A FUZZY LOGIC ENABLED DEMAND SIDE MANAGEMENT SYSTEM FOR RESIDENTIAL ELECTRICAL ENERGY CONTROL

by

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Declaration

I declare that the dissertation titled, **“A fuzzy logic enabled demand side management system for residential electrical energy control”** is my own work and that all the sources used and quoted have been indicated and acknowledged by means of complete references.

Signature

(Mrs L.B. Rabaza)

01 December 2020

Date

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I am deeply grateful to my dearest husband, my pillar, Msebenzi, for his unconditional love, endless support, understanding and encouragement, our lovely son Live who always cheers us during difficult and hopeless times in our life.

Dedication

I dedicate this dissertation to:

My great-grandmother Martha, who taught me the self-discipline and determination.

My late parents Zuko and Nobantu Mabutyana who always wanted the change in our family.

My pillar, my dearest husband Msebenzi and our lovely son Live.

Entire Mabutyana and Rabaza families.

Abstract

Globally, energy management has become a challenge and a concern due to rapid increase of demand and energy security. Among the five sectors, residential sector, in South Africa, is the second in electricity consumption and is responsible of about 17% of the total generated capacity with high contribution during peak demand. In order to mitigate this increase, policy and legislations have been implemented. Apart from the policy documents introduced, utilities have further introduced the demand side management (DSM) initiatives such as demand response (incentive based and price based) to encourage the load reduction during peak hours. Manually managing peak hour consumption is a tedious process. Also, it is difficult for the users to manually respond to the offered incentives and price based tariffs.

It is within the settings of the problem that this dissertation seeks to enhance the residential electricity consumption by scheduling the household appliances in line with the response to the time of use (ToU) tariffs. Further, the dissertation seeks to develop a system that will manage the amount of electricity as desired by the consumer for the given a timeframe by integrating the optimisation technique to make the intelligent decisions that link ToU with residential electrical energy consumption. This results in "A fuzzy logic enabled demand side management system for residential electrical energy control". The system simulation was developed in LabVIEW VI 2019. The simulation assisted in implementation and verification of different scenarios aimed in this study such as time of use tariffs, load consumption and remaining daily electricity limit. Furthermore, the model was developed to verify the fuzzy ruling in real time control for 24 hours with the calculated daily electricity limit. The collected results showed that the model was able to control the residential load consumption and enhance the consumption by scheduling the house hold appliances considering the time of use tariff and available amount of electricity.

Keywords: Fuzzy logic, demand side management, demand response, time of use, residential electrical energy control.

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List of Abbreviations

AFLL:	Adaptive Fuzzy Logic Learning
AMI:	Advanced Metering Infrastructure
ANFIS:	Adaptive Neuro Fuzzy Inference System
ANN:	Artificial Neural Network
CBA:	Cost Benefit Analyser
CG:	Cost Generator
CO_2:	Carbon
CPI:	Consumer Price Index
CPP:	Critical Peak Pricing
CS:	Cuckoo Search
CSP:	Concentrated Solar Power
CTL:	Coal to Liquid
DoE:	Department of Energy
DR:	Demand Response
DSM:	Demand Side Management
DSRM:	Design Science Research Methodology
EE:	Energy Efficiency
EM:	Energy Management
EMPC:	Economic Model Predictive Controller
ESS:	Energy Storage System
FBE:	Free Basic Electricity
FIS:	Fuzzy Inference System
FLDC:	Fuzzy Logic Droop Controller
FLID:	Fuzzy Logic Island Detector
FLS:	Fuzzy Logic System
GA:	Genetic Algorithm
GDP:	Gross Domestic Production
GTL:	Gas to Liquid
HEMS:	Home Energy Management System
HGA:	Hierarchical Genetic Algorithm
HMM:	Hidden Markov Model
HVAC:	Heating, Ventilation and Air Conditioning

IEP:	Integrated Energy Plan
IGCC:	Integrated Gas Combined Cycle
INEP:	Integrated National Electrification Program
IBT:	Inclined Block Tariff
IoT:	Internet of Things
ISEP:	Integrated Strategic Electricity Planning
KW:	Kilowatt
LNG:	Liquefied Natural Gas
MEPS:	Minimum Energy Performance Standards
MF:	Membership Functions
MW:	Mega Watt
NEES:	National Energy Efficiency Strategy
NERSA:	National Energy Regulator South Africa
NRCS:	National Regulator for Compulsory Standards
OECD:	Organisation Co-Operation and Development
PSO:	Particle Swarm Optimisation
PV:	Photovoltaic
PWC:	Price Waterhouse Coopers
RDP:	Reconstruction and Development Program
REIPP:	Renewable Energy Independent Power Producers
REIPPP:	Renewable Energy Independent Power Producers Program
RMSE:	Root Mean Square Error
rpm:	rotation per min
RTP:	Real Time Pricing
SA:	South Africa
SABS:	South Africa Bureau of Standards
SFLL:	Supervised Fuzzy Logic Learning
STLC:	Short Term Load Consumption
ToU:	Time of Use
USC:	Ultra Supercritical

Chapter 1: Introduction

1.1. Background

Globally, energy management has become a challenge due to rapid increase in energy demand and energy security concerns. In South Africa electricity supply problems have resulted in load shedding and steep increase in electricity cost. Due to the electricity supply problems encountered by the country, the government has reviewed the energy policies and included in its reviews, the demand side management (DSM), energy efficiency and energy conservation legislations and policies. There are five economic sectors in South Africa which are power demanding. These are residential, commercial, industrial, transport and agriculture. Among the five stated economic sectors, the residential sector is the second (Contributing one of the highest electricity consumption). Over and above, it is responsible for 17% use of the total generated capacity and contributes to about 30% during peak demand [1]. For example, and out of contextually, the residential consumption increased by 14% as of 2009 [2]. All in all, the electricity use in residential sector is influenced by the rapid growth in population, electrification programme, climate change, geographical area and more over the greater demand for comfort. Given the demand driven by the residential sector, there are certain initiatives that have been put in place to mitigate the growing demand. These include but are not limited to measures such as Time of Use (ToU), Real Time Pricing (RTP), DSM, demand response programmes. These are some of the home energy management systems that have been introduced and implemented to encourage residential consumers to participate in energy load management programmes [3]. Also, advanced metering infrastructure system are now being deployed as part of growing smart grid initiatives to provide foundation platform for engaging the consumer to demand side management. Regardless of all these measures to mitigate energy demand, the most and probably one of the deterrents in energy management is the usage of pricing within the ambit of all these measures. Thus, it is difficult to respond to changing price signals even under given incentives. Also, but not usually implemented on wide scale, residential energy conservation can be achieved through the use of automation (see for example [4], [5]) and also through the use of artificial intelligence to make intelligent decision in scheduling so as to automate appliances through pattern usage recognition [6], [7], [8]. In essence, artificial intelligence can be integrated in residential energy conservation as it can be used in situations where adaptive learning is required. Apart from artificial intelligence and automation, fuzzy logic can also be used in energy management systems [9], [10]. Fuzzy logic is used in context where situation involving high complex system whose behaviour are not understood and in situation where approximate, but a fast solution is required.

1.2. Problem statement

The continuing increase in electricity demand in South Africa has contributed intensively to load shedding and increase in electricity cost. South Africa is an energy intensive country where the economy is directly related to the energy consumption. Eskom, the electricity supplier is not capable of provide the adequate supply of electricity. Nowadays, management of energy load is being shifted more towards the demand side than supply side. However, there are different users with different preferences and interests in load management towards demand side. With these challenges in demand side, there is a need for an independent and automatic energy management system. With its advantage in providing artificial intelligence, fuzzy logic can provide innovative solution and intervention in the management of energy consumption especially for the residential sector.

1.3. Research objectives

The main objective of this study is to design a fuzzy logic enabled system to control the residential electricity consumption.

The primary objectives are to:

(i) Design the fuzzy logic enabled system that will be able to manage the amount of electricity as desired by the consumer for the given time frame.

(ii) Use fuzzy logic to enhance the electricity consumption by scheduling the household appliances in response to the ToU tariffs.

(iii) Design the fuzzy logic rules that will switch off the appliances in an orderly manner to achieve objective (i) and (ii).

1.4. Research questions

In order to reach the goal of controlling the residential electricity energy consumption, the following research questions are answered in this study:

(i) How can fuzzy logic enable system be able to manage the desired amount of electricity for given time frame?

(ii) How can the fuzzy logic be used to enhance the electricity consumption of the household considering the ToU tariffs?

(iii) How can the fuzzy logic rules be designed to switch off the appliances in an orderly manner to manage the amount of electricity for given time frame and schedule the appliances in an orderly manner?

1.5 Research methodology

The chosen methodology for this study is Design Science Research (DSR) because of its potential in the application of achieving the practical solutions. DSR is the methodology that not only describe, explain and predict the problem but develops the artefact that can help people to fulfil their needs, overcome their problems and grasp new opportunities. Authors in [11] and [12] explain the DSR as the paradigm with fundamental knowledge theory, understanding of problem design and its solution obtained in the construction and application of artefacts. An artefact described here as manmade object with the purpose of being able to solve the existing problem [11]. The DSR process include six steps namely problem identification and motivation, objectives for solution, design and development, demonstration, evaluation and communication [13]. Based on the knowledge and observation of high electricity demand in the South Africa, this research proceeded with a problem centered approach. The objective of the study is to design the fuzzy logic enabled system to control the residential electricity consumption by building using fuzzy model. The simulations of the experiment done by fuzzy logic model will be demonstrated so as to evaluate the effectiveness of the designed model [14]. In this dissertation, we will not only demonstrate the technology skills and knowledge, but the model will be analysed explained, justified and evaluated [15].

1.6. Limitations

Although the electrical energy demand has been noticed to be a global challenge in every sector, this study will be limited to the South African urban residential sector.

1.7. Contribution of the study

This study has been identified to be beneficial to the following:

- Residential electricity consumers.

