seeker Combination $(\gamma, \pi, \sigma) = (1, 0, 0)$

It was observed that for the *green energy seeker combination function* in figure 6.4, while the average power stayed at 2620.47W, the initial peak power which was recorded

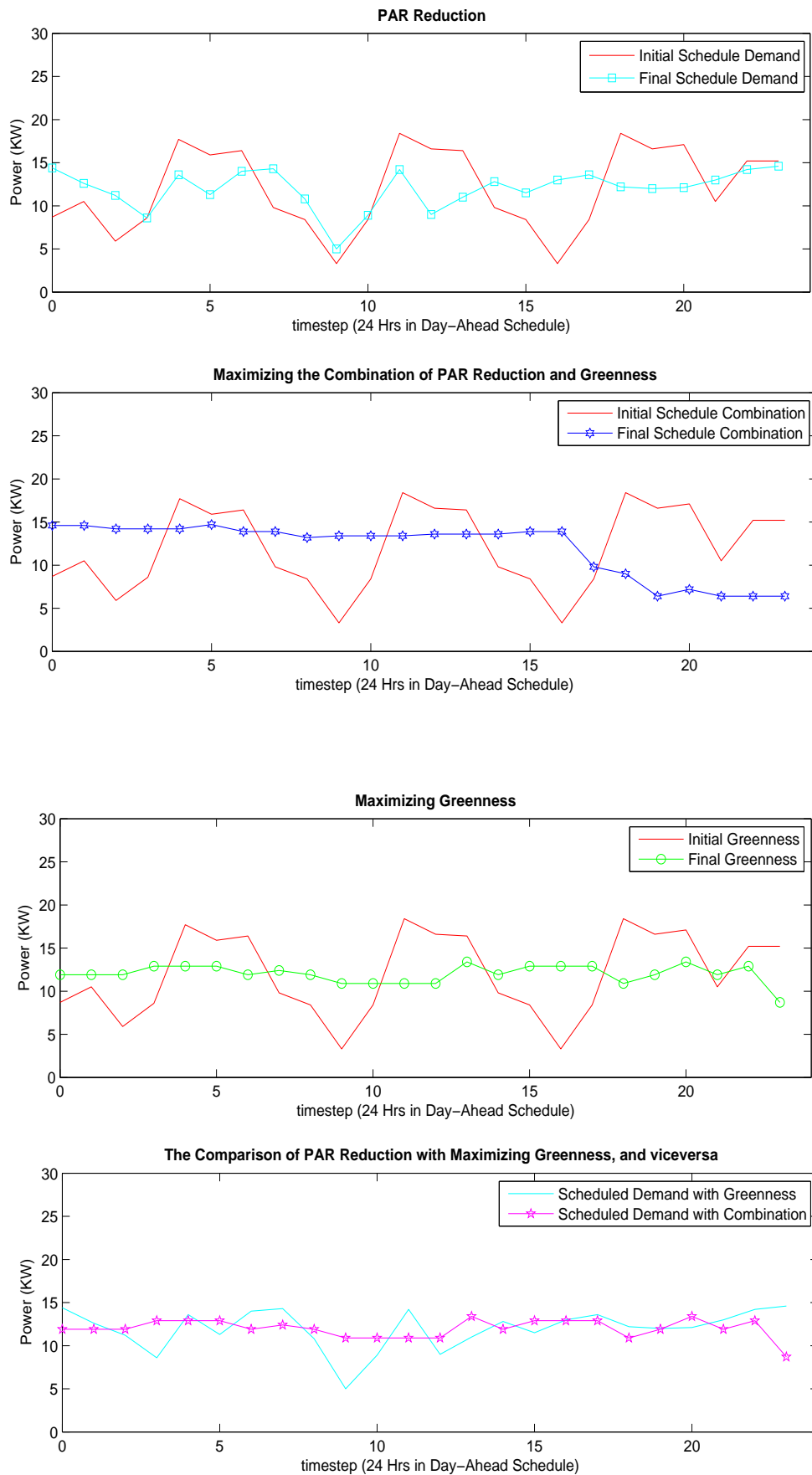Figure 6.1: Utility Maximization Function Implementations in a day-ahead schedule
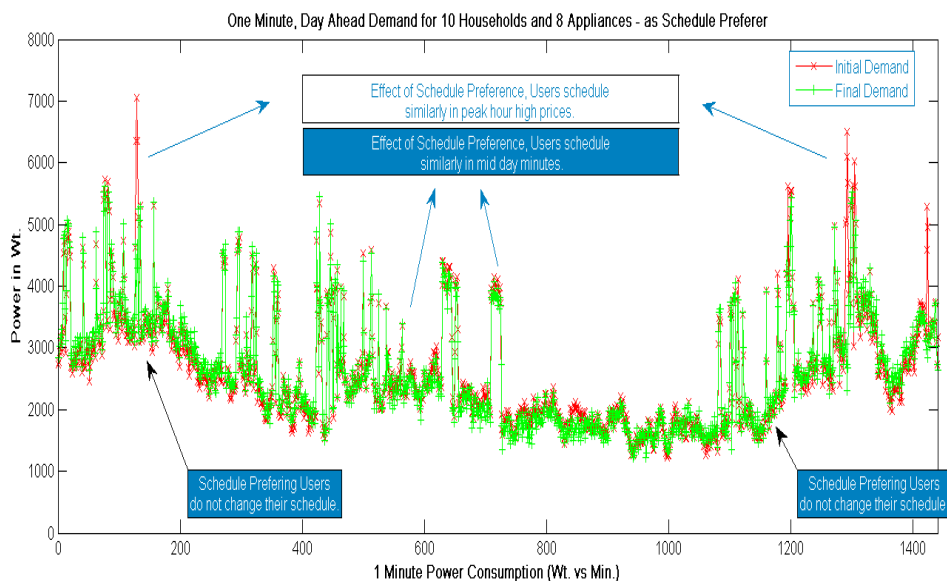
Figure 6.2: Day-ahead per minute schedule preferrer combination
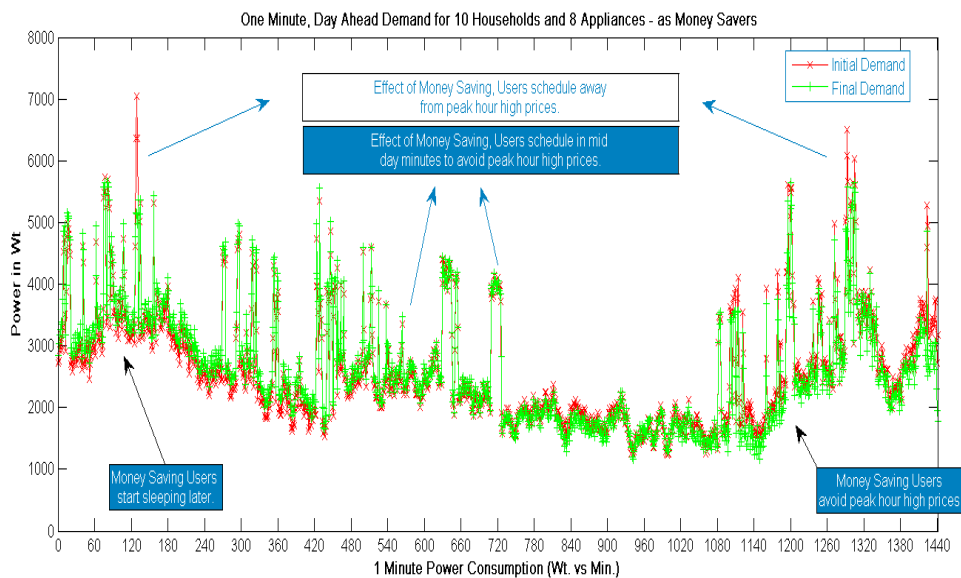
Figure 6.3: Day-ahead per minute money saver combination

