A Thesis

entitled

Community-Based Optimal Scheduling of Smart Home Appliances Incorporating Occupancy Error

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master Of Science Degree in Electrical Engineering

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May 2013
An Abstract of

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One challenge facing the utility is management of peak demands since electricity cannot be stored in bulk so the utility has to match demand at any point in time. Demand response management has proven to be a significant way of reducing these peaks. Scheduling of electrical appliances and proper design of the electricity tariffs are some of the mechanisms used in demand response management to reduce these peaks. With proper design demand response scheme, the consumer will be motivated to either shift their loads from peaking periods or reduce their consumption. It was the aim of this study to come out with scheduling scheme to reduce peaking in the grid taking into account occupancy error detection factor and combining wind energy and solar to reduce the intermittency nature of these renewables. In this study a mixed integer linear programming based smart appliance scheduling scheme with real-time pricing and algorithm to service as motion sensor were proposed. It can be said that the proposed scheduling scheme and pricing scheme (real-time pricing) provided enough incentives for the customers to encourage them to accept the proposed scheme. Significant savings on electricity bill of the community was realized using the proposed schemes. Savings made on occupancy error detection alone was not significant as compared to the total power
consumed by the community, but it must be realized that this is just a conceptual study and it does not represent reality. It was therefore recommended that the proposed scheduling scheme incorporating occupancy error detection mechanism should be deployed in a real community of residential housing and simulate in realistic conditions.
I dedicate this to my lovely uncle, Mr. K. Baah and my Late Brother, Richard Yaw Ansu-Djan for their fatherly role they played in my life.
Acknowledgements

My first most thanks goes to Jehovah Jireh, my utmost provider, Jehovah-Rohi, my shepherd for His sufficient grace for me. If I look at where you picked me from, all I have to say is: Ebenezer, this is how far you’ve brought me, thank you. Secondly, I wish to thank my advisor, Dr. Lingfeng Wang for his advice and support throughout my studies here at University of Toledo. My sincere gratitude also goes to Dr. Richard Molyet for his friendly welcome anytime I knock on his door, his wonderful support and for accepting to be on my thesis committee. I also want to thank Dr. Weiqing Sun of Engineering Technology Department for not hesitating to be a member of my thesis committee. Not forgetting my wonderful family back home, thank you all for your diverse investment you made in my life. I also want thank all the wonderful people in my life for their support, advises and prayers especially, Nana Osei Kwame, Yaw Asante Kyereme, Elder Aaron and Edwina Kofi-Opata. Last but not the least, I wish to thank Christopher Adika Otiano, you’ve been a wonderful friend to me, thank you soo much.
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List of Abbreviations

AMI............................Advanced Metering Infrastructure
CPP ............................Critical-Peak Pricing
DoE ............................Department of Energy
DR ............................Demand Response
EMS ............................Energy Management System
HVAC ..........................Heating Ventilation and Air Conditioning
RTP ............................Real-Time Pricing
TOU ............................Time Of Use
TV ..............................Television
Chapter 1

Introduction

1.1 Background of the Study

Household electric power consumption, which according to U.S. Department of Energy reported by Wikipedia constitutes 34.4% percent of all electricity produced in the United States in 2011, varies between different hours of the day, between days of the week, and between seasons of the year [46]. For this reason it becomes a big challenge for the utility managing peak demands since electricity cannot be stored in bulk so the utility has to match demand at any point in time. Demand response management has proven to be a significant way of reducing these peaks. Scheduling of electrical appliances and proper design of the electricity tariffs are some of the mechanisms used in demand response management to reduce these peaks. By these, the customer is motivated to participate in load balancing of the grid with the aim of saving money on electric bills.

Demand response programs, according to U.S. Department of Energy, is a way forward to deal with increasing demand for electricity, so it is prudent for the service providers (utilities) to rely on demand response programs to encourage users to shift their loads away from peak times and reduce their usage [1]. Benefits of demand response programs if well-structured will include financial benefits to the participant (the
customer), reliability benefits by reducing peak demand, environmental benefits and market-wide financial benefits. To actualize these benefits in any demand response program, the residential user is expected to play a crucial role by adoption of intelligent mechanisms for managing the energy demand [2].

U.S. Department of Energy defined demand response as:

“tariff or program established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized” [3].

In that same document, DoE went ahead and categorized demand response into two. The first is price-based demand response such as real-time pricing (RTP), critical-peak pricing (CPP) and time-of-use (TOU) tariffs, which give customers time-varying rates that reflect the value and cost of electricity in different time periods. Armed with this information, customers tend to use less electricity at times when electricity prices are high. The second is incentive-based demand response programs as a program that pays participating customers to reduce their loads at times requested by the program sponsor, triggered either by a grid reliability problem or high electricity prices. By analyzing the above definition of demand response, [4] deemed demand response technologies as smart grid technologies. Demand response technologies include products and services that help in the active monitoring and dynamic control of electricity usage [4]. Smart meters are one of the most well-known examples.

Real-time pricing is considered as a very direct and efficient tool to actualize demand response programs and the benefits that come with it. In Real-time pricing
demand response programs, the service provider (utility) announces electricity prices on a rolling basis, thus the price for a given time period is determined and announced before the start of the period – for example, an hour ahead or day ahead. With the development of smart metering technologies, these real-time price signals can be provided to consumers multiple times a day, hour, or even seconds [5].

Advanced metering infrastructure allows measurement in pre-set time intervals, and sends time-based price signals to customers to encourage them to reduce and shift usage [4]. One well-known example of advanced metering infrastructure is the ‘smart meter’. The meters and other technologies allow two-way communication between the customer and the service provider, and enable generation of information used by both the customer and electricity providers [4]. This time-based information is normally sent and presented to customers via in-home display devices, emails, text or voice messages which help customers track and better understand their electricity consumption and control their consumption accordingly [4].

Since the introduction of motion sensors into electricity consumption management, motion sensor controls, in lighting systems for instance, have promised significant energy and dollar savings potential in a variety of commercial lighting applications [6]. Motion sensors automatically control lighting systems to turn lights off when spaces are unoccupied. Occupancy sensors controls give building owners (customers) and operators additional opportunities to improve energy savings without compromising their comfort or their usage behavior [6]. Making occupancy error sensors an integral part of the future smart grid, more particularly incorporating it into demand
response programs will go a long way towards helping achieve the ultimate aims of demand response programs.

1.2 Problem Statement

It is now clear around the globe that the emerging ‘Smart Grid’ technology is the future for the electricity generation and delivery markets and is expected to provide residential users flexibility in controlling their electricity bills. The driving force in realizing this is the smart meter, which delivers ‘real-time’ electricity prices to customers, based on which they manage their consumption [7]. Appliance scheduling is an important demand response tool for reducing peaking in the electric grid and reducing the household electricity bill. In this scheme the consumer sends a request to the controller to use a certain amount of energy at a certain time interval. The grid operator accepts appliance requests to use a certain amount of power for a specified duration within a predefined time period. The controller accepts and schedules the request in such a manner so as to ensure smoothing of the power demand profile and minimization of energy costs. The customer accepts to cooperate with such a program with the aim of reducing their electricity bills. Despite the potential reduction in customer electricity bill, the customer will most likely reject such a program if the customer is asked to manually be part of this scheduling process. Automation of such process, therefore, becomes crucial.

Renewable energy around the world has received high attention in recent times due to its numerous advantages over traditional fossil fuel sources. One major advantage among these advantages is its fuel free and its emission-free or low emissions which makes it 'low cost' and environmental friendly. Unfortunately, there is a major drawback in exploring these numerous advantages of renewable energies; thus intermittency nature
of these renewables. To reduce this intermittency problem, it is desirable to combine different renewable energy sources to complement each other, thus one will be high when the other is low and vice versa. One good example of such complement is wind energy and solar energy. In the daytime when wind speeds are low, the solar will be providing power, and when the sunlight goes down in the night, the wind will be in full gear to boost energy production.