  This study will give them the opportunity to save in electricity bills by controlling the consumption. They will also benefit in that they will be able to use desired amount of electricity for desired time frame.

- Electricity Entity.

  The study will reduce peak load and help the grid by improving efficiency and alleviate the cost of recurring upgrades.

- The researchers.

  This study will serve as the background and added information on studies related to demand side management.

1.8. The dissertation roadmap

In this section we introduce the chapters that will be followed. In particular the following chapters will constitute parts of this dissertation

Chapter 1: Introduction

Presents the background, the problem statement, research questions, objectives, contribution and methodology of the study.

Chapter 2: Literature review

This chapter presents the detailed background and outlook of energy in South Africa. The formulation of detailed problem statement and energy management is outlined and presented in this chapter.

Chapter 3: Application of Fuzzy Logic in energy management

This chapter outlines the concept of fuzzy logic and its application in energy management.

Chapter 4: Research methodology and design

In this chapter the detailed methodology and system design is discussed. The arrangement of conditions and activities that were performed to collect the information that aims to combine the relevance of research purpose are presented. This chapter also determines the fuzzy logic controller functionality and its architecture and explains in detail how it has been designed and developed.

Chapter 5: Presentation of results and analysis

The comparison of the study objectives and the actual observed results from the designed fuzzy logic designed enabled system for residential electrical energy control is presented in this chapter. The results are presented descriptively in form of tables and graphs. This chapter concludes by analysing, justifying and evaluating the results.

Chapter 6: Findings, Implications, Recommendations and Conclusion

Chapter 6 summarises the contribution of the study and further recommendations for an open problem which might worth analysis in future.

Chapter 2: Literature Review

This chapter presents the detailed background and outlook of energy in South Africa. The knowledge gap identification in the area of energy management is outlined and presented in this chapter.

2.1. Introduction to energy

Energy is fundamental to any country's economy [16], and is the vital force that powers businesses, manufacturing, transportation of goods and service delivery. In essence, energy is the enabler of economic growth and stability.

2.1.1. Global energy outlook

The authors in [17] postulate that energy demand, globally, is set to grow by 37% by 2040. It is envisaged that global energy demand will increase dramatically, particularly, driven by prosperity, increase in living standards and economic growth in most countries. With this increase, comes with it the challenges in the need for proper policy formulation and implementation in some countries. The energy outlook has with it many concerns in terms of energy stability and usage. Other issues such as responding to energy shortage and usage has necessitated the need for proper policy implementation within certain energy sectors. Different energy sectors have different demand patterns based on their potential usage. Of late, there has been growing concern to transit from high carbon (coal) based energy systems to lower carbon energy systems, like renewable energies. Renewable energy such as solar energy and wind energy are expected to grow exponentially in the next 30 years because of their low carbon foot print and to offset the demand for electricity on the already constrained grid. Also, within this growth, is the demand for natural gas as more and more people are turning toward the use of gas in heating and cooking.

Overall, demand for natural gas is expected to be the fastest in terms of growth among fossil fuels due to increasingly flexible global trade in liquefied natural gas (LNG). The exponential growth of LNG is partly driven by the demand for cooking and heating. China and the Middle East are some of regions that have fuelled the increase in gas demand, as such it is expected that gas may be the leading fuel (in terms of demand) in the Organisation for Economic Co-Operation and Development (OECD) energy mix by 2030 [18]. Notwithstanding the increase in the demand of LNG, global oil market remains susceptible to numerous or a wide range of risk factors. These include natural disasters, technical accidents and geopolitical tensions [19]. The Conflict between

Russia and Ukraine and the political tension between Qatar and its neighbours in the Gulf has reignited concerns about oil security [20].

Although coal is abundant, and its supply is secure, its future use is constrained by measures of tackling air pollution and the need to reduce global carbon (CO_2) emissions. Globally, coal demand is expected to grow by 15% by 2040 [18].

Renewable energy technologies (RETs), a critical element of low carbon energy systems with, low carbon foot print, are rapidly gaining popularity, helped by global subsidies amounting to $120 billion dollars in 2013 [20]. With rapid cost reduction and continued support, renewable energy is expected to account for almost half of the world's total in energy production in 2040 [21]. As global economies continue to grow and government policies change, the energy mix will continue to diversify. It si anticipated that, nuclear and renewable energy will grow strongly with natural gas growing the most. The diversification of energy supplies reflects economies of scale and advanced technology as well as policies aimed at reducing emissions. In essence, techno-economic growth and development worldwide will, increasingly, be powered by electricity, making global electricity demand to rise by 60% between 2015-2040 This will account for 55% of world`s energy demand growth. These facts offer challenges alongside opportunities and will alter the global energy landscape [17].

2.1.2 South African energy overview

According to [17], energy in South Africa is heavily dominated by coal, which is cheap and which is placed among cheapest energy globally. Apart from coal, which contributes 59% of the total primary energy supply, South Africa also gets energy from solar, wind, hydropower, biomass and nuclear power. Much of primary energy is transported over the grid lines (generation, transmission and finally distribution) to the consumers. Figure 2.1 shows the primary energy supply of South Africa in 2015.

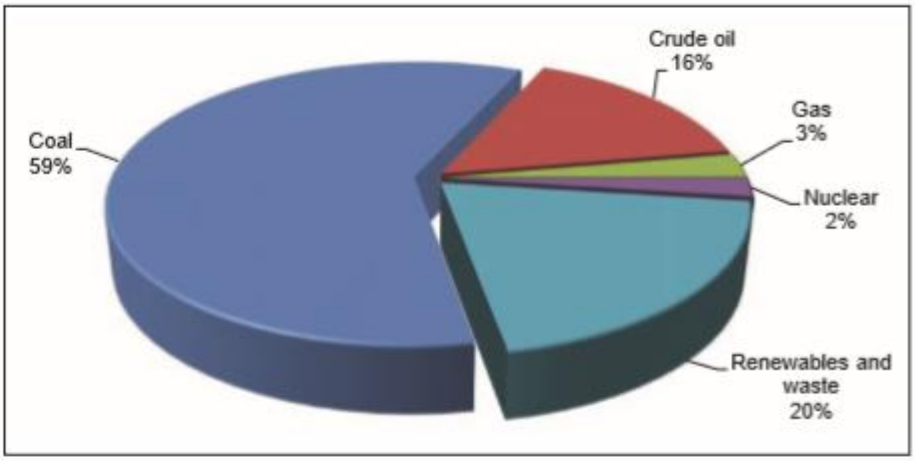


Figure 2.1: Energy supply in South Africa 2015. Source [16]

South Africa has limited oil and natural gas. Given the shortage of reserves, more than 90% of the country's crude oil is imported from Saudi Arabia, Nigeria and Angola [22]. The country generated 5% of its fuel needs from gas (GTL), 39% from coal (CTL) and 56% from crude oil during the transformation period [23]. Most petroleum products are refined in South Africa; such as petrol, diesel, paraffin liquid, residual fuel, petroleum gas and jet fuel. However, to meet the domestic demand some petroleum products have to be imported to supplement the shortfall. Petroleum products imported from other places constitute; Asia (84%), Europe (4%) and America (2%). In 2015 83 % of crude oil was imported and 17% was produced from indigenous sources. South Africa has limited reserves in natural gas at 27million cubic meter. As a result, the country imported 74% of natural gas from Mozambique while domestic production amounted to 26% [24]. South Africa has the world's fifth largest reserve of recoverable gas, valued at 66.7 billion tons [25]. Coal from South Africa is collected from collieries ranging from one of the world's largest coal mines to the smallest coal mines. Approximately 51 % of South Africa's coal mining is carried out underground, while the rest is carried out using the process of open cast mining. Production of coal in South Africa is concentrated in large mines that account for about 70% of production. The usage of coal for local electricity production is among the cheapest in the world. In 2015, 77% of coal was sold locally for domestic production while 33% was exported. As traditional fossil fuel-based energy costs continue to rise, renewable energy is becoming a viable option. In 2003, the government approved the participation of the private sector in electricity production with ESKOM agreeing to a 70% stake in the production of electricity while Independent Power Producers (IPPs)- from renewable energies such as wind and solar- should split the remaining 30% of power generation. The Independent Power Producer Programme for Renewable Energy was developed in 2010 with the goal of bringing additional power into the electricity system through public offering or private sector investment in wind, solar, photovoltaic, concentrated solar power (CSP), biomass and small hydro technologies [17]. As for 2015 renewable energy technologies contributed about 14725 MW to the total energy supply of the country. The net output capacity is as shown in Figure 2.2.

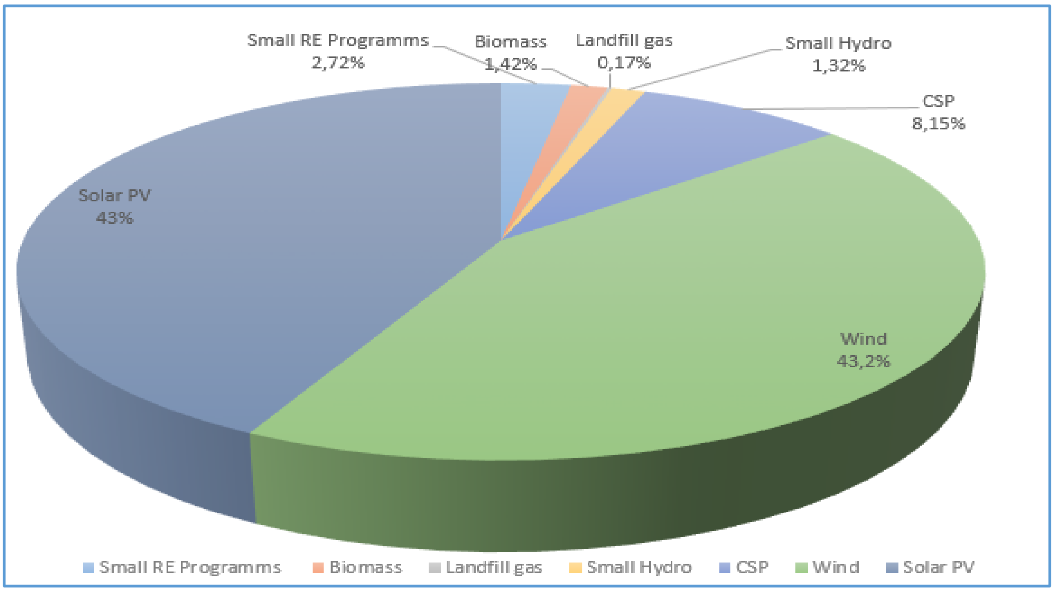


Figure 2.2: Capacity of REIPP. Source [17]

South Africa is one of the world's top countries with uranium reserves, accounting for a substantial base of an estimated 279,100 tons of uranium or approximately 5.2% of the world's proven reserves [26]. Generally, uranium produced in South Africa is a product of gold or copper mining. Uranium is used by nuclear power plants to generate electricity, contributing about 2% to the total supply of energy.