as 4429.53W has been reduced to 2959.53W corresponding to a change of 33.19%, while the initial standard deviation was reduced from a value of 906.38 to a final value of 872.34, corresponding to a change of 3.76%.

Figure 6.4: Day-ahead per minute green energy seeker combination

6.3.4 Balanced or Optimized Combination $(\gamma, \pi, \sigma) = (0.125, 0.125, 0.75)$
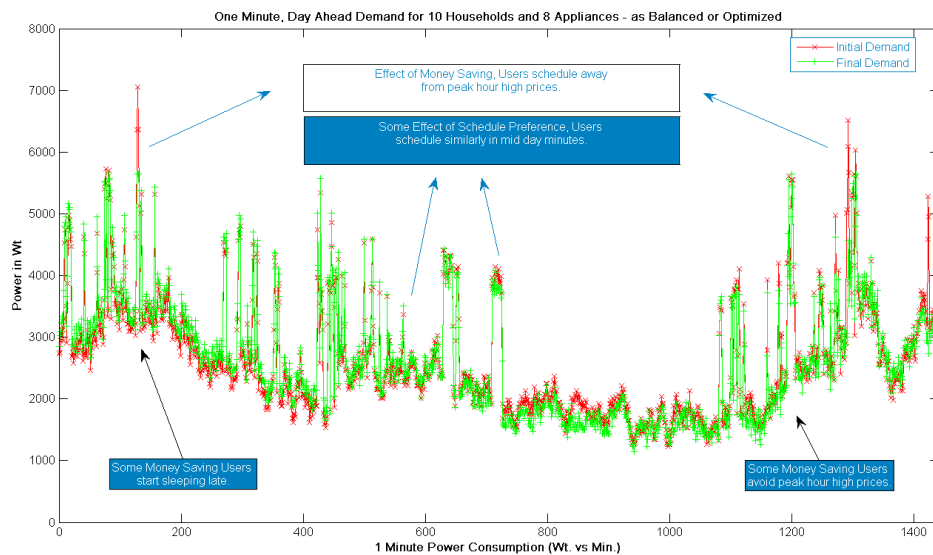
Figure 6.5: Day-ahead per minute balanced or optimized combination