Automatic scheduling of appliances has proven to be a good way of shifting house loads and reducing energy usage, but it is a fact that not all appliances in a household is schedulable; and even of those which are schedulable, the consumer has a choice, in most programs, to override them. So there is a high possibility of appliance being left ‘on’ (unknowingly or knowingly) when its service is not needed. This phenomenon is termed in this research as “occupancy error”. Appliances such as HVAC, TV and indoor-lighting can be equipped with sensors to detect occupancy and report to the controller for the controller to use these signals as part of a scheduling problem. It is therefore believed that if occupancy error sensors are incorporated in scheduling problems in demand response programs, energy will be saved and consumption will be more efficient.

1.3 Research Objectives

It is the aim of this research to come out with a scheduling program which takes into consideration occupancy error factor and combines wind power and solar to reduce intermittency problem of these renewables, reduce peaking in the electric grid and reduce individual household electricity bill in the community. Therefore, the specific objectives of this study are:
• To propose a community-based scheduling program to obtain cost savings for individual households in the community by optimizing energy consumption.

• To analyze the impact of this scheduling program on peak demand and on the power profile of the community as a whole.

• To find out how wind power and solar will complement each other to meet the energy needs of the community.

• To assess the impact of incorporating occupancy sensors’ signal into appliances scheduling program, thus to find the savings on electricity bills of individual household in the community.

1.3 Thesis Organization

This thesis is organized as follows: Chapter one, which deals with the background of the study, the problem statement and the specific objectives of the study. Chapter Two briefly introduce the concept of the smart grid and various smart grid technologies and the benefits and challenges associated with it are outlined. This chapter serves as the literature review for this research. Chapter Three gives a mathematical formulation of the problem to be solved, thus the scheduling problem and other mathematical models need to achieve the set objectives. Chapter Four reports some experimental results from a case study of the proposed system for residential energy demand response management. Finally, Chapter Five presents concluding remarks and recommendations for further work.
Chapter 2

Concept of Smart Grid and Demand Response

2.1 The Smart Grid Overview

The electric power grid is considered the biggest machine and the most complex machine ever built in the history of the world and it has served the world population for several years. In this modern day the world economy basically revolves around this infrastructure. Otto Lynch, vice president of Power Line Systems, was quoted in April 26, 2012 in Washington Post to have said, “Electricity was primarily a luxury when most of the world grid was initially built but today it has become an absolute necessity” [38]. He went ahead to explain how businesses cannot operate today without reliable electricity, thus business comes to a standstill when the electricity is out. Without electricity, there will not be internet service, our credit cards would not run, our personal computers and iPhones become useless [8]. To avoid this adversity, the grid needs immediate and revolutionary action. One prudent action is heavy investment in expansion programs and building new lines. But in the face of environmental concerns raised around the world, couple with the cost effectiveness, this option does not seem the best option for the future energy need. One very attractive and promising alternative research has found is the invention of ‘The Smart Grid’ which has the aim of ensuring a
sustainable and environmental-friendly system and making the existing grid infrastructure as efficient as possible [9], [10]. This is achieved through the use of intelligent, automated supply-side and demand-side devices and legislate business practices that provide incentives for the efficient production, transport, and consumption of electricity across the entire electricity supply chain [9], [10]. In fact, [11] concluded that smart grid is far more beneficial than upgrading the existing conventional power grid to its most powerful state. This was in the sense that the smart grid opens up avenues for the integration of distributed energy storage and demand-side management. The smart grid has been defined in many ways by different researchers and writers but most of the definitions consist of same fundamental concept; effectiveness, efficiency, reliability, and environmental friendliness. One of such comprehensive definitions is the definition by the U.S. Department of Energy. They defined smart grid as “the electricity delivery system (from point of generation to point of consumption) integrated with communications and information technology for enhanced grid operations, customer services, and environmental benefits” [12]. Wikipedia also defined the smart grid as “an electrical grid that uses information and communications technology to gather and act on information, such as information about the behaviors of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity” [13].

Analyzing these definitions bring to bear, the attributes of the smart grid: Reliability, efficiency, sustainability (the environment), economics and customer services oriented.
• The grid must be more reliable. A reliable grid is the one which provides desirable amount of power, at a time it is needed and delivers it to the point it is needed. Reliable grid is also able to stand disturbances to a high degree, thus take corrective actions to restore the grid to its normal state in less time [1], [15], [17].

• The grid must be more secure. A grid is said to be secured if it can withstand both physical, natural or artificial (such as theft-artificial and natural disaster-natural) and cyber-attacks without much impact on power delivery [1], [15], [17].

• The grid must be more economical. As the saying goes; engineering without economics is not engineering; before any innovation can be called beneficial it must be affordable (economical) and smart grid is no exception. It should be economical for the utilities to operate and affordable for the consumers to pay, thus utilities operate under the basic laws of demand and supply [1], [15], [17].

• The grid must be more efficient. The grid must be efficient from both the provider and the consumer point of view. From the provider’s stance of view, losses in the grid must be minimized (thus minimized both transmission and distribution losses) while maintaining highest quality of supply as possible. The grid must give the consumers alternatives to reduce usage and shift usage to avoid peaks in the grid [1], [15], [17].

• The grid must be more environmentally friendly. This is one major reason why smart grid is advocated, environmental friendliness. It should be possible and easy to integrate renewables onto the grid with much impact or disturbances. Allowing more renewable energy integration will help save the deteriorating environment thus; phase out more fossil fuel plants [1], [15], [17].
• The grid must be customer oriented. The grid must be operated on pure business principles where the consumer has enough information on the product (electricity) provided by the provider (utility) which gives the consumer more choice. This information, for example aid the consumer to choose when to use electricity to save him/her cost on electricity bills [1], [15], [17].

2.2 Smart Grid Topology

Figure 2-1 depicts the various component of the smart grid. The most essential feature which makes the grid smart is the two-way communication between the utility and its customers, the major difference between the smart grid and the most powerful conventional power grid. The Smart Grid consists of controls, computers, automation, and new technologies and equipment working together [12].

2-1: Components of the smart grid [12]
Broadly, as can be seen from Figure 2-1, the smart grid consists of:

*Integrated communications:* this enables two-way communication between the customer and the utility and it consists of two-way communication technologies and is built to provide real time information (such as prices, fault warnings and possible attack) to both the customer and service provider (utility) [15].

*Sensing and measurement:* this consists of sensors and smart measuring gauges that takes primary data from the system and transforms the data into information. Based on this information, the health of various components of the grid can be assessed [15]. This information also helps the consumer schedule the electricity usage.

*Advanced Metering Infrastructure (AMI):* AMI enable two-way communication between the meter (thus the customer’s end) and the central system. AMI consists of hardware and software components which measure time-based information and transmit this information to point of need. To the system operator, AMI provides benefits, such as reduction in labor involved in meter reading, increased meter reading accuracy, easier energy theft detection, easier outage management and provides utilities with the ability to detect problems on their systems and operate them more efficiently [1], [14]. To the customer it provides easy detection of meter failures, billing accuracy improvements, faster service restoration, flexible billing cycles and provides consumers with the ability to use electricity more efficiently [1], [14]. AMI is the heart of the smart grid and enables demand response programs.

*Phasor measurement units:* this is made of high speed sensors used to monitor power quality. It main function is to sample voltage and current many times per second at a given location and then compares these samples with a pre-set voltage and current values
This comparison gives the level of quality of power at a particular location and time.

*Advanced components:* These include superconductivity materials, energy storage devices, power electronics, and microelectronic devices to provide greater reliability and power quality in the system.

*Advanced control:* These are control systems embedded in the grid to diagnose and analyze the conditions in the modern grid and are aimed to eliminate, mitigate, and prevent outages and power quality disturbances [15], [16]. This diagnosis and analysis is done at all levels in the grid (thus transmission, distribution and customer levels) [15].

*Interface devices:* These are the devices that come between the customer’s point of power tapping and the power provider’s point of power delivery. There are two kinds of these interfaces, the meter and energy services interfaces. Electricity is usually measured, recorded, and communicated through these interfaces and pricing and demand response signaling also occur through these interfaces [17]. These interfaces are also used for service provision such as remote connection and disconnection of service and maintenance purposes [17].