2.2. Eskom: The Electricity supplier in South Africa

The South African electricity body representing the nation on the southern Africa Power Pool within the SADC region is Eskom. Eskom is the largest electricity producer in Africa, among the world's eleventh largest electricity firms in terms of production and among the top nine in terms of revenue. It is the largest state-owned enterprise in South Africa and is divided into generation, transmission and distribution. Eskom generates approximately about 95% electricity used in South Africa and about 45% electricity used in Africa. The entity has 26 operational power stations and 2 coal fired power stations under construction. By the end of financial year 2018 Eskom had 48628 employees to provide service to 16.789,974 customers. Eskom’s network consists of 381594 km of high, medium and low voltage lines [27].

President Ramaphosa declared in his 2019 State of the Nation (SONA) address that the government would separate ESKOM into three new state-owned entities based on generation, transmission and distribution. This would be undertaken to help handle the company's series of operational and financial issues facing ESKOM. [28].

2.3. Generation technologies of electricity in South Africa

Eskom supplies electricity to different economic sectors in South Africa namely residential, commercial, industrial, agricultural, and other distributors such as municipalities. Eskom uses various technologies to generate the electricity, the combination is called plant mix [29].

2.3.1 Coal fired technology

Coal-fired technologies use coal as the source of electricity. Coal-fired plants generate energy and produce steam by burning coal in a boiler. Under immense pressure, the steam produced flows into a turbine that spins a generator to produce electricity. To begin the process again the steam is then cooled, condensed back to water and returned to the boiler. The coal fired technology has different types technologies as explained in [30].

(i) *Subcritical plant*

This technology has efficiencies of about 30% and they are the most common types of plants used globally because they are faster and less costly to build compared to other techniques.

(ii) Supercritical

With thermal efficiencies of about 40 %, supercritical plants make up to 22 % of the global coal-fired power stations. The high capital cost of super critical technology is mainly due to the alloys used and the welding methods needed for fire vapor and temperature operation. Fuel savings can partially or entirely offset the high cost. This form emits less carbon emissions by about 20 % than the subcritical plant.

(iii) Ultra-Supercritical (USC) and Advanced Ultra Super Critical

This type uses even more higher temperature and pressure to drive efficiency of up to 45%. Currently around 3% of global coal uses such technology. This technology also reduces carbon emissions up to around 7% less when compared to subcritical plants with the same amount of coal input.

(iv) *Integrated Gasification Combined Cycle (IGCC)*

For power generation, gasification can also be used. IGCC plants use gasifiers to convert coal to syngas that drive electricity generation through the usage of a combined cycle turbine. As the fuel is cleaned before it is fired in the gas turbine, IGCC plants can achieve efficiencies of around 45 % and have low emissions. The cost of IGCC investments is relatively high and the cost of supercritical plants may be twice that. The benefit of using this technology is its low cost and the absence of coal transport.

Eskom coal plants makes up the largest portion in its plant mix. These are base load stations that operate 24h hours a day to meet the demand of electricity. The coal stations have an output net of 34952 MW [31].

2.3.2 Nuclear technology

The nuclear operating facilities use the nuclear fission process. Heavy nuclei are broken apart to form lighter ones. The process of fission will create neutrons that will start a chain reaction. A fission process usually triggers another fission process, triggering a chain reaction. In nuclear technology, nuclear reactors are constructed in a way that preserves this chain reaction in a controlled way. In a nuclear plant, fission takes place in a nuclear cell while the rest of the reactor is designed to convert the induced thermal energy into electricity and to ensure that no radioactive material created during the process is released into the atmosphere. Similar to gas or coal, nuclear power plants are thermal plants. They produce steam from heated water which in turn drives turbines. In existing nuclear plants, compared to other technologies, electricity can be produced at a low cost. It is possible to change nuclear production to satisfy varying demand/supply imbalances. Nuclear power station has the advantage of reliability, security, operating cost predictable and low emissions. In South Africa, Koeberg is the only Africa nuclear power station with 1830 MW [32].

2.3.3. Hydropower/ Hydro-electrical technology

Hydropower depends on the conversion of potential energy into kinetic energy. Through the transformation of hydro energy into mechanical energy, commercially available technologies use flowing water in order to drive the turbine connected to the generator. It is a flexible energy source which can respond to different power system requirements, different physical and environmental constraints as well as stakeholders' interests. Hydropower is broadly categorised into four main types of technologies as explained below:

(i) *Storage Hydropower*

This kind of technology uses the dam for water storage which is then released when needed. By releasing water from the reservoir through operating gates into turbines which in in turn drives the generators. In this way electricity is generated. Hydropower storage can be controlled to provide both base load power and peak load through its ability to shut down and start up within a limited period of time and in compliance with system requirements. It also has adequate storage space to function independently of the hydrological inflow for many weeks or even up to months or years.

(ii) *Pumped Storage Hydropower*

Pumped storage hydropower involves the usage of pumped water that is cycled by pumps between a lower and upper reservoir. At a period of low demand, the pumps use excess energy from the system. Water is released back to the lower reservoir through turbines to generate electricity when electricity demand is high. Its value is in the provision of energy storage, thus, enabling peak demand to be met, and in essence assuring a guaranteed supply, when in combination with other renewables and other ancillary services to the electrical grid.

(iii) *Run a river hydropower*

This facility, channels flowing water from river through a canal or penstock to drive a turbine. It provides a continuous supply of electricity is generally installed to provide base load power to the electrical grid.

(iv) *Offshore Marine Technology*

This is a less established, but a growing group of hydropower technologies that use the power of currents or waves to generate electricity from seawater. These includes (river, ocean and waves) tidal barrage and tidal stream, osmotic and ocean thermal technology. Apart from the above technologies, Eskom’s generation mix also includes two conventional hydroelectric power station (Vanderkloof and Gariep) with net output of 600 MW and two hydro pumped storages (Ingula, Drakensburg, Palmiet, Collywobbles, Ncorha) with net output of 2738.3 MW. These stations are used when there is a sudden increase, or peak in demand for electricity which can not immediately be met by the base load stations [32].

2.3.4. Gas turbine technology

In particular, gas turbines are a type of internal combustion engine in which hot gases that spin a turbine to generate power are produced by burning the air-fuel mixture. It relies on hot gas output during the combustion of fuel. Various fuels, including natural gas, fuel oils and synthetic fuels, can be used by the gas turbine. There are three main parts of gas turbines built on the same shaft: compressor, combustion and the turbine. The movement of air and its diffusion through the rotating blades by the stators increases the pressure and reduces the volume. Given the fact there is no heat applied, the compressed air often causes the temperature to rise. Under constant pressure conditions, the fuel air mixture ignites, and hot combustion gases are directed through the turbine. In the process the gases expand rapidly and set the shaft in motion (rotation). To maintain continuous combustion, the shaft rotation drives the compressor to draw in and compress more air. The shaft power also produces enough energy that in turn continues to generate electricity. Eskom has four gas turbines power stations (Acacia, Ankerlig, Gourinkwa, Port Rex) which are only used during peak periods and during extreme emergencies due to their very high operating costs. These plants have total net output of 1378 MW [32].

2.3.5. Wind turbine technology

For all intents and purposes, wind energy turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft which spins the generator to create electricity. The gear box connects low speed shaft to the high-speed shaft and increase the rotational speed from about 30-60 rotation per minute (rpm) to about 1000-1800 rpm. Wind energy is renewable and sustainable. Wind energy is also free and reduces fossil fuel consumption with small carbon foot print. In terms of installation costs, wind energy generation requires measurement of wind profiles so as to determine the possibility of erecting a wind energy farm. In essence, the installation may require an erection of wind turbine (for testing purposes) to measure wind speed over a period of time. The disadvantage of wind energy is in its noise pollution and visual pollution. Within this particular domain, Eskom has invested into two wind farms (Sere and Klipheuwel) with an output of 103.2 MW in total. The electricity generated by the wind facility is fed directly into the regional distribution network. In 2002/03 Eskom erected three wind turbines as an experiment and more precisely, into the potential of wind energy in South Africa [32]. Figure 2.3 shows the map of Eskom`s power stations.