In figure 6.5, it was observed that for the *balanced or optimized combination*

function, while the average power stayed at 2620.47W, the initial peak power which was recorded as 4429.53W has been reduced to 3019.53W corresponding to a change of 31.83%, while the initial standard deviation was reduced from a value of 906.38 to a final value of 921.42, corresponding to a change of 1.63%.

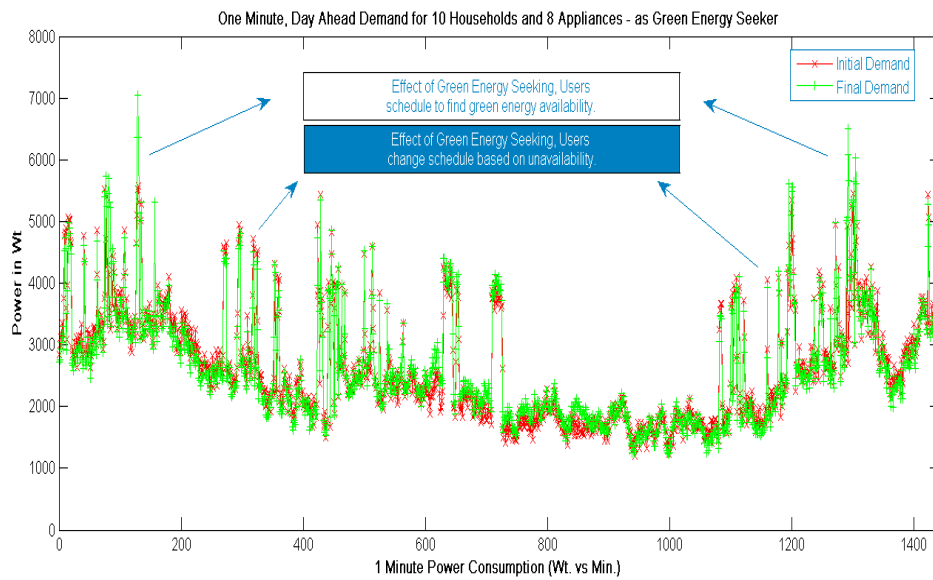Finally, considering the *optimal combination function*, while the average power stayed at 2620.47W, the initial peak power which was recorded as 4429.53W has been reduced to 3019.53W corresponding to a change of 31.83%, while the initial standard deviation was reduced from a value of 906.38 to a final value of 909.28, corresponding to a change of 0.32%.

Concerning the specific appliance level energy cost reduction using peak to average ratio reduction using upper aggregate power bound method, the following results have been obtained.

Figure 6.6: Appliance Based Household Optimization for a Day in May (hr. vs. Whr. plot1)

The groups of appliances monitored by the Qmunity application :