*The smart home:* Smart Home is a home that utilizes home controller to integrate the home’s automation systems and through the home controller, communications between all the automated systems in the home are made possible [18]. A smart home comes with smart appliances/equipment that can be automated and its operation scheduled.

*Energy management systems (EMSs):* these systems control customers’ consumption, onsite generation (renewables) and storage (batteries and PHEVs) [19].
2.3 Advanced Metering Infrastructure (AMI)

The AMI is a measurement and collection system at the customer point in the smart grid environment and serves as communication networks between the customer and the service provider. It also functions as data reception and management systems and makes the information available to the service provider [20]. The difference between the records of AMI and the conventional metering system records is that the AMI records the time of day that a customer uses electricity, while the conventional metering system only records the total use over the course of the day or the month. In terms of features, the AMI is different from the conventional metering by the fact that the AMI system has time-based measurement and two-way communication [4]. Smart meter (or AMI) enables frequent transfer of information and data between the customer and the service provider. In this manner of data transfer, the customer has timely and easily accessible information on their usage [4]. As noted earlier the AMI is different from the conventional metering by the fact that the AMI system has time-based measurement and two-way communication [4]. In addition to the customer having information on the amount of usage and time of usage, the customer also receives price signals ahead of usage. With the customer having access to this information, he can then make decisions to reduce or shift consumption to save him/her money on the electricity bill while helping reduce peaking in the system. This reduction or shifting of consumption is key in every demand response program. Benefits accrue to the system operator, including reduction in labor involved in meter reading, increased meter reading accuracy, easier energy theft detection, easier outage management and provides utilities with the ability to detect problems on their systems and operate them more efficiently [1], [14]. Adoption of smart
metering infrastructure in homes technically transforms home environments into energy-aware smart spaces thus help save energy [21].

Despite these numerous benefits to both the operator and the customer, there are challenges to the successful implementation of smart metering. Some of the challenges noted by [21] include provision to the home environment visibility of grid conditions, full implementation of dynamic prices lack of knowledge on the implications of demand response functionality of the smart grid in energy-aware smart homes.

2.4 The Smart Home

“Smart Home is the term commonly used to define a residence that uses a home controller to integrate the residence's various home automation systems” [18]. Most of the home controller uses Window-based personal computer programing to control and coordinate various home automated devices. The home controller integrates the various home systems, thereby making communication with one another possible [18]. This enables single button and voice control of the various home systems simultaneously, in preprogrammed scenarios or operating modes [18]

Depending on the type of appliances, devices, and networks that are installed and the level of automation desired, the smart home will have different levels of sophistication. Some of the configurations, combinations and options for energy management in the smart home include a simple email notice for a manual demand response by the consumer, and a smart meter directly communicating with a specific appliance to ask it to turn on and off [22]. As a more sophisticated example, a smart meter communicates with an Energy Management System (EMS) home controller inside the house. The energy management system home controller could connect together in-
home smart appliances in different ways (wire or wireless), to the smart meter and to the
demand response backend system over the Internet using an existing broadband
connection [22]

Advantages of smart home include making life easier and more convenient, provides energy efficiency, energy savings, and also as concluded by [18], smart homes that employ artificial intelligence benefit people who are elderly or disabled most by offering them the opportunity to be independent, rather than staying in an assisted living facility.

2.5 The Smart Appliance

“The term ‘Smart Appliance’ with respect to the smart grid refers to a modernization of the electricity usage system of a home appliance so that it monitors, protects and automatically adjusts its operation to the needs of its owner” [22]. Some of the key features noted by [22] include the following:

- The ability to adjust demand of electrical energy use.
- Provide reminders to the consumer to move usage to a time of the day when electricity prices are lower.
- Automatically “shed” or reduce usage based on the consumer’s previously established guidelines or manual overrides.
- Maintain its integrity of operation and help prevent brown or blackouts.
- The ability of the consumer to override all previously programmed selections or instructions.
• The ability to allow for a “total home energy usage” approach to enable the consumer to develop their own Energy Usage Profile and use the data according to how it best benefits them.

The two main reasons for a consumer accepting to adopt smart appliances are economic gain to the consumer and environmental reasons, but the latter is among only a small percentage of consumers who are environmentally conscious or environmental advocates. Most consumers will readily accept to shift to smart appliances for economic gains rather than environmental gains [23]. To trigger consumers to buy smart appliances, [23] suggested that the utilities should offer the customers attractive tariff and other incentives to influence them in that direction.

All smart appliances are classified as receivers and the means of controlling them are through transmitters such as the ‘remote control or keypad’ [18]. For instance, if an appliance is needed to be turned ‘on’ or ‘off’, the transmitter (the remote or the keypad), will send a signal (message) to the receiver (appliance) in the form of a code which may include an alert to the system that it's issuing a command, identifying a unit number for the device that should receive the command and code that contains the actual command [18].

2.6 Demand Response

Shifting or spreading energy usage in order to smooth or reduce peak demand will go a long way towards improving efficiency in the power network. Influencing consumers in doing this shifting or spreading energy usage, not necessarily reducing energy usage is normally term as demand response. U.S. Department of Energy (DOE) in its February 2006 report to Congress defined demand response as a “tariff or program
established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized” [3]. As the definition stated, demand response is a program to motivate consumers to either reduce or shift their consumption, and the definition identified two main means of motivating consumers: price-based or incentive-based motivations. The Department went ahead to define priced-based and incentive-based motivations. “Price-based demand response gives customers time-varying rates that reflect the value and cost of electricity in different time periods. Armed with this information, customers tend to use less electricity at times when electricity prices are high” [3]. “While incentive-based demand response programs pay participating customers to reduce their loads at times requested by the program sponsor, triggered either by a grid reliability problem or high electricity prices” [3]. In the case of price-based demand response, the utility set different prices at times of the day normally, high prices at normal peak periods in order to entice the consumers to shift their loads to less peak periods where prices are relatively low. Different types of price-based demand programs available in the market include real-time pricing (RTP), critical-peak pricing (CPP) and time-of-use (TOU) tariffs. In this research, emphasis will be placed on real-time pricing tariff. In price-based demand respond program, the utility communicates the prices for different times to the consumer in advance for the consumer to plan his/her energy usage ahead. The consumers can do this planning scheduling manually or automatically but research has shown that consumers are not willing to do this manually; that is where advanced metering infrastructure comes in to do this automatically to reduce inconveniences to the customer.
Research indicates that consumers are ready to accept smart grid programs as long as their interface with the smart grid is simple, less time consuming and minimal interference with how they live their lives (consumption behavior). Consumers may not be willing to accept demand response program if they have to sit around for an hour a day to change how their appliances uses energy or use hours adjusting appliances to function to their specifications; rather they will accept to spend two hours per year or less to set usage to their comfort, price and environmental preferences – enabling collaboration with the Grid to occur automatically on their behalf and at the same time save money [1]. For consumers’ acceptance, the smart grid must be simple to deal with, as simple as “set-it-and-forget-it” technology which enables consumers to easily adjust their own energy use [1].

In [1] some the Incentive-based demand response outlined include direct load control, interruptible/curtailable service, demand bidding/buy back, emergency demand response program, capacity market program, and ancillary service markets.

Apart from price-based and incentive-based demand response programs the Federal Energy Regulatory Commission also classified demand response as dispatchable or non-dispatchable demand response. According to the commission, dispatchable demand response refers to planned changes in consumption that the customer agrees to make in response to direction from someone other than the customer, while non-dispatchable demand response was defined as programs and products, in which the customer decides whether to reduce consumption and when to reduce consumption based on a retail rate design that changes over time [24].
Sometimes people confuse demand response with energy efficiency, but they are two different concepts. In broader terms we can say energy efficiency is just a subset of demand response. Efficiency in general terms is measured as a ratio of output to input, in that sense energy efficiency can be defined as devices or practices that provide the same level (or higher) of output or benefit by using less energy [4]. Energy efficiency usually focuses on reducing overall energy use, not just at certain times, while demand response improves the overall efficiency of the electricity system [4]. In this sense, demand response is different from the traditional energy efficiency in this manner: traditional energy efficiency focused on reducing the overall usage, while demand response looks at more dynamic and controllable usage reduction and shifting, meaning that it can be “dispatched” to meet rising demands in lieu of turning on a power plant [4].