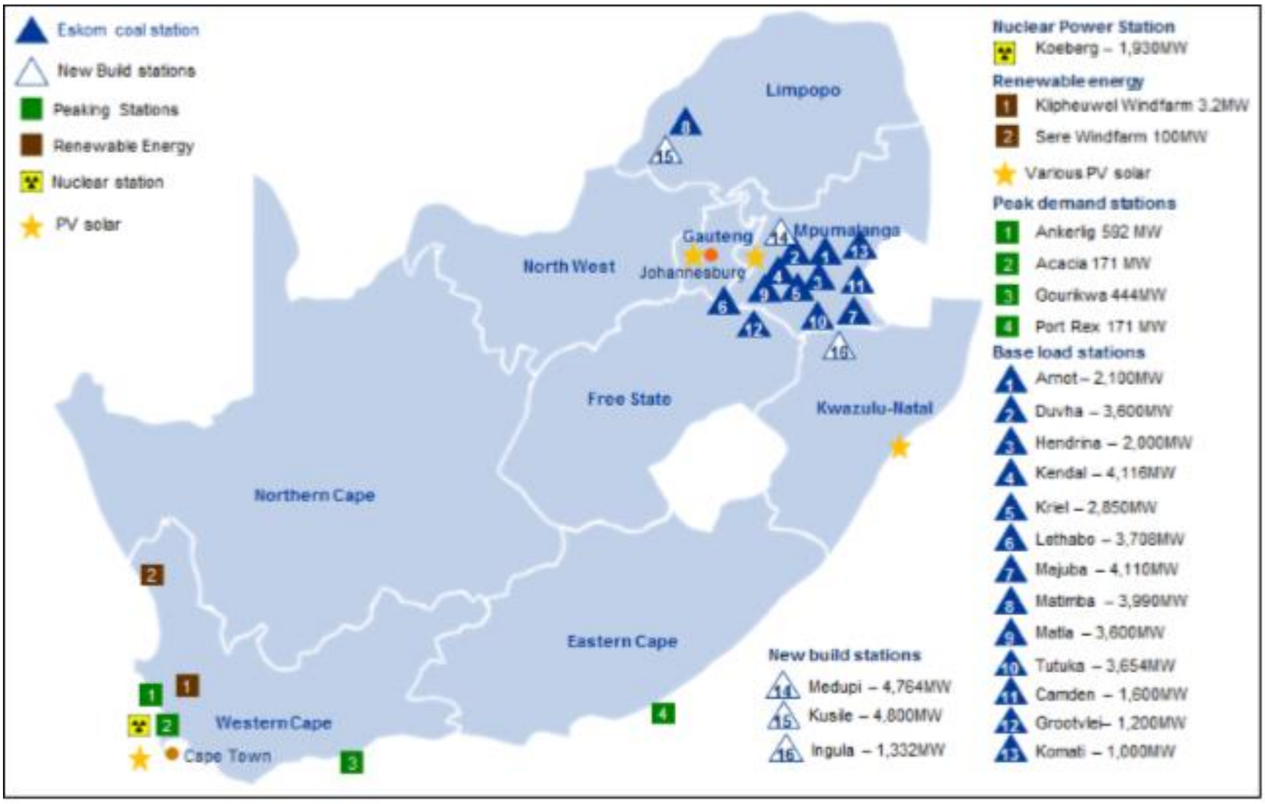


Figure 2.3: Map of Eskom power station. Source: [33]

2.4. Electricity demand in South Africa

The demand for electricity is specified by [34] as the quantity of electricity needed by all users operating at one time in buildings, areas or cities. Essentially, in South Africa, around 40% of the population had access to electricity in 1987 which spelled greater demands in the usage of electricity [35].

2.4.1 South Africa and the electricity crisis: Reasons why

The steady economic growth coupled by increasing focus in industrialisation, electrification programme to increase electricity access in deep rural areas, increasing population and urbanisation have resulted in steep increase in energy demand. The energy demand has been driven by step on step series of issues that have increased the demand for energy in South Africa. Such issues were primarily driven by:

(i) Government electrification programme

In 1992, nearly three million households had access to grid electricity, equating to about 36% of the population. As such, the Reconstruction and Development Program (RDP) was launched in 1994 by the newly appointed democratic government, the purpose of which was to fulfil the fundamental goal of ensuring access to appropriate and affordable energy to the entire population [36]. Thus far, over 6.7 million households (85.87%) have received electricity through Integrated National Electrification Program (INEP) as of March 2016 [17]. In attempting to enable the low-income areas and households to afford electricity; the government introduced the Free Basic Electricity (FBE) which allows the households 50 kWh of free electricity per month for basic energy needs [37]. In 2017 3.51 million low income areas and household received FBE [38]. Such policy structures and initiatives contributed strongly to the demand of electricity.

(ii) Population growth

South Africa population increased to about 57.73 million in 2018 representing an overall 1.55% growth between 2017 and 2018. The population growth increases the demand in electricity. Given the fact that there is also high unemployment rate, there will be more households that benefit from FBE. The negative impact of the increasing population affects the economic growth of the country by subsidising the households that cannot afford electricity.

(iii) Economic growth and urbanisation

Electrical power system supply affects every user across the country of South Africa. It affects the country's economy directly/or indirectly through multiple channels. Due to South Africa's heavy industrialisation and rapid population growth, it remains an energy intensive country where power consumption and Gross Domestic Product (GDP) are directly related [39]. As the economy grows, the demand for power energy will continue to grow. Since urbanisation is linked to economic growth and development, it also has a direct relationship to energy demand especially in the urban areas. [40]. In the development process, urbanisation plays an important role in the urbanisation. As a developing country, people migrate from rural to urban areas. When urbanisation occurs, there is always an upsurge in the number of people living in high densities areas, like Soweto, where they may qualify for basic electricity tariffs. In the same vein, and a probable cause of high demand of energy, are entrepreneurs who may choose to locate their businesses to cities where localised economies increase their productivity.

Figure 2.4 shows the relationship between urbanisation and economic growth in South Africa as compared to other countries in Africa.

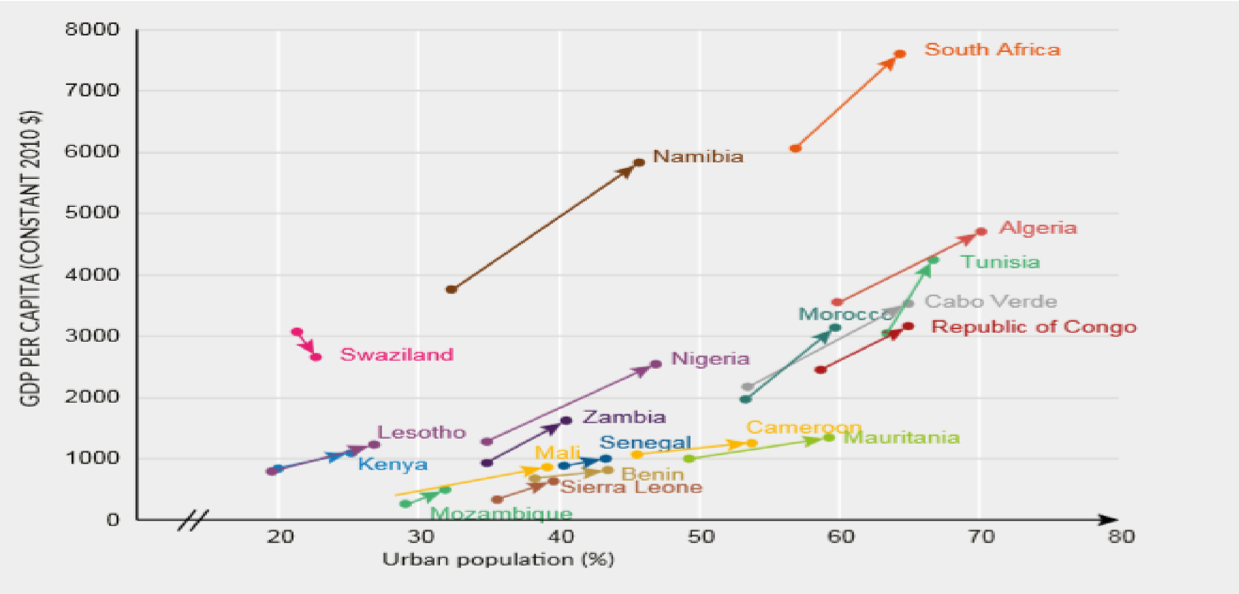


Figure 2.4: Urbanisation per capita 2000-2014. Source: [41]

In short, with approximately 64 % of the country's population currently residing in urban areas, of which 40 % are concentrated in metropolitan municipalities, South Africa continues to undergo rapid urbanisation. By 2030, the urban population is estimated to be 70%, with more people moving to cities for jobs [42].

2.4.2. Electricity consumption in South Africa

Electricity is central to social and economic development and by extension it is known to play a significant role in the advancement of life. Its division into different facets of economic growth may induce certain patterns in terms of energy demand and usage. Energy usage patterns or consumption (a representation of energy usage in South Africa) may be derived from industrial, commercial, transport, agriculture and residential sectors [43]. Authors in [1] present a descriptive South African electricity usage or consumption as follows (see Figure 2.5):