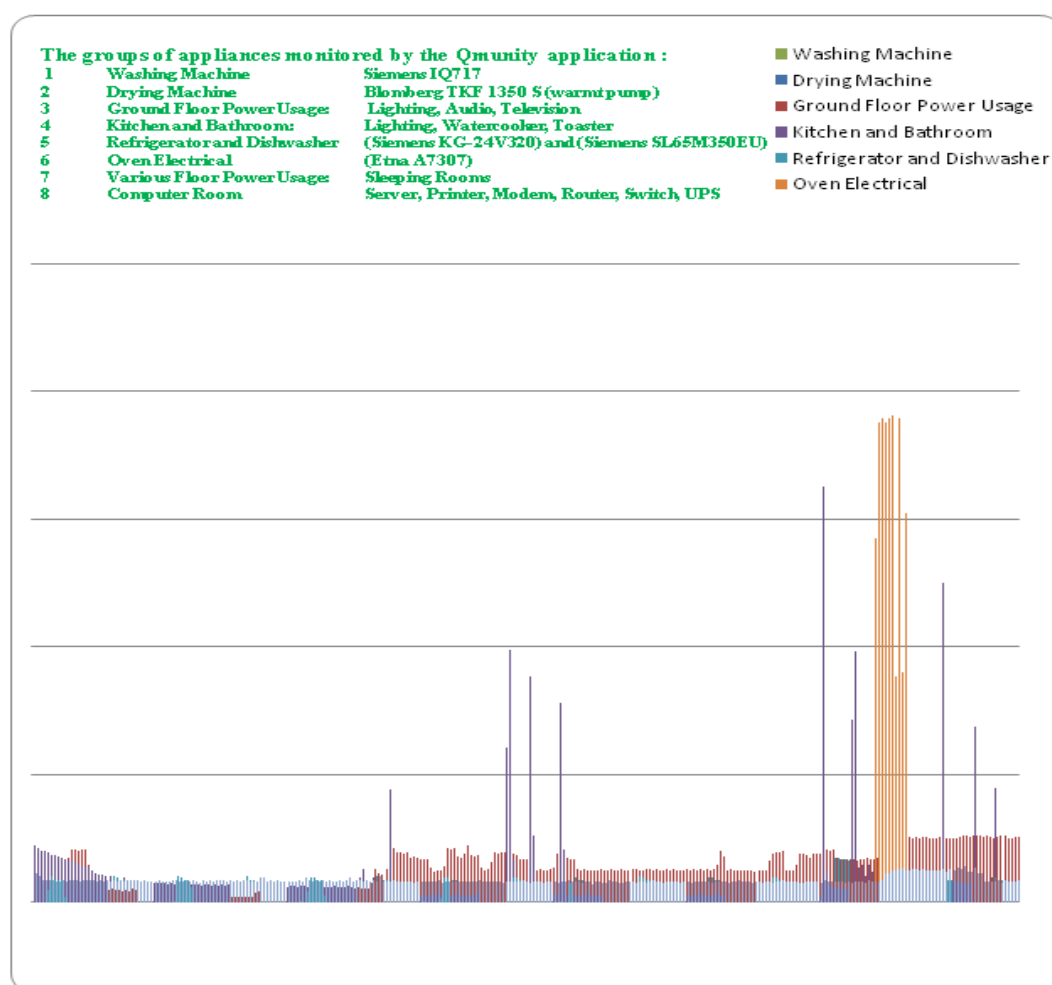|		
1	Washing Machine	Siemens IQ717
2	Drying Machine	Blomberg TKF 1350 S (warmtpump)
3	Ground Floor Power Usage:	Lighting, Audio, Television
4	Kitchen and Bathroom:	Lighting, Watercooker, Toaster
5	Refrigerator and Dishwasher	(Siemens KG-24V320) and (Siemens SL65M350EU)
6	Oven Electrical	(Etna A7307)
7	Various Floor Power Usage:	Sleeping Rooms
8	Computer Room	Server, Printer, Modem, Router, Switch, UPS