2.7 Benefits of Demand Response

Benefits of demand response can be classified in three categories, benefits to the utility or the service provider, benefits to the customer, and environmental benefit (or broadly, social benefits). Some of the major benefits identified are:
2.1: Demand response benefits [3], [4]

<table>
<thead>
<tr>
<th>Benefits to customer</th>
<th>Benefits to service provider</th>
<th>Social benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>• bill savings and incentive payments earned by customers for adjusting their electricity demand in response to time-varying electricity rates or incentive-based programs</td>
<td>• lower wholesale market prices that result because demand response averts the need to use the most costly-to-run power plants during periods of otherwise high demand, driving production costs and prices down for all wholesale electricity purchasers</td>
<td>• help improve energy resource efficiency thus helping to protect the environment</td>
</tr>
<tr>
<td>• receive reliable services and minimal inconveniences</td>
<td>• operational security and adequacy savings that result because demand response lowers the likelihood and consequences of forced outages that impose financial costs and inconvenience on customers</td>
<td>• reduce demand during peak periods, including via dynamic energy storage, making it an ideal complement to wind and other intermittent resources and allowing it to help support the increased deployment of renewable energy</td>
</tr>
</tbody>
</table>

2.8 Demand Shifting

In most cases demand response programs are not intended to reduce consumption but to shift consumption from one time slot to another to avoid peaking. As noted earlier, shifting or spreading energy usage in order to smooth or reduce peak demand will go a long way towards improving efficiency in the power network. Figure 2-2 below illustrates the load-shifting principle in demand response program.
In Figure 2-2 above, without any demand response program, the demand exceeds the utility’s nominal capacity at the peaking period while in Figure 2-3, the demand profile falls below the nominal capacity after load-shifting principle is applied. Here, loads are shifted from the peaking periods to periods where load profile is below normal.
capacity set by the service provider in order to smooth the load profile. As noted earlier, in most cases, demand response programs do not directly reduce the demand for electricity by households, but they try to influence households to shift their appliances usage away from peak periods to off-peak periods, thus most demand response programs aim at shifting the electricity loads of household appliances away from peak periods to off-peak periods [25].

2.9 Dynamic Pricing

If electricity too is allowed to follow dynamic pricing system as in the normal markets where prices are determined by demand and supply conditions, then as the price changes, the consumer can decide whether or not his/her usage should be adjusted [22]. The smart grid and any demand response program that comes with it will not mean much if the consumer is not motivated or influenced by such program to participate in it. According to the National Energy Technology Laboratory’s study on how to enable active participation by consumers, they recommended innovative rate structures that provide economic benefits to both the consumer and the utility is integral to these programs [26]. There are different types of dynamic pricing currently in the market. Examples of such pricing systems include real-time pricing (RTP), critical-peak pricing (CPP) and time-of-use (TOU) tariffs. If properly developed, the Time of Use (TOU) tariff will create the conditions that will influence consumers to change their appliance’s behavior by using appliances when the rates are lower to save them money on their total electricity bill [27]. Around the globe, most utilities are yet to adapt any form of dynamic pricing, thus still stick to the fixed pricing system where consumers pay a fixed amount per kW of energy use irrespective of demand and supply conditions at time of use. In
short, it would not mean anything to the consumers to shift their away from peak to off-peak period if paying the same rate. Advantages of TOU include reduction of strain on the grid during demand peaks by incentivizing consumers to shift consumption in time, and lower generation costs, since they are disproportionally affected by the peak, rather than the average, electricity demand [27]. [22] also noted that it is not necessary for the consumer to change his consumption behavior largely if there is proper tariffs in place to incentivize consumer’s actions.

In order to implement dynamic pricing effectively, the following requirement suggested by [28] should be considered in the program:

- clear standards, required to describe dynamic pricing information
- the pricing structure must allow manufacturers to build devices or appliances that are capable of managing this benefit
- provide consumers with the proper incentives
- timely delivery of the pricing information from the utility
- the consumer must be able to easily set rules defining their preferences to govern their usage of electricity in the home [28]

2.10 Real-Time Pricing

Since bulk electricity storage is economically unwise, at least for now, the service providers have to match the fluctuating demand at all times. For this reason, a pricing system which is time-based is needed to reflect the fact that the costs of generating and delivering electricity change during the day in order to meet fluctuating demand [4].
Introduction of time-based pricing in the electricity market is part of the new business and policy areas known as demand response and smart grid [4].

Research has shown that flat rate pricing is a simple but inefficient means of pricing electricity. In flat rate pricing system, the utility set fix prices according to their demand forecast and its associated cost. The customer stands to lose if the utility overforecast their demand and the utility also stands to lose if they underforecast. One major disadvantage of flat rate pricing in demand response environments is that customers will not be willing to shift demand to avoid high peaks, since they will be paying the same rate whether shift or not. This calls for more realistic pricing, demand-response friendly, which is based on a demand and supply concept that can influence consumers to shift their loads from peak hours. One pricing system which has shown to meet these requirements is real-time pricing. “In real-time pricing, electricity prices vary continuously throughout the day as a function of environmental conditions, electricity supply and demand conditions” [29]. Real-time prices can be set with day-ahead or hour-ahead schedules but usually prices vary hourly and in some cases less [29].

Real-time pricing is a very important tool in demand response programs in a smart grid environment which can be referred to as a smart energy pricing scheme that is set for a specific time period on an advance basis and which may change according to load demands or price changes in the market [21]. Varying the prices customers paid for electricity consumed during these periods influenced them to vary their energy usage in response to these prices and to manage their energy costs by shifting usage to a lower tariff period [21].
One setback of using real-time pricing scheme is the transmission of sophisticated price signals and cost associated with it. With the introduction of advanced metering infrastructure and automatic schedulers, this problem seems to be a thing of the past and also solves the problem of customers’ capacity to use these signals, and reduce peak consumption or defer consumption from peaks to other periods accordingly [30].

2.11 Household Occupancy Error

Currently, the assumption of conditioning residential spaces is that the spaces are to the maximum capacity rather than detecting the actual occupancy and condition accordingly. There is therefore a need to find an innovative way to solve this problem since heating, cooling and ventilation accounts for 30% energy usage and for 50% of the electricity usage in the United States [31]. It is common to see in many homes that appliance have been left on (unknowingly or knowingly) when its service is not needed. This phenomenon is termed in this research “occupancy error”. Appliances such as HVAC, TV and indoor-lighting can be equipped with sensors to detect occupancy which is currently common in commercial and office buildings but is rare in homes. Many researches in home demand response in smart grid environments do not consider their effect or the possibility of occupancy error detection. Detection of occupancy is achieved by the use of motion sensors attached to the appliance or somewhere in the space where motion is to be measured.

Adoption of motion sensors in homes or offices is an inexpensive and effective scheme to reducing energy costs by turning off appliance like indoor lights, TV and HVACs when rooms or areas are unoccupied, thus when their services are not needed [32]. Occupancy sensors or motion sensors, as popularly known, detect the presence or
absence of people and turn the connected appliance on or off accordingly. According to [32], introduction of motion sensors may reduce lighting energy consumption by 50 percent or more in some circumstances. As a result, it's important to carefully consider a wide variety of issues before installing an occupancy sensor in any specific location. Motion sensor and associated occupancy detection program, according to [32], will be more effective in spaces that are often unoccupied, including storerooms, hallways, restrooms, loading docks, corridors, and stairwells.
Chapter 3

Problem Formulation and Algorithm

3.1 Overview

In this section, community-based smart home power consumption scheduling will be formulated using mix integer linear programming. The daily power consumption tasks of the community are scheduled based on their given operation time frame with the ultimate aim of minimizing electricity bills of individual homes in the community and reducing the power consumption, thereby reducing network peaking of the community as a whole. Considering controlling community made of private homes presents additional advantages over controlling individual private homes, thus the controller or energy management system schedules the entire household tasks of the community with respect to the community-owned local generators such as wind mills and photovoltaic plants [33]. Some of the advantages of community-based scheduling controller over individual private homes are: low communication and computer requirements and cost, more predictable consumption patterns, ability to impose peak demand response and balancing power policies at the community level, etc. [33]. It also comes with disadvantages; one such disadvantage is the privacy concern due to making household tasks transparent to a shared controller [33].
In brief, when an appliance is switched on by an individual user, the appliance sends a request to the community controller to use power. The controller will then determine if there is enough power to turn on that appliance without exceeding the maximum consumption at that instant or else the controller will put in a group of waiting lists. These groups of waiting appliances are determined by priority of the appliance, whether the appliance is preemptive or not, and the price of electricity at that instant. When an appliance finishes its task and stops consuming power, the controller will detect this and determine whether the appliance can be turned on based on the preset conditions.