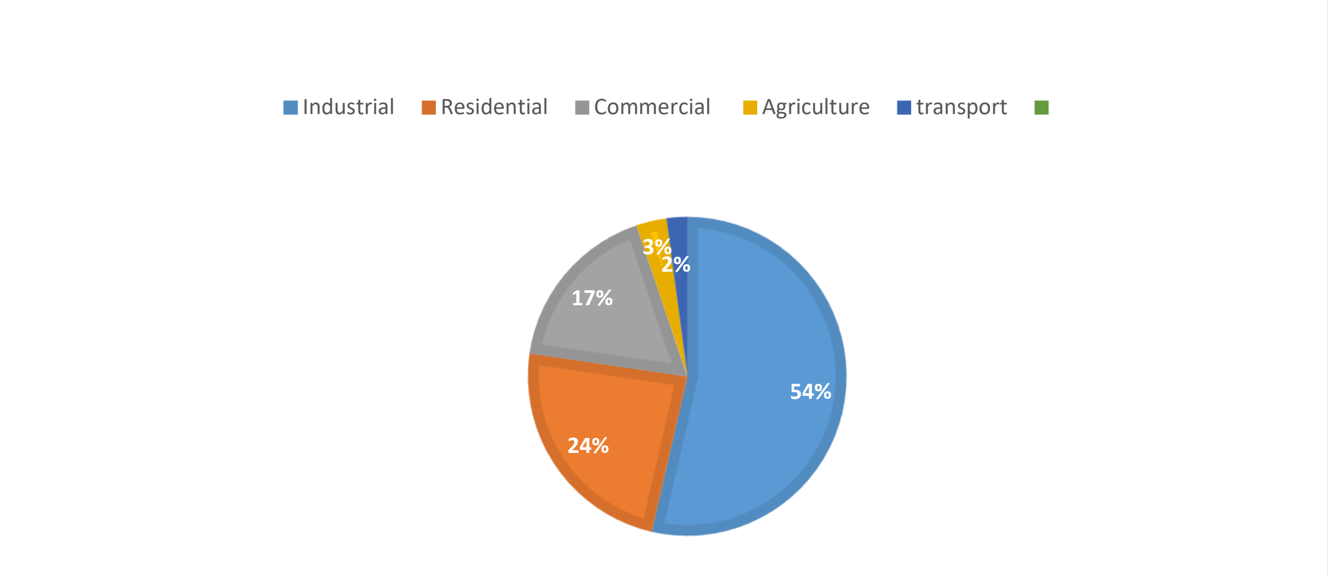


Figure 2.5: Electricity consumption in South Africa

As illustrated in Figure 2.5 residential sector is seen as the huge consumer, (mostly derived from the reasons given in our previous literature arguments) and has been one of the large sectors in terms consuming electricity and accounts for 17% of electricity consumption in total electricity generated in South Africa. More definite than not, this increased by 14% as from 2009 [2]. Household electricity energy consumption patterns differ, depending on the kind of locality in which they reside. In the underdeveloped rural area, wood is the principal fuel for cooking and heating while in urban areas electricity is the single point of energy source for domestic activities [44], [36]. The survey of related behaviour and perception in SA done in 2012 seem to agree with [45]; that the well-established traits in residential energy in SA pertains to the salience of geographic location of the household. The three factors that have been proven significantly are urban location, climate condition and associated space heating in winter. The load profile in Figure 2.6 shows the impact of seasons and climate induced electricity demand.

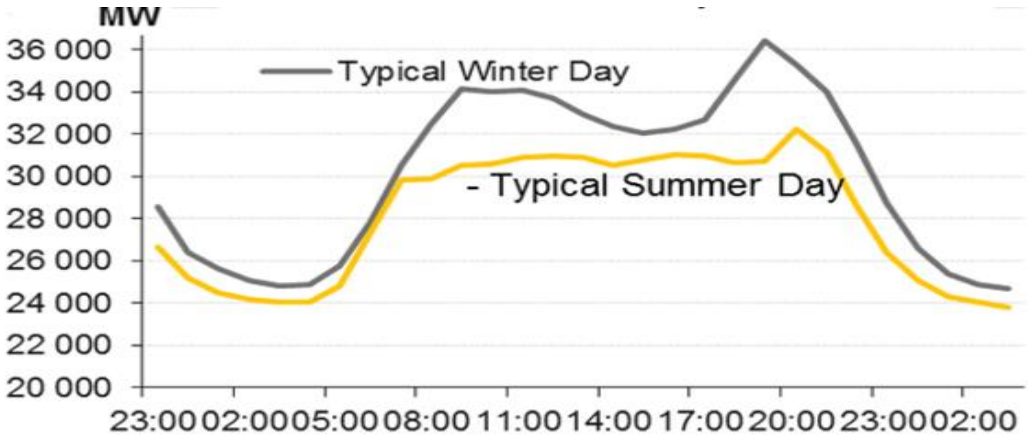


Figure 2.6: Summer and winter load profiles. Source: [46]

The winter profiles in terms of consumption seem to be more than the summer ones. The probable reason, without digression from the stats provided, is that in winter electricity demand increases during morning and even peak hours due to cold weather. The demand picks more in the evening when residential consumers arrive from work and switch stoves, heaters and lights. Figure 2.7 shows that even though the residential sector is responsible for high consumption it is also seen that the consumption also depends on where the household resides (geographic location).

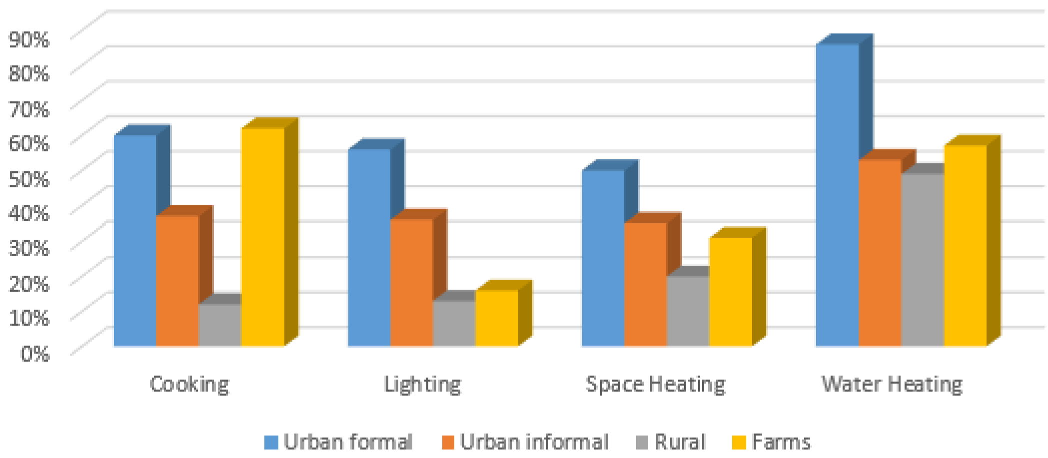


Figure 2.7: Residential electricity consumption per location

The urban formal is the most consumers of electricity hence they mostly rely on a single source of energy for cooking, lighting, space and water heating. Due to many electric appliances used in modern homes, urban households are struggling to know the amount of electrical energy they consume daily, during peak and off-peak periods. The increasing number of electrical appliances causes the demand in residential electrical energy use. Increase in number of home appliance consumption and the search for comfort has contributed to an upward surge in energy demand in households [47]. In order to save energy, one of the best ways is to know how much one is using in the first place, this is the anatomy from where this dissertation will shape its path. As a matter of fact, the state-owned company provides the list of items and how they contribute to the electrical bill as shown in Figure 2.8.

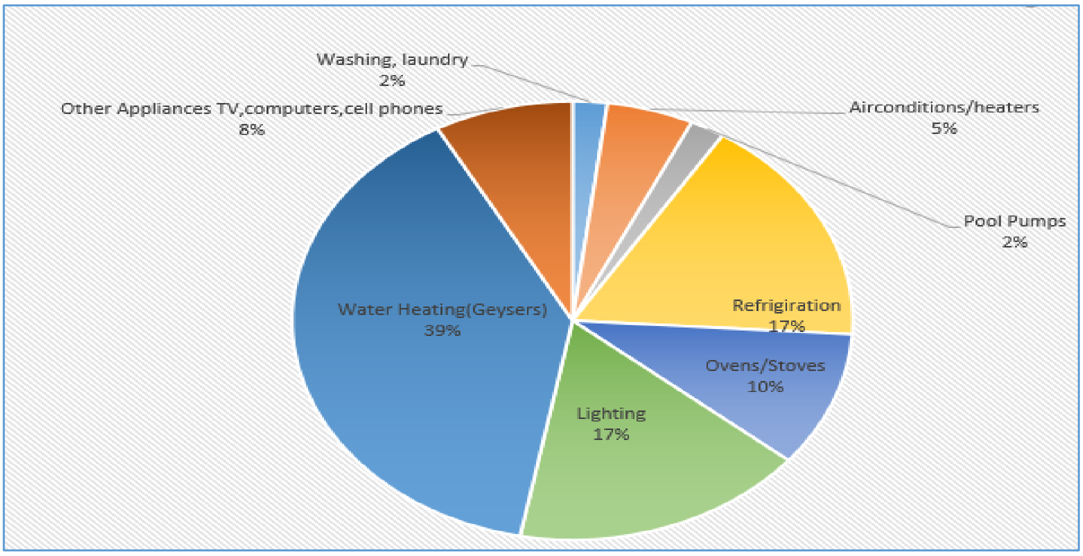


Figure 2.8: Household electricity consumption. Source: [48]

Critical analysis of Figure 2.8 shows that the geyser is the one of the appliances that consume energy in households reaching up to 39% of total household consumption. In line with the above, [49] suggests that a number of energy efficiency measures that can be implemented in residential power consumption. The following are some of the suggestions:

(i) Since the geyser is the single largest residential load, using 39%, of the household electricity, it should be switched off when not in use.

(ii) Insulating geyser and hot water pipes save energy and money.

(iii) Reducing the temperature at the geyser thermostat to 60% saves electricity.

(iv) Use fluorescent lamps to replace the incandescent bulbs.

In line with the energy usage in South Africa, 89 % of households in SA use electricity for lighting and 77% for cooking. Moreover, according to the report released by sustainable energy Africa, the total amount of electricity used for electrical appliances amounts to 66 % which are categorised into three namely, geyser 31%, kettles 23%, stoves 7% for water heating. Figure 2.9 shows typical residential customers` daily peak consumption.