- ■ Washing Machine
- ■ Drying Machine
- ■ Ground Floor Power Usage
- ■ Kitchen and Bathroom
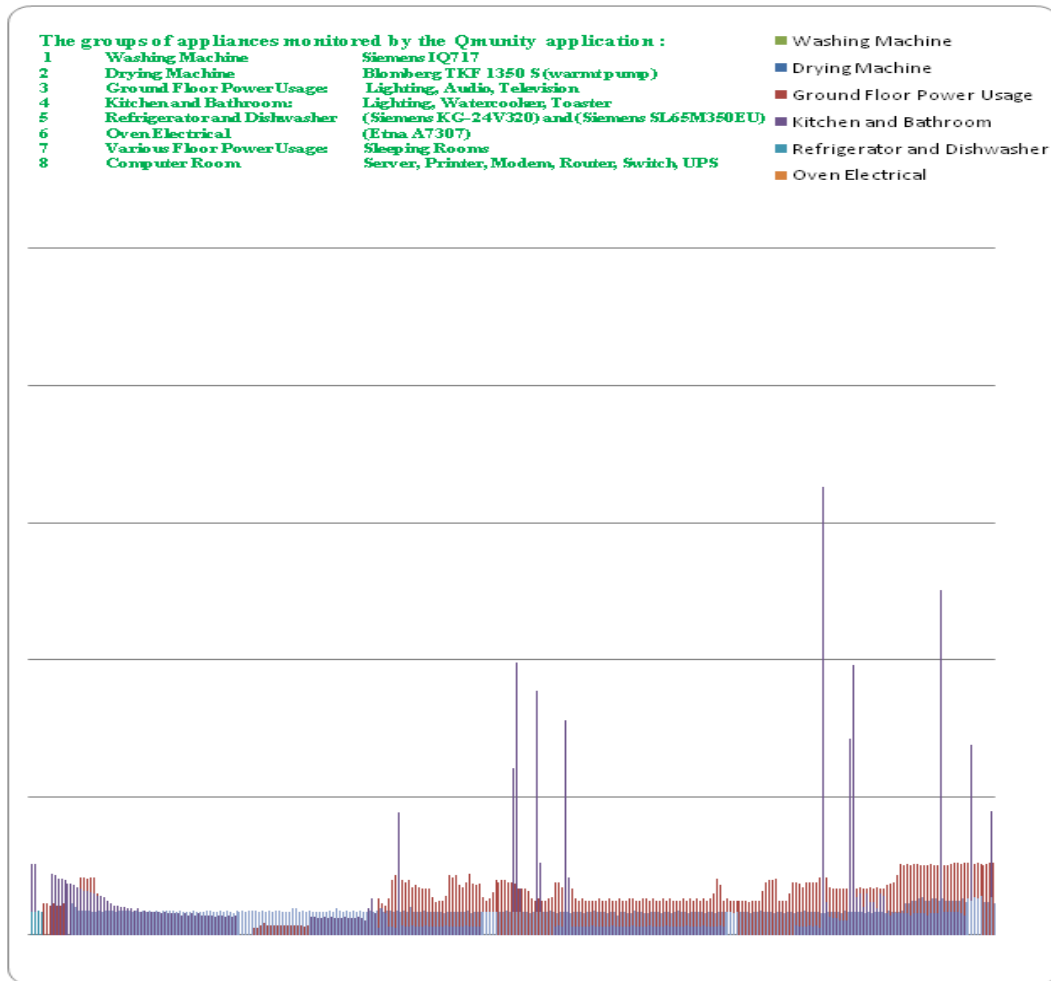- ■ Refrigerator and Dishwasher
- ■ Oven Electrical

Figure 6.7: Appliance Based Household Optimization for a Day in May (hr. vs. Whr. plot2)

6.3.5 Discussions

As can be seen from the figures in figure 6.1, the peak reduction algorithm has brought a reduction of 22.28% in the peak power of the aggregate energy profile (from 18.4 to 14.3 kWh) of the energy community. While the maximizing greenness algorithm has brought 20.65% reduction in the peak demand of the aggregate energy profile (from 18.4 to 14.6 kWh) while bringing the difference between the green energy desire of the energy community and the green energy production in the community to 2000Whrs. One of the combination functions that have been implemented is a combination of maximizing greenness and minimizing peak reduction using upper power bound method. This combination function has been found to reduce the peak power (from 18.4 to 15.9 kWh) of the energy community by 13.59%. It can be analyzed that the consideration of the type of energy resource has brought a significant additional impact in the stability and higher peak reduction of the

aggregate energy profile of the energy community. Moreover, the combination of functions approach provides a different angle for solving the problem, which when implemented in a proper and optimal manner provided the most desired result which is more efficient than implementing the functions individually.

For the day-ahead schedule household optimization implementation in a day in May, it can be inferred from the obtained results that the initial average power and the final average power values have both stayed the same at 402.8W, while the initial peak which was 1979.38W occurring at time index 253[1] has been reduced to a final peak value of 1594.34 which occurred at time index 231[2], giving a substantial peak reduction implementation of 24% change in the value of peak demand. Considering the initial standard deviation which was at a value of 378.58, the peak reduction algorithm has resulted in a final standard deviation value of 199.05, which accounts to 47.42% reduction in standard deviation of daily power demand.

6.3.6   Time and Work Complexity

Time and work complexity calculations have been performed on the four utility maximization formula that have been derived in this paper, and their combination functions to find out if they meet various optimality constraint requirements.

To compute the time and work complexity, with n representing the number of time steps inside the duration of time T, which is lower bounded by both the number of households or the number of appliances in each household, for the maximizing greenness utility maximization formula the time complexity is $O(n^3)$ while the work complexity is $O(n^4)$. For the cost minimization utility maximization formula, time complexity is $O(n^3)$ while the work complexity is $O(n^4)$. For the peak reduction formula, using the upper and lower power bounds explained earlier, the time complexity is O(n) while the work complexity is $O(n2)$. On the other hand, the appliance based pricing scheme formula has been found to have time complexity is O(n) while the work complexity is $O(n^5)$, where n represents the number of time steps inside the duration in time T where the various utility maximization formulas are implemented.

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[1]one time index corresponds to one twelfth of an hour: in a day-ahead schedule, there are a total of 288 time indexes.