The assumption in this modeling is that the community has locally generated power (from wind and solar) supplemented by power from the grid. For simplicity, it is further assumed that no power is stored or sold to the utility; therefore, negative values of power billed are replaced with zero(0).

Optimization of energy use of a house with a set of $A$ appliances in each household in the community was considered in the scheduling problem formulation. The community is assumed to have a smart scheduling device to coordinate appliances energy consumption.

3.2 Occupant Error Detection

It is assumed that appliances such as TV, HVAC and indoor light are equipped with sensors to detect whether there is an occupant or not. If the sensors detect that there is no occupant for some specified time, it is assumed that the occupant left the appliance in operation in error so it sends a signal to the controller to take of that particular appliance. The signal, $\alpha$, its binary and defined as $\alpha$ is 1 if the sensors detect any appliance left in error, 0 otherwise.
3.3 Power demand Function

\[ p_a \triangleq [p_{1.1.a}, p_{2.1.a}, \ldots, p_{h.1.a}, \ldots, p_{1.2.a}, p_{2.2.a}, \ldots, p_{h.2.a}, \ldots, p_{1.n.a}, p_{2.n.a}, \ldots, p_{h.n.a}], \]
\[ \forall h \in [1, \ldots, 24], \forall a \in A_n \text{ and } \forall n \in N \ldots \ldots \ldots \ldots (1) \]

where \( p_{h.n.a} \) refers to the energy consumption of appliance \( a \) in the hour \( h \) in the household \( n \).

Therefore, the total daily power \( P_a \) consumed by appliance \( a_n \) is given by:

\[ P_a = \sum_{h=1}^{24} p_{h.n.a} \ldots \ldots \ldots (2) \]

For a single household power, \( P_{tn} \), consumed by all its appliances for a single day is given by:

\[ P_{tn} = \sum_{a=1}^{A} \left[ \left( \sum_{h=1}^{24} p_{h.n.a} \right) - \alpha_{h.n.a} \left( \sum_{h=1}^{24} p_{h.n.a} \right) \right] \ldots \ldots (3) \]

where \( \alpha_{h.n.a} \) is the occupancy signal sent from appliance \( a \) in household \( n \) at hour \( h \).

Therefore, the second term represents energy savings due to the action of the occupancy sensors.

Finally, total power, \( P_{tc} \), consumed by all appliances for a given community in a single day is given by:

\[ P_{tc} = \sum_{n=1}^{N} \sum_{a=1}^{A} \left[ \left( \sum_{h=1}^{24} p_{h.n.a} \right) - \alpha_{h.n.a} \left( \sum_{h=1}^{24} p_{h.n.a} \right) \right] \ldots \ldots \ldots (4) \]

power demand for all appliances in the community has been determined, the power imported from the grid \( P_{grid} \) can be determined by subtracting the locally-generated
(from wind and solar) power, $P_G$ from the total power demand of the community, $P_{Tc}$.

Thus:

$$P_{grid} = \varnothing(P_{Tc} - P_G) \ldots \ldots \ldots (5)$$

Where $\varnothing = \begin{cases} 0, & P_{Tc} - P_G < 0 \\ 1, & P_{Tc} - P_G \geq 0 \end{cases}$.

Since it is assumed that no energy is stored nor sold to the power grid.

**3.4 Energy Cost Function**

If the total Load (power) at each hour of the day is denoted by $L_h$ and $l^h_n$ as load of household $n$ at hour $h$ then it can be said that

$$L_h := \sum_{n \in N} l^h_n \quad \text{where } h = 1,2,3,\ldots,24 \ldots \ldots \ldots (6)$$

Consider total cost of energy at each hour as $C_{t,h}$, for system with real-time pricing, the following expression can said to be true.

$$C_{t,h_1}(L) \neq C_{t,h_2}(L), \quad \forall \ h_1, h_2 \in H, \text{where } h_1 \neq h_2 \ldots \ldots (7)$$

Thus, the cost of the same load can be different at different times of the day.

**3.5 The Objective Function**

The objective function is to minimize the daily electricity cost of the individual household in the community.

Let $n_i$ be household $i$, $\forall \ n \in N$, where $N$ is the set of households in the community. Also let $a_i$ denote appliance $i$, $\forall \ a \in A_n$, where $A_n$ denotes a set of appliance in household $n$. 
For each hour of the day \( h \in H \{1,2,3, \ldots, H\} \) and \( p_{h,n,a} \) denotes the corresponding one-hour energy consumption that is scheduled for appliance \( a \) from household \( n \). The objective is formulated as:

\[
\min_{P_{1} \ldots P_{N}} \sum_{h=1}^{H} C_{t,h} \left( \sum_{n \in N} \sum_{a \in A_{n}} p_{h,n,a} \right) \quad \ldots \quad (8)
\]

The above minimization problem is subjected to the following constraint functions:

3.6 Constraint Functions

The following sections give and explain the various constraints to the above optimization problem.

3.6.1 Energy Constraint

Energy requirement of an appliance ensures that the system fulfill their energy requirement. Thus:

\[
P_{a} = \sum_{h=1}^{24} p_{h,n,a} = E_{a,n} \quad \ldots \quad (9)
\]

Where \( E_{a,n} \) is the energy requirement of appliance \( a \) in household \( n \)

3.6.2 Imported Power Limit

For each hour there is a limit on amount of power the community is allowed to import from the power grid, if this power limit is denoted by \( P_{lim} \) then the objective function is subject to:

\[
P_{grid} = \Phi(P_{\tau} - P_{G}) \leq P_{lim} \quad \ldots \quad (10)
\]
3.6.3 Starting and Finishing Time

For the convenience of the customer, the starting time of each task cannot be earlier than the given earliest time, thus tasks are scheduled to start at or after their earliest starting time. This poses the following constraint:

\[ \sum_{t \in ST_{a,n}} Ts_{a,n,t} = 1, \quad \forall a, n \ldots \ldots \ldots (11) \]

Where:

- \( t \) is the time interval
- \( Ts_{a,n,t} = 1 \) if appliance \( a \) in home \( n \) starts at time \( t \), 0 otherwise
- \( ST_{a,n} \) is the earliest starting time of task \( a \) in home \( n \)

Again, for the convenience of the customer, the finishing time of each task cannot be later than the given latest time, thus tasks are scheduled to finish at or before their deadline. This poses the following constraint:

\[ \sum_{t \in ET_{a,n}} Te_{a,n,t} = 1, \quad \forall a, n \ldots \ldots \ldots (12) \]

Where:

- \( Te_{a,n,t} = 1 \) if appliance \( a \) in home \( n \) ends at time \( t \), 0 otherwise
- \( ET_{a,n} \) is the latest ending time of task \( a \) in home \( n \)

3.6.4 Consumer Priority Constraint

The consumer set priorities for each appliance in terms of positive integers greater than zero. Therefore, if a consumer send more than one task at a time, the controller consider the one with the highest priority first. Where priority 1, \( \varphi_1 \) is higher or greater than priority 2, \( \varphi_2 \), thus : \( \varphi_1 > \varphi_2 \)
3.6.5 Preemptive and Non-Preemptive Constraint

Household appliances can be classified as preemptive or non-preemptive. Non-preemptive appliances are those appliances, once started cannot be stopped till its running time is over while preemptive ones are those that can be paused or stopped during its operation period. For simplicity, in this study it was assumed that all household appliances are non-preemptive; thus once started, it cannot be stopped till the end of its specified operation period.