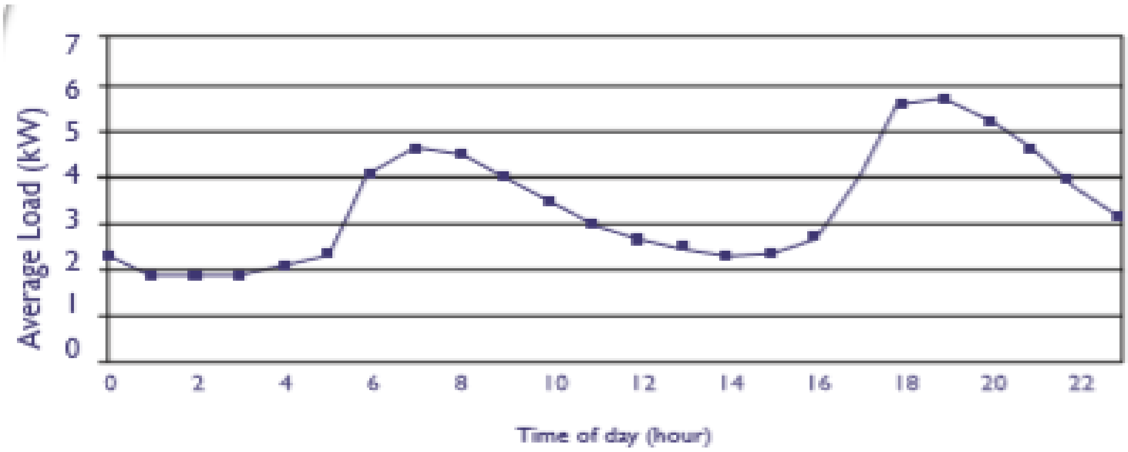


Figure 2.9: Residential electricity peak consumption. **Source: [50]**

Indeed, and from Figure 2.9, most energy consumption occur during peak demands which are between 6 -10 in the morning and 5-9 in the evening.

2.4.3. Electricity shortage

Even though there is high energy demand in South Africa, poor procurement of coal that is used to generate most of electricity in the country, the backlog in maintenance of infrastructure, illegal connections and poor payment electricity has all contributed to poor state of the electricity in the country and by extension the construction of the new power plants. The units that were intended to alleviate the country's power constraints are also having the technical flaws and unreliable. All in all, the following are the causes of the electricity shortage in South Africa:

(i) Coal shortage

The commission of enquiry, on state capture is making some startling revelations on the influence of private on government business. The recent testimony in Box 2 on corruption around coal supply in Eskom has far reaching implications for the economy. Eskom was forced to conclude multibillion rand deal with Tegeta coal, in just 48 hours, to supply low quality coal that led to generation problems in Eskom This resulted in the current load shedding. As per energy experts in Box 1, Eskom power station are very particular about the grade used for electricity generation. The Price Waterhouse Coopers (PWC), tabled at standing committee on public accounts also revealed corruption in awarding the tender to Tegeta coal mine that could not meet regulatory requirements, especially with regards to coal quality.

1

BOX 1: QUALITY OF COAL SUPPLIED

The quality of the coal becomes a major issue because Eskom power stations are very particular about the grade of coal needed for power generation.

Roger Lilley, editor of *Energise Magazine* at EE Publishers, explains the coal shortage at power stations and why their current solutions will cost the utility even more in the long term: “Each power station has its own coal supply, usually from a mine that is close by.

“What is happening now is they are bringing coal from other mines, because of mine closures or the mines are unable to supply the quantity or the quality of coal supplies that is needed to generate electricity.

“That means they have to bring coal from other mines, either by truck or by train, depending on the proximity of a railway line, so it’s an operational matter between the mines and the power stations.

“The quality of the coal becomes an issue, because Eskom power stations are very particular about the grade of coal, which can cause issues with the boiler.

“If a particular mine is unable to produce that grade, they have to look for coal from other mines. It is presently becoming an issue at the Hendrina power station.

“The problem is that Eskom is very close-lipped in terms of providing in-depth data.” “[Colleague] Chris Yelland [editor of EE Publishers] gets information from other sources and it invariably gets proven right.” (The citizens.2018, April,19)

BOX 2: CAUSES OF COAL SHORTAGE

State capture inquiry: Eskom forced to conclude multibillion-rand Tegeta coal supply deal in just 48 hours:

“There was considerable pressure on Eskom to conclude a coal deal with Gupta-linked Tegeta in less than 48 hours in 2015, the state capture commission of inquiry has heard.

Hofmeyr was addressing commission chairperson, Deputy Chief Justice Raymond Zondo before she presented the evidence of Eskom's now deceased executive, Mark Van Der Riet, and acting managing director, Daniel Mashigo.

She submitted that at the time of the agreement relating to the R4.3bn deal, Tegeta was not in a good financial position to enable it to provide coal to Eskom.

Tegeta is a Gupta-owned firm which has been under business rescue since February 2018.

During the business rescue period, Tegeta-owned Brakfontein mine was unable to honour its contractual obligations to supply coal to Eskom's Majuba Power Station in Mpumalanga.

Hofmeyr said the evidence team had an understanding that Van der Riet's affidavit and Mashigo's testimony would shed light on some of the irregularities in the procurement of coal from Tegeta's Brakfontein coal mine.

"Van Der Riet's testimony is important as it looks at the significance of the quality of coal that is supplied to Eskom and its relation to the load shedding incidents the power utility has been experiencing," Hofmeyr submitted.

"R500m in penalties have now been levelled against Tegeta, which has been in business rescue since February 2018," Hofmeyr continued.

On Tuesday, Mashigo gave a brief structural outline of what was considered to be acceptable coal.

In 2015, National Treasury started an investigation into Eskom's coal contracts with Tegeta, while another forensic report by Price Waterhouse Coopers (PwC) was later discussed at a meeting of Parliament's Standing Committee on Public Accounts (Scopa).

The PwC report revealed that Tegeta started supplying coal to Eskom before the coal mining group met regulatory requirements.

The coal supply agreement with Tegeta was signed on March 10, 2015 and although Eskom invited competitive bids for coal supply, it only approached Tegeta.

The initial value of the contract was R3.7bn, but Eskom later intended on expanding it by a further R2.9bn for the Brakfontein operation.

The commission also heard that Tegeta got the tender even though 29 out of 30 coal samples from the Tegeta Brakfontein colliery failed Eskom's analysis tests.

In addition, Mashigo testified that Tegeta did not comply with all the requirements at the time that it started its contract with the power utility.

He told the commission that putting Tegeta under business rescue did not help the situation and led to a dire coal shortage instead.

"They were unable to supply coal as needed by the Majuba Power Station and Eskom had to source coal from other suppliers." (*Pelane Phakgadi* . 2019-02-26 16:32)”

(ii) Illegal connections

According to [53], 11% of South African population did not have electricity access while other 3.6% or 578005 households accessed electricity illegally. The average revenue loss by Eskom due to illegal connections amounts to about R2 billion a year. (see for example BOX 3).

BOX 3: ILLEGAL CONNECTIONS

Faizel Patel, Radio Islam News - 25-05-2018

Residents of Northern Place in Lenasia say they are fed up following electricity outages due to illegal connections.

In a post circulating on social media, residents have complained about the informal settlement that has mushroomed in Northern Place near the Khanqa Sheikh Zakariyya Masjid including the myriad of illegal connections that are posing a risk to the community.

Residents have accused the informal settlement of stealing power and cables that are connected to homes in the area.

A resident say they drafted petitions and engaged with authorities, but their concerns have fell on deaf ears.

The illegal electricity connections in Northern Place in Lenasia

“I am one of the residents of Lenasia Drive Extension 1 in Lenasia. Because of the informal settlement we’re having endless problems. Every day we don’t have lights, every week we have electricity theft, electricity cable theft. Please help us.”

Generally, When Eskom supplies a community with electricity it first establishes how much electricity is needed by the particular number of people or homes and base their distribution connection network on the connection analysis. It is from the planned home supply system that illegal connections are drawn. This essential may result in the system being overloaded and consequently may lead to system failure due to unpredicted demand. In Box 3, the implications of illegal connections are revealed as the households experience severe electricity shortage.

(iii) Aging infrastructure

The concern of the infrastructure with the distribution components is also contributing. Lack of maintenance of its infrastructure has also led to blackouts in some areas. The old distribution cabinets as shown in (refer to Box 4) alone may induce elements of illegal connections and possible electricity losses during the distribution phase. Box 5 illustrates reasons as to why there is shortage electricity in South Africa. Particular mention here is attributed to ageing infrastructure. Inclusive in the narrative of ageing infrastructure, are the electrical cabinets and generating power stations that are not in proper state to meet the demand of current South African demand.

BOX 4: AGING INFRASTRUCTURE

The real reasons for power blackouts in South Africa.

The real reasons why South Africans are experiencing power blackouts are the delay in the completion of the Medupi and Kusile power stations, and the poor state of Eskom's local power distribution network. Speaking at the recent MyBroadband Cloud and Hosting Conference, Yelland said load shedding is just one of the causes of power outages.

He said none of the usual excuses for electricity blackouts – like bad weather, deferred generation maintenance, and Eskom's financial crisis – address the underlying problems.

The real problems are the **delay in the Medupi and Kusile power stations** (4,800MW each), and the **inadequate investment in distribution maintenance and refurbishment**.

"It is now 2015 and the first unit from Medupi has been synchronised, but it has not been handed over for commercial use yet," he said. "We are 12 units behind, and 7 years late on the construction of Medupi and Kusile." "The non-load-shedding outages were caused by aging infrastructure, a lack of distribution network maintenance, cable theft, and overloading the system because of cable theft."

The real problem for most of these issues, said Yelland, is the inadequate investment in distribution maintenance and refurbishment.

Yelland illustrated the dismal state of Eskom's local distribution infrastructure through the photos posted below.

City Power switch gear cubicle

A City Power 11KV switch gear cubicle on the side of Beyers Naude Drive is strapped together with band-it."I saw this broken cubicle for four months, and I was reporting it for all four months. After three months they put the band-it around it. Before that the doors were lying in the veld," said Yelland.

Eskom distribution box in Sandton

City Power mini sub-station

(My broadband.2015, June, 10)

BOX 5: SHORTAGE OF CAPACITY

ESKOM WARNS OF HIGH RISK OF LOAD SHEDDING DUE TO SHORTAGE OF CAPACITY

The power utility, though, says that it will only implement the rolling power cuts if absolutely necessary.
Eyewitness News | *about 20 hours ago*

JOHANNESBURG - Eskom has warned that there is a high risk of load shedding for Monday due to a shortage of capacity due to the loss of generating units at its power stations.