[2]one time index corresponds to one twelfth of an hour: in a day-ahead schedule, there are a total of 288 time indexes.

Chapter 7

Conclusions and Future Work

In conclusion, this paper addressed two important problems that challenge smart grid based energy communities emerging today. First, smart grid based energy communities need a control architecture with which they could plan and design their energy related equipments and components in the community. Second, such energy communities need a mechanism with which they can maximize their utility in their usage of energy. By addressing these two problems, the paper has contributed two important components for these smart grid based energy communities, namely a smart grid based control architecture and optimal utility maximization mechanisms.

The first part of this paper identified the role of a control architecture in a smart grids based energy community. It outlined the requirements, the specification and the design of the control architecture for the smart grid based energy community. In the process, a number of aspects that relate to demand side management such as demand control mechanisms and regulation control mechanisms were identified, compared and contrasted. Furthermore, the integration of these mechanisms into a control architecture that can be implemented in a smart grid based energy community was presented. Following that, the architectural design specification steps were taken which consisted of a layered architectural specification and a device based architectural specification. Both of these specifications focused on the control architectural components and showed what kind of control mechanisms could be implemented through control lines that communicate the architectural components.

The second part of this paper focused on utility maximization mechanisms for a smart grid based energy community. First, utility functions were presented based on resource classifications in an energy community. Then, an in-depth discussion of the resource based scheduling and optimization problem followed. The formulated novel utility maximization techniques include a function that maximizes aggregate greenness of the energy community and a function that minimizes aggregate cost reduction in the energy community. The two distinct objectives were formulated aiming to increase the use of renewable energy resources and decrease the unit cost of energy resources respectively. Meanwhile, a separate consideration of the schedule preference of prosumer households was formulated which took into consideration how much the original schedule preference of prosumer households were still preserved while aiming to achieve the objectives of maximizing the use of renewable energy resources and minimize the aggregate energy cost of the energy

community.

Following that, the implementation of the utility maximization functions was presented. The implementation considered the greenness desire of prosumer households, the schedule preference of prosumer households and the money saving desire of prosumer households in the energy community. Based on these preferences, different combinational approaches were presented. In addition, an optimal combination approach that made use of the concept of Lagrangian multipliers mathematical model has been implemented. The optimal decision then identified what is an optimal amount of combination possible between the three utility components defined by the utility formulae using the aggregate income level of prosumer households and the aggregate preference indexes over the individual utility components.

With the use of the control architecture tailored towards a smart grid based energy community and the utility maximization mechanisms, the paper contributes a lot to the field of smart grid in general and smart grid based energy communities in particular. The results achieved enable smart grid based energy communities with the benefits of maximized use of green energy resources and minimized aggregate energy cost in the energy community. In addition, it has been outlined that different appliances provide different utilities to the prosumer therefore novel appliance based control and pricing scheme has been implemented that benefit energy communities as it helps differentiate the utility procured from a type of appliance operation from another.

The results achieved were found to be very interesting which motivate future work in the area of smart grids in general, and in smart grid based energy communities in particular. It has been found that the utility maximization functions such as maximizing the use of green energy resources in an energy community and minimizing aggregate energy cost could be implemented at various levels in a society starting from the level of the energy community. Thus, these mechanisms could serve as better ways to solve the societal problems of rising energy cost by aiming to maximize the use of renewable energy resources and by minimizing energy cost. This would then contribute in an unprecedented manner towards reducing the electricity bill, and maximizing quality and comfort of electricity usage of the society.

Chapter 8

Glossary

In this section, an overview of terms and abbreviations frequently used in this paper is given.

AMI: advanced metering infrastructure, two way communication infrastructure between a smart meter with an IP address and the utility company.

CIS: customer information system.

DR: demand response.

DSM: demand side management.

ED: economic dispatch.

EMC: electromagnetic compatibility.

EMS: energy management system.

HAN: home area network.

HVAC: heating/ventilation and air conditioning.

ISO/RTO: independent system operatorm, regional transmission organization.

LAN: local area network.

Premises Network: personal customer network wiring.

Prosumer: an economically motivated entity that produces, consumes and stores power (thus the term 'pro' - from 'producer' and 'sumer' - from 'consumer').

Retailer: saler of goods and services from individuals or businesses to end users.

WAMS: wide area measurement system.

UC: unit commitment.