If \( b \) and \( c \) are defined as decision variables, where \( b_{a,n}^h = 1 \) if and only if for appliance \( a \), in household \( n \) is ‘on’ during time slot \( h \), otherwise zero (0) and \( c_{a,n}^h = 1 \) if and only if appliance \( a \), in household \( n \) has finished by time slot \( h \), otherwise zero (0) then the non-preemptiveness constraint can be model as:

\[
\begin{align*}
b_{a,n}^h \leq 1 - c_{a,n}^h & \quad \forall a, n, h \quad \text{(13)} \\
b_{a,n}^{h-1} - b_{a,n}^h \leq c_{a,n}^h & \quad \forall a, n, \forall h = 2, 3, H \quad \text{(14)} \\
c_{a,n}^{h-1} \leq c_{a,n}^h & \quad \forall a, n, \forall h = 2, 3, H \quad \text{(15)}
\end{align*}
\]

In the above constraint equation, it suggests that if \( b_{a,n}^h = 1 \) then \( c_{a,n}^h = 0 \) and vice versa. \( c_{a,n}^h = 1 \) when \( b_{a,n}^h \) switch from 1 to 0. Equation 14 imposes that if the process is finished at time slot \( h - 1 \), then it is also finished at time slot \( h \).

3.7 Tariff Setting

As quoted earlier, an important characteristic of the smart grid is real-time pricing, which is a smart energy pricing scheme that is set for a specific time period on an advance basis and which may change according to load demands or price changes in the market. Prices paid for electricity by consumers are very important in demand response programs. This influences the consumers to vary their energy usage in response to these
prices and manage their energy costs by shifting usage to a lower tariff period [21]. To produce real-time tariffs, correlated to electricity demand patterns, equation proposed by [21] was adopted in this study.

\[
Tariff = \alpha \cdot Basic Tariff \cdot \left( \frac{Instant Demand}{Average Demand} \right) 
\]

where \( \alpha \) is a coefficient used to weight the prices according to differences in demands. Basic tariff is base price, set by the utility per kWh energy used based on average demand of that particular catchment. Using this equation with \( \alpha = 1 \), real-time tariffs that give incentives to consumers to utilize their electrical appliances not in peak hours were produced. With this tariff setting, tariffs fluctuate around the basic tariff; thus customers consuming energy below the average at the time of consumption get an incentive in the form of tariff reduction whilst those who go beyond the average pay penalty in the form of higher tariff.

### 3.8 Locally Generated Energy

In the future smart grid environment, it should be easy to integrate renewable energies and incorporate the concept of distributed energy. As noted earlier, one major challenge of integrating renewables is their intermittency nature. To reduce this intermittency problem, wind and solar were combined to complement each other. Wind and solar energy are very good complement since in the day-time when wind speeds are low, the solar radiations are high and when the sunlight goes down in the night, the wind speeds will be high to boost energy production.

Wind power is a measure of the energy available in the wind. It is a function of the cube (third power) of the wind speed. With available wind data of the community and wind turbine specifications, wind power generation can mathematically be modeled as:
\[ P_{\text{wind}} = \beta \cdot \left[ \frac{1}{2} \rho A v^3 C_p \right] \]  

\[ \beta = \begin{cases} 1 & v_{\text{min}} \leq \beta \leq v_{\text{max}} \\ 0 & \text{otherwise} \end{cases} \]  

Where:

- \( P_{\text{wind}} \) is the wind power generated (W)
- \( \rho \) is air density (kg/m\(^3\))
- \( v \) is wind velocity (m/s)
- \( A \) is the turbine swept area (m\(^2\))
- \( C_p \) is power coefficient (thus wind turbines cannot operate at its maximum capacity. The \( C_p \) value is unique to each turbine type and is a function of wind speed that the turbine is operating in)
- \( \beta \) is a binary and decision variable depending on minimum and maximum speeds of the wind turbine, it can generate power. These limits are set by the manufacturer.
- \( v_{\text{min}} \) is minimum wind speed below which the wind turbine cannot generate power (m/s)
- \( v_{\text{max}} \) is maximum wind speed above which the wind turbine ceases to generate power (m/s)

Likewise, solar energy generated can mathematically modeled as:

\[ P_{\text{solar}} = \text{prevailing solar radiation} \left( \frac{W}{m^2} \right) \times \text{Panel Area} (m^2) \]  

3.9 Scheduling Algorithm

In this section the dynamic programming algorithm that was used to solve the scheduling problem is presented. The goal of the algorithm is to coordinate devices so as to limit energy consumption, reduce energy costs and reduce energy consumption peaks of the community.
In brief, when the user turns on an appliance, a signal will be sent to the controller or the scheduler indicating that the appliance wants to consume power. The controller then calculates if there is enough power to turn on that appliance without exceeding the maximum power limit or capacity. If there is enough power, the user request will be granted, otherwise the controller proceeds to examine the priorities of all the appliances that have requested to use power within that time slot. The controller first grants the requests of all the non-schedulable appliances regardless of the power limit, and then grants requests of the schedulable appliances base on available power. If the power available for that time slot is used up, the scheduler looks two hour prior to that time slot under consideration and two hours ahead for lowest possible prices and schedules the remaining loads to those hours optimally. This algorithm is summarized in Figure 3-1 below.
Request to consume power

Compare requested power with available power:
Enough power?

Yes

Grant all the request

No

Signal from motion sensor

Turn-on all the non-schedulable appliances

Yes

Limit reached?

Yes

Add appliances base on priority till limit reach

No

Still loads to be scheduled?

Yes

Look h-1, h-2, h+1, h+2 and h for prices time slot. Add appliances base on their priorities to lowest price first till all the above slot reached their limits

No

Still loads to be scheduled?

Add the remaining loads to any hour within $h - 2 \leq h \leq h + 2$ with lowest price (override power limits)
Chapter 4

Experimental Results

4.1 Case Description and Assumptions

In this section simulation results and analysis of results obtained by applying the proposed model is presented. For simplicity, the following considerations and assumptions were made:

- A community of ten (10) residential houses was considered
- The power need of the community is met by power from locally installed wind generator, locally installed solar panels and the grid
- Time horizon of one day was assumed, starting from hour 01:00 until hour 24:00.
- For simplicity it was assumed that no power will be sold to the utility and that no power is stored
- All appliances are non-preemptive

In evaluating the performance of the proposed model, the daily energy use of household appliances using power rating data obtained from U.S. Department of Energy [34], [35] were simulated. In this data, power rating for various appliances was given in the form range (minimum and maximum) so the averages of these ranges were computed.
and used in this research. The household appliances were categorized into two: schedulable and non-schedulable appliances. Schedulable appliances are those which its usage can be deferred to later time during the period under consideration and non-schedulable appliances are ones which its time of usage is determined by the customer and it is not negotiable. In all, 19 appliances were considered in this study. The Table 4.1 below shows the list of appliances considered and their power ratings.