The power utility, though, says that it will only implement the rolling power cuts if absolutely necessary.

Last month, the country experienced five straight days of power cuts with the escalation of stage 4 load shedding.

At the time, the utility said that cutting its maintenance expenditure has had a major impact on the performance of its plants.

(ENWnews, n.d.)

2.5. Electricity price increase

Between 1970 and early 2000, South Africa enjoyed a long period of sustained electricity supply at some of the lowest prices in the world. However, the situation changed dramatically in June 2006 as country`s growing economy began to make full use of generation capacity that was built in 1970s and 1980s [57].

The increasing tariffs are necessary to recoup investments and in expanding the supply capacity and transmission network to meet growing demand [58]. The cost of producing electricity has to be absorbed into a price strategy.

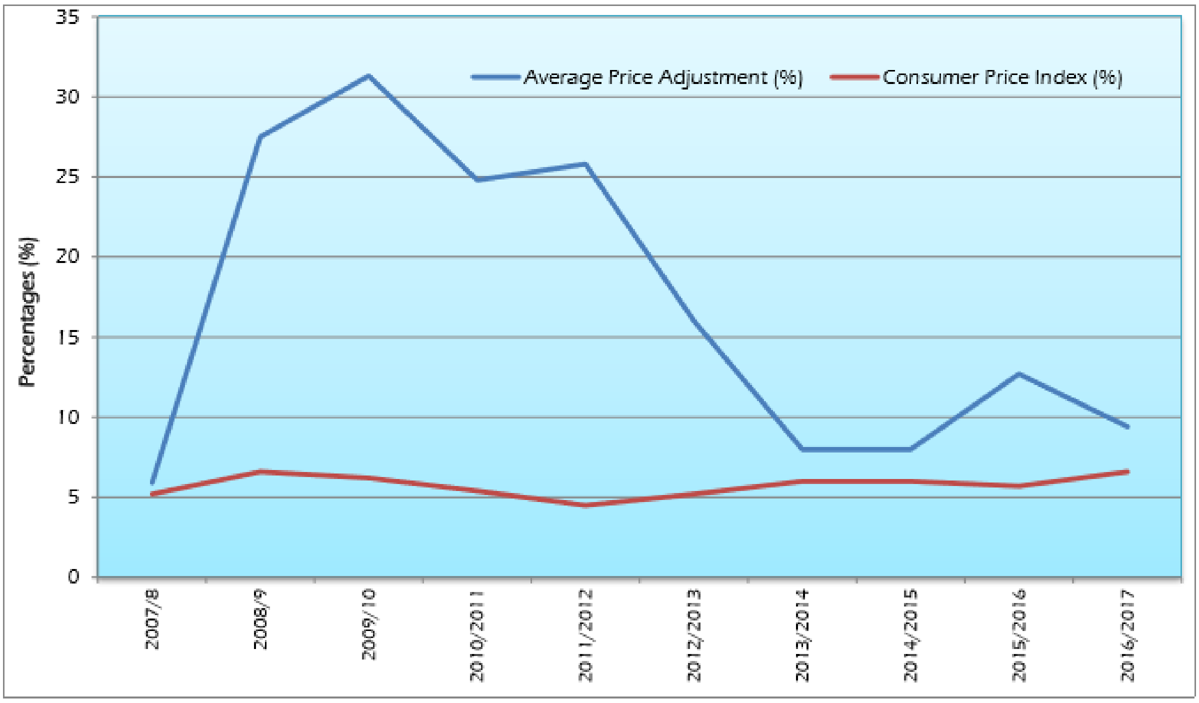


Figure 2.10: Average electricity price and consumer index price. Source: [59]

Even under the pretext of recouping investments, we must make mention here that, and as shown in Figure 2.10, the tariff adjustment has always been above the consumer Price Index (CPI) which makes the cost of living very unbearable for the poor and low-income households.

2.6. Electricity demand forecast

In order to sustain the supply efficiency to avoid the blackouts, Eskom has to forecast the overall demand including that towards exports in order to find best mitigation measure.

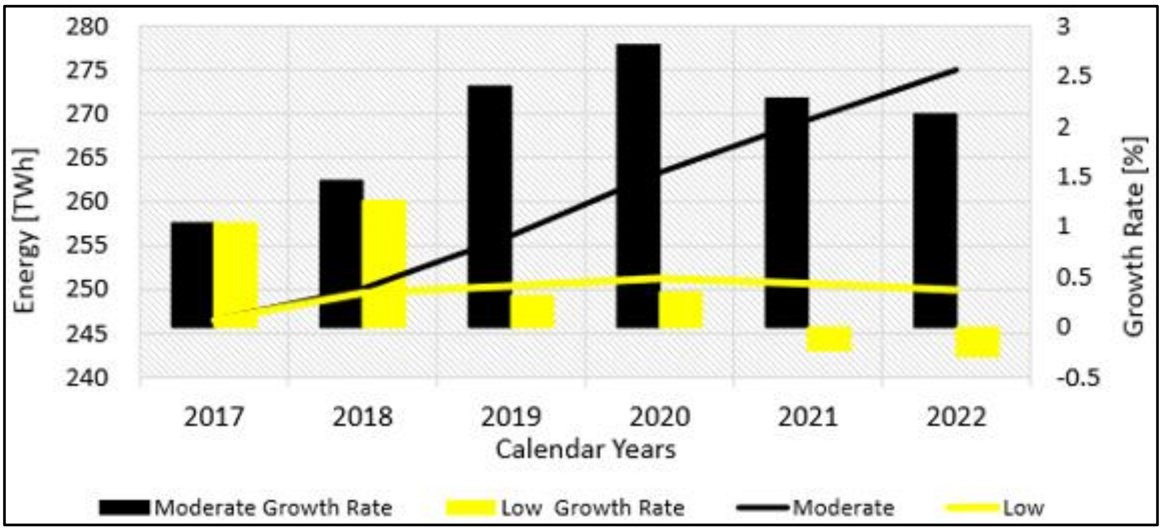


Figure 2.11: Energy demand forecast. Source: [60]

To illustrate this, in order to increase sales both locally and internationally ESKOM usually carries out a five-year forecast for five years taking into account the current economic conditions. This is summarised in Table 2.1. Of uttermost important in the forecasting is installed capacity which determines the amount of energy to be used and sold outside South Africa, especially in the advent of independent power producers.

Table 2.1: Electricity installed capacity. Source: [60]

	2017	2018	2019	2020	2021	2022
Coal	35795	35795	35795	35238	34307	33565
Nuclear	1860	1860	1860	1860	1860	1860
Pumped storage	2724	2724	2724	2724	2724	2724
Diesel	2409	2409	2409	2409	2409	2409
Hydro	600	600	600	600	600	600
Wind	100	100	100	100	100	100
	43,488	**43,488**	**43,488**	**42,931**	**42,000**	**41,258**

Table 2.2 shows the installed capacity of Renewable Energy Independent Power Producers (REIPP) as licenced by NERSA. The above existing installed capacity excludes the coal fired Medupi and Kusile. In line with IRP2010, the three coal fired stations namely Arnot, Hendrina and Camden were modelled with a 50-year life of plant.

Table 2.2: Renewable energy independent power producer. Source: [60]

	2017	2018	2019	2020	2021	2022
Wind	1,470	1,982	1,982	1,982	1,982	1,982
PV	1,474	1,474	1,474	1,474	1,474	1,474
CSP	200	300	500	500	500	500
Landfill	11	13	13	13	13	13
Hydro	14	14	14	14	14	14
Biomass	-	17	17	17	17	17
	3,169	**3,800**	**4,000**	**4,000**	**4,000**	**4,000**

2.7. Challenges of future demand for electricity in South Africa

Several challenges do exist in terms of future demand in electricity usage. Some of these are listed below:

(i) More than 70% of electricity in South Africa is generated by coal. In view of rising demand of coal worldwide, especially with demand in China coal prices are likely to rise markedly.

(ii) With an international concern in reducing the CO_2, coal fired power stations have to be limited as base loads.

(iii) The best option is the gas however the gas reserves are limited in the country, then would be expensive to import gas for base load stations.

(iv) South Africa has limited water supply to generate energy with hydropower stations.

2.8. Energy management in South Africa

In response to the shortage of energy supply in South Africa, the South African government introduced an energy white paper which was the premier policy document that guides all subsequent policies, strategies and legislations within the energy sector. Since 1998 government included demand side management (DSM) and energy efficiency (EE) measures in policy documents and legislations to encourage the consumption patterns. Energy saving initiatives were also included in both the National Energy Act 2008 and the Electricity Regulation Act 2006. Below is the brief discussion of policies, strategies and legislations on energy white paper.

(i) White Paper on Renewable Energy

It was published in November 2003 with the goal of outlining the policy theory of government`s vision and strategic objective of promoting the use of renewable energies and of informing the relevant institutions of their role in the process. This Act set the target of additional 10 000GW of renewable energy contribution to final consumption.

(ii) Integrated Resource Plan 2010 (IRP2010)

The demand profile for electricity over the next 20 years is determined in IRP2010 and details how this demand from various sources such as nuclear energy, coal, gas and renewable energies can be most effectively met.

(iii) National Energy Act

The National Energy Act of 2008 is the framework legislation that ensures diverse energy resources are available in suitable quantities and in affordable prices to the South African economy in support of economic growth and poverty alleviation. The National Energy Act also takes into account the environment management requirement, international engagement and responsibilities and interactions between the sectors of the economic, the establishment of institution responsibilities for promoting the efficient energy generation and consumption, energy modelling and preparation of increased renewable energies generation and consumption.

(iv) Electricity Regulation Act, 2006

Incorporates ambitious requirements to licence the investments into ripple control facilities, allowing it to remotely control supply of electricity.