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Appendix A

CPLEX Implementation I

The first optimization algorithm implementation is presented below aims at reducing the peak to average ratio for the aggregate energy profile of the energy community.

```
{Minimize (sum_Peak_Diff);

Subject to
{
forall (t in timestep)
init_power_Per_Time_Step[t] ==sum(h in household, a in appliance)
(operating_Power[t][h][a] *is_Appliance_Operating[t][h][a]);

forall (t in timestep)
power_Per_Time_Step[t] ==sum(h in household, a in appliance)
(operating_Power[t][h][a] *sched_Final[t][h][a]);

forall (t in timestep)
sum(t in timestep)init_power_Per_Time_Step[t] ==
sum(t in timestep)power_Per_Time_Step[t];


forall (t in timestep)forall(h in household)forall(a in appliance)
{
sched_Final[t][h][a] ==0||sched_Final[t][h][a] ==1;
sum(t in timestep, h in household, a in appliance)sched_Final[t][h][a]
==sum(t in timestep, h in household, a in appliance)is_Appliance_Operating[t][h][a];
// the new operating decision
}
avg_power == sum ( t in timestep) (init_power_Per_Time_Step[t] /t);

forall (t in timestep)
Peak_Diff[t] == power_Per_Time_Step[t] -avg_power;
```

```
sum_Peak_Diff == sum (t in timestep) (Peak_Diff[t]);
//forall (t in timestep)
//sqr_Peak_Diff[t] == (Peak_Diff[t]*Peak_Diff[t]);
//sum_Sqr_Peak_Diff == sum (t in timestep) (sqr_Peak_Diff[t]);
};
```

The second algorithm implementation presents a relatively less complex mechanism of solving the problem by introducing a new auxiliary variable for the upper bound on the power in the energy community at each time step. It is also to be noted that the second algorithm could have more than one optimal solution.

```
{Minimize (upperBound);

Subject to
{
forall (t in timestep)
init_power_Per_Time_Step[t] ==sum (h in household, a in appliance)
(operating_Power[t][h][a] *is_Appliance_Operating[t][h][a]);

forall (t in timestep)
power_Per_Time_Step[t] ==sum(h in household, a in appliance)
(operating_Power[t][h][a] *sched_Final[t][h][a]);

forall (t in timestep)
sum(t in timestep)init_power_Per_Time_Step[t] ==
sum(t in timestep)power_Per_Time_Step[t];


forall (t in timestep)forall(h in household)forall(a in appliance)
{
sched_Final[t][h][a] ==0||sched_Final[t][h][a] ==1;
sum(t in timestep in household, a in appliance)sched_Final[t][h][a] ==
sum(t in timestep in household, a in appliance)is_Appliance_Operating[t][h][a];
// the new operating decision
}

forall (t in timestep)
power_Per_Time_Step[t] <=upperBound;

};
```