4.1: List of appliances and their power ratings

<table>
<thead>
<tr>
<th>No.</th>
<th>Appliance</th>
<th>Power rating(kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Washing machine</td>
<td>0.43</td>
</tr>
<tr>
<td>2</td>
<td>Dryer (cloth)</td>
<td>3.4</td>
</tr>
<tr>
<td>3</td>
<td>Dishwasher</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>Electric car</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Indoor lighting</td>
<td>0.36</td>
</tr>
<tr>
<td>6</td>
<td>Laptop</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>Desktop</td>
<td>0.27</td>
</tr>
<tr>
<td>8</td>
<td>Refrigerator</td>
<td>0.725</td>
</tr>
<tr>
<td>9</td>
<td>Cooker (hot plate)</td>
<td>1.2</td>
</tr>
<tr>
<td>10</td>
<td>Cooker oven</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>Microwave oven</td>
<td>0.93</td>
</tr>
<tr>
<td>12</td>
<td>Vacuum cleaner</td>
<td>1.22</td>
</tr>
<tr>
<td>13</td>
<td>HVAC</td>
<td>2.8</td>
</tr>
<tr>
<td>14</td>
<td>Clothes iron</td>
<td>1.4</td>
</tr>
<tr>
<td>15</td>
<td>TV</td>
<td>0.22</td>
</tr>
<tr>
<td>16</td>
<td>Water heater</td>
<td>5</td>
</tr>
<tr>
<td>17</td>
<td>Hand dryer</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>Coffee maker</td>
<td>0.75</td>
</tr>
<tr>
<td>19</td>
<td>Portable stand fan</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Each household in the community was chosen to have between 14 and 19 appliances. The following sample table below (Table 4.2), summarized the power ratings, earliest and latest time, task duration, and priority values of various appliances in household 1.
4.2: Appliances Characteristics of Household 1

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Power rating(kW)</th>
<th>Earliest starting time(hr)</th>
<th>Latest ending time(hr)</th>
<th>Task duration(hr)</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Set I – Schedulable Appliances</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Washing machine</td>
<td>0.43</td>
<td>21</td>
<td>2</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>2 Dryer (cloth)</td>
<td>3.40</td>
<td>24</td>
<td>5</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>3 Dishwasher</td>
<td>1.80</td>
<td>21</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4 Electric car</td>
<td>5.00</td>
<td>18</td>
<td>8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Set II – Non-Schedulable Appliances</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Indoor lighting</td>
<td>0.36</td>
<td>18</td>
<td>24</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>2 Laptop</td>
<td>0.27</td>
<td>6</td>
<td>22</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3 Desktop</td>
<td>0.05</td>
<td>6</td>
<td>22</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4 Refrigerator</td>
<td>0.725</td>
<td>0</td>
<td>24</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>5 Cooker (hot plate)</td>
<td>1.2</td>
<td>8</td>
<td>19</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6 Cooker oven</td>
<td>3.00</td>
<td>8</td>
<td>19</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>7 Microwave oven</td>
<td>0.93</td>
<td>7</td>
<td>21</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>8 Vacuum cleaner</td>
<td>1.22</td>
<td>9</td>
<td>17</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>9 HVAC</td>
<td>2.8</td>
<td>0</td>
<td>24</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>10 Clothes iron</td>
<td>1.40</td>
<td>6</td>
<td>9</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>11 TV</td>
<td>0.22</td>
<td>6</td>
<td>22</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>12 Water heater</td>
<td>5.00</td>
<td>6</td>
<td>22</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

4.2 Locally Generated Power – Wind and Solar

Renewable energy resources such as wind and solar are intermittent thus fluctuate hour by hour, day by day and season by season; therefore their power outputs are inconsistent and somewhat unpredictable, while on the other end of the transmission line, consumers’ power demand are also variable but somewhat predictable throughout the day [36]. Wind and solar resources will always be intermittent when they are considered separately, but combining the two reduces the intermittency of the output power. To this reason, this study combined wind and solar resources to meet the energy demand of the community.
Wind speed data and solar radiation data were obtained from Bowbells Switch Station of North Dakota Agricultural weather Network Center (NDAWN). Wind speeds and solar radiations were by picking a typical winter day at random using Matlab. All days between December, 1, 2012 and February, 15, 2013, inclusive were considered and January, 9, 2013 was picked. Wind turbine with blade size of 11 meters and power coefficient of 0.4, and air density of 1.23kg/m\(^3\) were assumed for the community. Therefore using Equation (17), wind power generated during the day using the wind hourly speeds obtained from NDAWN, were calculated. In calculating the wind power, it was further assumed that all the wind speeds obtained were within lower and upper speed limits of the wind turbine within which it can produce power (thus cutoff speeds). Similarly, Equation (18) was used to calculate solar power generated during the day using the hourly solar radiation data obtained from NDAWN, assuming 100m\(^2\) of solar panels installed in the community. The Figure 4-1 below shows wind power profile, solar power profile and profile of combined resources (wind and solar).

![Image of power profile](image-url)

4-1: Locally generated power profile
From Figure 4-1 above, it can be seen that between the hours of 5:00 and 14:00 the wind speed fell but the solar came in at hour 9:00 to supplement the power generation. The solar power went to 0kW at hour 18:00 but from that hour onwards, the wind power picked up. It is obvious from Figure 4.1 that combining different renewables will reduce the problem of intermittency.

4.3 Power Consumption Limits

The locally generated power from wind and solar was used as a primary source of power for the community. At any point in time during the day, if the power generated from the local resources is not able to meet the community’s power demand, the system imports power from the grid. But as stated earlier, for simplicity of this study, if at any point in time the locally generated power is greater than what the community needs, the excess power will be discarded. In this study, to reduce peaking in the grid, limits were imposed on how much power can be imported from the grid. These limits were designed as follows: The day under consideration was divided into four slots of ‘time of use’. The average for each slot was obtained and set as a consumption limit for all the hours within that time slot. The idea here is to flatten demand within each time slot or time of use. These limits became the maximum power that can be consumed. This means that the system cannot import power more than the difference between the power locally generated and the set limits. Table 4.3 gives the various time slots and the set limits.

4.3: Time slots and set limits

<table>
<thead>
<tr>
<th>Time Slot (hours)</th>
<th>Description</th>
<th>Power Limit (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01:00 – 05:00</td>
<td>Early morning</td>
<td>15.43</td>
</tr>
<tr>
<td>06:00 – 11:00</td>
<td>Morning</td>
<td>28.41</td>
</tr>
<tr>
<td>11:00 – 17:00</td>
<td>Afternoon</td>
<td>34.57</td>
</tr>
<tr>
<td>18:00 – 24:00</td>
<td>Night</td>
<td>50.74</td>
</tr>
</tbody>
</table>
4.4 Real-Time Pricing

Under real-time pricing, a network operator sets the price level for a period according to a predefined scheme which depends on the state of demand and costs, and announces this price shortly before the period begins [30]. Real-time pricing provides benefits to both the utility and the customers, because it is a strategic tool which provides customers with the same type of cost and load management signals that are provided to the electric supply system. It is a critical element in economically efficient least-cost strategies because it provides the customer with symmetric signals that encourage both reduction in consumption (high prices) and also increases in consumption (low prices) [37].

In this study, apart from making sure that the load does not exceed the supply limits, the scheduling scheme shift loads to periods where the prices are relatively low to ensure cost effectiveness. The real-time pricing in this study was designed based on the average power consumption of the community and hourly power consumption. Equation (16) was used to design these prices. Base tariff of $0.10(10 cent) obtained by averaging electricity prices of all States in the United States as reported on the official Nebraska government website. As stated earlier α was assumed to be 1 for simplicity. Figure 4-2 below shows price signals for the day under consideration using the method just described above.
4-2: Price signal for the day

Prices range from US$0.032 and US$0.221 with the minimum price at hour 03:00 and the highest price at hour 20:00.

4.5 Power Consumption without Load Scheduling

This experiment aims at demonstrating how the superposition of regular load causes high peak load. This is the profile of the community’s power consumption without applying the proposed scheduling scheme and is used as a base line to compare the effects of the smart network with.
4-3: Unscheduled load profile for the community

As can be seen in Figure 4-3, without scheduling appliances usage in the community, in some instance during the day, the power consumption of the community far exceeds the set limits. This brings peaking in the system. Examples of such peaking in this situation are between the hours of 06:00 and 08:00 and also between the hours of 17:00 and 21:00. To avoid these peakings, the proposed scheduling scheme was used to schedule the appliances usage in the community and results are presented in the preceding sections.

4.6 Power Consumption with Load Scheduling

The objective here is not to reduce the demand for electricity by households, but to try to shift households demand away from peak periods to off-peak periods. The effect of demand shifting, as shown in Figure 4-4 below, was obtained by scheduling household appliances using the proposed scheduling scheme.
4-4: Scheduled load profile for the community

As shown in Figure 4-4 above, the consumption result after scheduling household appliances is smoother, suggesting the pricing scheme adopted does succeed in shaping demand, and the profile begins to resemble the set limits (capacity). It can be seen that at hours 01:00, 07:00 and 18:00 the power consumed by the community exceeded the set consumption limits. This is because at those particular hours more unschedulable appliances were turned on in the community. In total, power consumption exceeded the set limits by 6.97kW in the day under consideration. If this happen in scheme where usage above the set limits is not allowed, 6.97kW of energy will be shed. In other schemes, violating the set limits will be allowed but the customer will pay a penalty for that. In this study, only the power limit constraint was allowed to be violated, so that no power would be shed and for simplicity, no penalty was set for exceeding these limits.