The third algorithm is relatively less complex as it is based mainly on appliance duration of operation flexibility as a way of describing the operational flexibility characteristics of an appliance. For example, it assumes that if an appliance has the same start duration of operation and start time of operation, the appliance could not be shifted from the initial time duration to operate at another time duration.

```
Minimize (sum_sched_power_Per_Time_Step);

Subject to
{
/*
Constraint that the final schedule should either be 1 or 0 but not both
*/
forall(h in household)forall(a in appliance)forall (t in timestep)
{
sched_Final[h][a][t] ==0||sched_Final[h][a][t] ==1;
}

/*
How much power does the initial appliance schedule consume.
This is also the Unit of power that could be scheduled from one timestep to another,
since any appliance should not consume more or less than it should.
*/
forall (t in timestep)forall(h in household)forall(a in appliance)
{
init_power[h][a][t] ==  (operating_Power[h][a][t] *
is_Appliance_Operating[h][a][t]+ standby_Power[h][a][t]
* (1-is_Appliance_Operating[h][a][t] ));
}

/*
How much aggregate power does the initial appliance schedule consume per timestep.
*/
forall (t in timestep)
{
init_power_Per_Time_Step[t] ==sum(h in household, a in appliance) init_power[h][a][t];
}

/*
How much power does the final scheduled appliance schedule consume.
*/
forall(h in household)forall(a in appliance)forall (t in timestep)
{
sched_power[h][a][t] ==  (operating_Power[h][a][t] *sched_Final[h][a][t]+
```

```
standby_Power[h][a][t] * (1-sched_Final[h][a][t] ));
}


/*
Condition that no appliance should consume more or less than initial schedule.
*/
forall(h in household)forall(a in appliance)
{
sum(t in timestep)sched_power[h][a][t] ==sum(t in timestep)init_power[h][a][t];
}


/*
How much aggregate power does the scheduled appliance schedule consume per timestep.
*/
forall (t in timestep)
{
sched_power_Per_Time_Step[t] ==sum(h in household, a in appliance) (sched_power[h][a]
[t]);

}


/*
The number of timesteps that an appliance is operating before scheduling and
after scheduling should be equal.
*/
forall (t in timestep)forall(h in household)forall(a in appliance)
{
sum(t in (durationStart[h][a]..durationEnd[h][a]))
(sched_Final[h][a][t]) ==
sum(tin(durationStart[h][a]..durationEnd[h][a]))
(is_Appliance_Operating[h][a][t]);
}


/*
The number of timesteps an appliance is scheduled inside its duration of operation
should be equal  before and after scheduling.
The aggregate operating power per time step is calculated.
*/
forall(h in household)forall(a in appliance)
{
sum(tin(durationStart[h][a] ..durationEnd[h][a]))
(sched_power[h][a][t]) ==
sum(tin(durationStart[h][a]..durationEnd[h][a]))
(init_power[h][a][t]);
```

```
op_Power[h][a] ==max(t in timestep)(operating_Power[h][a][t]);

}

/*
        The final schedule should only consist of the same elements as
        the initial schedule (either operating power of the given appliance
        or its standby power). Over the whole timestep, the scheduled
        power for a given household appliance should be equal to its
        initial preferred scheduled power.
        */
forall(h in household)forall(a in appliance)
        {
forall (t in timestep)
{
(sched_power[h][a][t] <=op_Power[h][a]) || (sched_power[h][a][t] ==0.1) ;

}
sum(t in timestep)(sched_power[h][a][t]) ==sum(t in timestep)(init_power[h][a][t]);
}


/*
The condition that the sum of scheduled power per time step should be equal to the
initial power per time step.
*/

sum_init_power_Per_Time_Step == sum(t in timestep)init_power_Per_Time_Step[t];

sum_sched_power_Per_Time_Step == sum(t in timestep)sched_power_Per_Time_Step[t];

sum_sched_power_Per_Time_Step == sum_init_power_Per_Time_Step;


/*
The constraint that each scheduled power per time step should stay below some
upper bound which keeps on getting lower to decrease peaks and distribute load.
*/
forall (t in timestep)
{
sched_power_Per_Time_Step[t] <=upper_aggregate_power_bound;
sched_power_Per_Time_Step[t] <=max(t in timestep)init_power_Per_Time_Step[t];
}
};
```

Appendix B

CPLEX Implementation II

Regarding the level of greenness and utilization of green resources, the following algorithm aims at reducing the difference between the level of greenness requested by users and the possible extent to which a user can use green resources based on their availability and utilization.

```
Minimize (diff_aggregate_Greenness);


Subject to
{
/*
Constraint that the final schedule should either be 1 or 0 but not both
*/
forall(h in household)forall(a in appliance)forall (t in timestep)
{
sched_Final[h][a][t] ==0||sched_Final[h][a][t]==1;
}

/*
Condition that no appliance should consume more or less than initial schedule.
*/
forall (t in timestep)
{
sum(t in timestep)init_power_Per_Time_Step[t] ==sum(t in timestep)
sched_power_Per_Time_Step[t];
}

/*
How much power does the initial appliance schedule consume.
*/
forall (t in timestep)
```

```
{
init_power_Per_Time_Step[t] ==sum(h in household, a in appliance)
(operating_Power[h][a][t] *is_Appliance_Operating[h][a][t]  +
standby_Power[h][a][t] * (1-is_Appliance_Operating[h][a][t] ));
}


/*
How much power does the final appliance schedule consume.
*/
forall (t in timestep)
{
sched_power_Per_Time_Step[t] ==sum(h in household, a in appliance)
(operating_Power[h][a][t] *sched_Final[h][a][t]+standby_Power[h][a][t] *
(1-sched_Final[h][a][t] ));
}


/*
How much power does the initial production units schedule produce.
*/
forall (t in timestep)
{
prod_power_Per_Time_Step[t] ==
sum(h in household, p in productionUnit)(generated_Power[h][p][t] );
}


/*
How much green power does the final appliance schedule need to consume.
*/
forall (t in timestep)
{
sched_green_power_Per_Time_Step[t] == sched_power_Per_Time_Step[t] *
sum(h in household, a in appliance) (Greenness[h][a][t]);
}


/*
How much green power does the production units schedule produce.
*/
forall (t in timestep)
{
aggregate_green_Generated_Power[t] ==
prod_power_Per_Time_Step[t]*sum(h in household, p in productionUnit)
greenness_Generated_Power[h][p][t];
}
```

```
/*
Now minimize the difference between the scheduled appliances green power
requirement and the available aggregate green power production
*/
forall (t in timestep)
{
diff_aggregate_Greenness==sum(t in timestep) (sched_green_power_Per_Time_Step[t]-
aggregate_green_Generated_Power[t]);
}
};
```