4.7 Energy Cost and Savings

The major reason for a customer/consumer to accept any demand response program is the potential savings the customer could make on his/her electricity bill.
Research has found that dynamic pricing is very essential in any demand response program, and that is the driving force in influencing consumers’ consumption behavior. In this study real-time pricing was adopted and special pricing scheme was designed as has already been discussed. It is clear in Figure 4-4 in the previous section how this pricing scheme helped reduce peaking in the grid with the assumption that all the customers in the community accept to go by the prepared scheme. In this section, potential savings to the customers for accepting such scheme is presented.

4.4: Hourly cost of energy for the community

<table>
<thead>
<tr>
<th>Hour</th>
<th>Unscheduled cost ($)</th>
<th>Scheduled cost ($)</th>
<th>Savings ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01:00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>02:00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>03:00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>04:00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>05:00</td>
<td>0.37</td>
<td>0.10</td>
<td>0.27</td>
</tr>
<tr>
<td>06:00</td>
<td>2.47</td>
<td>2.26</td>
<td>0.21</td>
</tr>
<tr>
<td>07:00</td>
<td>2.88</td>
<td>2.88</td>
<td>0.00</td>
</tr>
<tr>
<td>08:00</td>
<td>3.85</td>
<td>2.50</td>
<td>1.34</td>
</tr>
<tr>
<td>09:00</td>
<td>1.18</td>
<td>1.61</td>
<td>(0.43)</td>
</tr>
<tr>
<td>10:00</td>
<td>0.68</td>
<td>1.11</td>
<td>(0.43)</td>
</tr>
<tr>
<td>11:00</td>
<td>0.07</td>
<td>0.07</td>
<td>0.00</td>
</tr>
<tr>
<td>12:00</td>
<td>0.18</td>
<td>0.18</td>
<td>0.00</td>
</tr>
<tr>
<td>13:00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>14:00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>15:00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>16:00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>17:00</td>
<td>5.61</td>
<td>2.54</td>
<td>3.08</td>
</tr>
<tr>
<td>18:00</td>
<td>2.33</td>
<td>2.33</td>
<td>0.00</td>
</tr>
<tr>
<td>19:00</td>
<td>7.45</td>
<td>4.75</td>
<td>2.70</td>
</tr>
<tr>
<td>20:00</td>
<td>10.66</td>
<td>5.36</td>
<td>5.31</td>
</tr>
<tr>
<td>21:00</td>
<td>3.10</td>
<td>3.10</td>
<td>0.00</td>
</tr>
<tr>
<td>22:00</td>
<td>3.01</td>
<td>3.21</td>
<td>(0.20)</td>
</tr>
<tr>
<td>23:00</td>
<td>2.10</td>
<td>3.60</td>
<td>(1.50)</td>
</tr>
<tr>
<td>24:00</td>
<td>1.79</td>
<td>1.79</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Total 47.72 37.38 10.35
Table 4.4 above presents hourly cost of energy (only energy imported from the grid) under unscheduled load scheme and under scheduled load scheme, and potential saving by adopting scheduled scheme. At some hours under the scheduled scheme, the community paid more in dollar terms for energy than they did under unscheduled scheme but in total, over the day under consideration, the community paid less in dollar terms for energy under the scheduled scheme than they did under unscheduled scheme. Under the savings column in Table 4.4 above, hours with negative savings value indicates at those hours the community paid more in dollar terms for energy under scheduled scheme than they did under unscheduled scheme. In general, the community saved 21.67% on electricity for that particular day under consideration for adopting demand response program presented in this study.

4.8 Power Consumption with Load Scheduling and Occupancy Error Detection

One of the objectives of this study was to determine the effect of occupancy error detection sensors in scheduling programs on energy consumption. In smart homes, some appliances are non-schedulable and so the user determines when to switch it on and when to switch it off. Usage of such appliances are non-negotiable, for example, the TV, indoor lighting, HVAC, etc. In this study, TV, indoor lighting and HVAC were considered as appliances users might leave ‘on’ in error. So it was assumed in this study that these appliances are equipped with motion sensors to send a signal to the controller if there is no motion in the defined space for some pre-set time and the actions of these sensors can be override by the user. For instance, if the user wants to sleep and wants the HVAC on, the user overrides the action of the sensor for the HVAC alone.
Since this study is hypothetical, the algorithm presented in figure 4.5 was written to represent the working of these sensors. The algorithm was purely based on probability (random numbers). It was assumed that there is a 5% chance of someone in a particular household leaving one of these appliances ‘on’ in an error. For simplicity, it was further assumed that one and only one of such appliances can be left ‘on’ at a time in each household. For every time slot just before the scheduler schedules, this algorithm runs and sends the necessary signal to the scheduler. In general, at the beginning of each time slot, for each household, a random number $U[0,1]$, is picked, if the random number is less than 0.05, that means an appliance is left on in error and a second random number is picked to determine the particular appliance that is left ‘on’ in error. The algorithm is presented in the Figure 4-5 below.
From the algorithm presented in Figure 4-5 above, if \( \alpha = 0 \) is sent to the scheduler, the scheduler will go ahead to schedule the appliances as programmed. But if
it sends $\alpha = 1$ for any appliance, the power requirement of that particular appliance would be deleted before the scheduler schedules the appliances.

The results of power consumption with load scheduling and occupancy error detection integrated is presented in the Figure 4-6 below.

From Figure 4-6 above it can be seen that at hours 02:00, 07:00, 08:00, 14:00, 16:00, 20:00 and 21:00, the program detected occupancy error and therefore deleted the amount of power accordingly. Total power saved during the day under consideration by introducing this program is 6.53kW representing 0.84% of the total power used by the community during the day. This figure of power saved by this action might not be significant as compared to the total power demand of the community but it must be realized that this is just a conceptual study and that it does not represent reality. It might be significant if implemented in real time. In [31], where real-time data was used, it was 8.1% savings of energy on ventilation alone was reported.
Chapter 5

Conclusions and Recommendations

It was the aim of this study to come out with a scheduling scheme to reduce peaking in the grid, taking into account occupancy error detection factor and combining wind energy and solar to reduce the intermittency nature of these renewables. Therefore, a scheduling scheme was proposed, taking into account ‘installed’ motion sensors for occupancy error detection for a community of ten residential households that would help consumers in saving money spent on electricity bill and that would allow service provided to reduce peaking in the network.

It can be said that the proposed pricing scheme (real-time pricing) provided enough incentives for the customers to encourage them to accept the proposed scheme. It was realized that wind and solar are good a complement to solve the problem intermittency in renewables. Without scheduling of appliances usage, peaking was seen in the system especially during the morning (between the hours of 06:00 and 08:00) and in the evening (between the hours of 17:00 and 21:00). After applying the proposed scheduling scheme, these peaks significantly reduced, though it could not eliminate them entirely. It was realized that without the scheduling, the demand profile exceeded the set limits by 90.2kW, but after applying the proposed scheduling scheme, the demand profile
only exceeded the set limits by 6.9kW. The community saved 21.67% on electricity bill for that particular day under consideration by adopting demand response program presented in this study. A simple algorithm was written to represent the chances of an occupant of a household to leave either TV or HVAC or indoor lighting on in error. By this algorithm combining with the scheduling scheme presented, the community saved 0.84% on power usage for that day.

Based on the results presented in this study, it is therefore recommended that the proposed scheduling scheme incorporating occupancy error detection mechanism should be deployed in a real community of residential housing and simulate in realistic conditions. Further testing of this scheme is recommended using a larger number of houses and a large number of appliances, and considering more days, preferably a whole year, to determine the impact and savings during different seasons.
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