(v) National Energy Efficiency Strategy (NEES)

In 2005T, NEES was released by Government of South Africa through the Department of Energy (DoE). This approach enables of low cost and no cost interventions as well as higher cost initiatives with short payback periods. These are generally followed by medium-term and longer-term energy efficiency investment opportunities. The strategy recognises that there is a substantial potential for progress in energy efficiency across all sectors of national economy. As well as sectoral energy intensity changes, the NEES set an overall reduction target in energy intensity of 12% by 2015, as follows: manufacturing and mining (15%), power production (10 %), transport (9 %), commercial and public construction sector (15 %), and residential sector (15 %). The NEES extracted its mandate on Energy Policy (1998) from the White Paper.

2.9. Demand side management

Demand side management is the mechanism by which the supplier of energy affects the way the consumers use electricity. DSM means preparing, execution and control of end-user activities to enable consumers to adopt their usage and track the level of electricity demand [34]. The supplier implements DSM techniques through direct or indirect control [61]. Any DSM technique implemented may result in one of the following forms of electricity demand reduction: Peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape [62] as shown in Figure 2.12

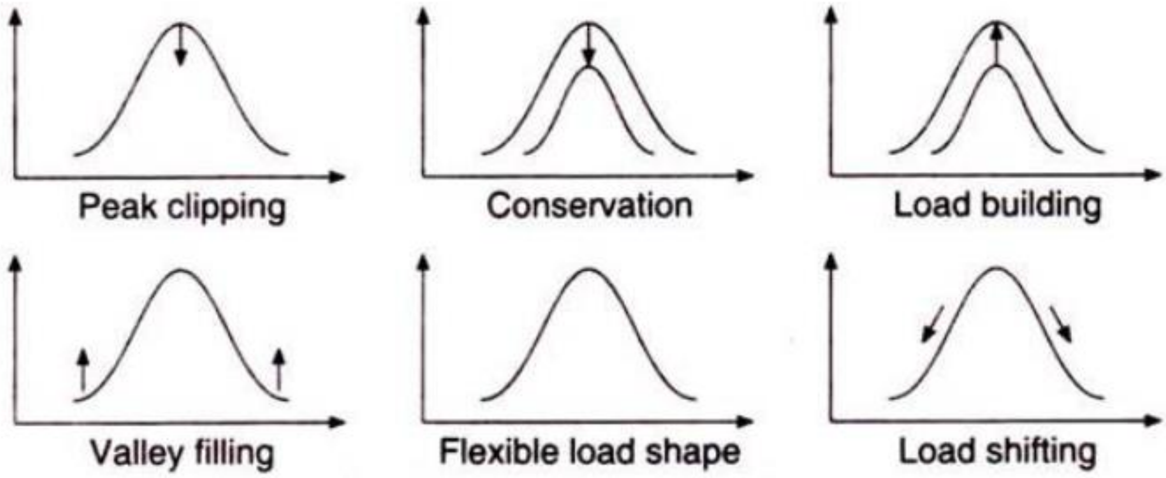


Figure 2.12: Techniques of demand side management load shaping.

The techniques of load shaping are explained in [63] as follows:

(i) Peak clipping is the technique used by utilities to reduce demand of customers` load profile at specific period by direct load control of equipment or use of tariff.

(ii) The technique Valley filling involves the decreasing the depth of valley demand by constructing the off-peak demand.

(iii) Strategic conservation is used by implementation of demand reduction approaches at customer side to achieve load shape. Conservation can minimise the load by using more energy efficient appliances or by reducing total consumption during the day.

(iv) The strategy is used to maximise load during the day by increasing the total consumption in a building.

(v) The technique of load shifting technique uses the time independency features of certain electrical appliances to move their usage from peak to non-peak.

(vi) Flexible load technique provides the smart grid reliability by locating flexible loads to customers who are willing to be controlled during critical demand periods in exchange of certain incentives.

2.9.1. Strategies of demand side management

DSM can be classified into two parts namely; Energy Efficiency (EE) and Demand Response (DR). Figure 2.13 shows the strategies of DSM. DR is classified into two main categories and subcategories as shown in Figure 2.13.

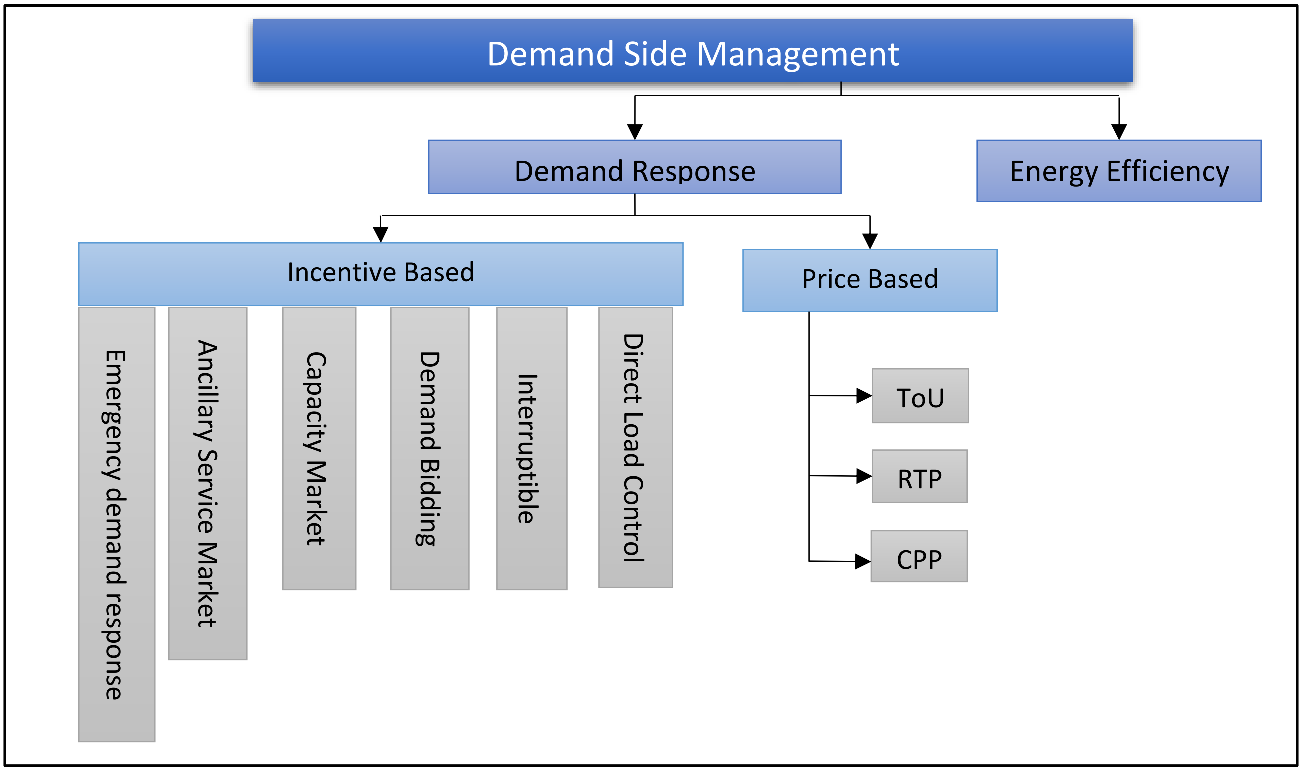


Figure 2.13: Strategies used in demand side management

EE is the DSM method for reducing energy consumption by replacing ordinary appliances with energy efficient appliances [64]. EE is defined in [65] as the theoretical minimum energy required for output of the mission and quantity of actual energy consumed, while authors in [66], [67] define DR as the changes in electricity use of end consumer in response to changes in electricity price over time from their usual consumption patterns. Moreover, customers participate in different schemes which are operated by the utility. The central component of DR initiatives is to motivate consumers to change electricity usage through incentives offered by the utility company. DR schemes are classified into two types namely incentive based scheme and price based scheme [68].

(i) Incentive based scheme.

Studies put forward by [68] explains that consumers are encouraged to reduce their energy consumption on the basis of incentive based deals or according or under a contractual agreement. This agreement is between a consumer and utility provider, which allows the program administrator some degree of authority to directly schedule, reduce or disconnect power so as to conserve energy. There are programs in incentive based energy management that give participating customers the load reduction incentives that are separate from, or additional to their retail electricity rates [69]. The programs included in incentive-based scheme as listed in [69] are as follows.

- *Direct load control.*

  Program operator shuts down electrical equipment remotely in short notice.
- *Interruptible/ curtail rates*

  In return for agreeing to reduce load during contingencies, consumers earn a rate discount or bill credit.
- *Demand bidding/Buybacks*

  Programs allow large customers to compete for wholesale electricity market and provide load discounts if they are willing to be reduced.
- *Emergency demand response*

  During the reliability triggered incidents, consumers receive bonus payments for the load reduction.
- *Capacity market*

  When system contingencies occur, customers commit to have pre-specified load reductions receive the assured capacity payments.
- *Ancillary service market*

  Customers sell load curtailments as operating reserves in a structured wholesale market.

(ii) Price based scheme

In price-based scheme, the customer is offered time varying rates that reflect the value and cost of electricity for different time periods [70]. The retailers offer the time varying tariffs such as Time of Use (ToU), Real Time Pricing (RTP) and Critical Peak Pricing (CPP). In ToU the electricity price depends on the time of the day and is pre-established and set in advance. In essence, ToU pricing divides the day into intervals and charges fixed rate within each interval of the day. While, CPP is a variant of ToU in which, the case of emergency situations such as high demand, the price is substantially raised. Whereas, in RTP, electricity prices can change as often as hourly, reflecting on the utility cost of the supplying energy to customers at that specific time.

2.9.2. Importance of demand side management

DSM is aimed to addressing the following issues as defined in [71]:

(i) Several DSM and EE efforts have been put in place with a sense of integrating resource planning aimed at reducing total cost and in meeting energy demand.
(ii) By minimising energy usage, leading to reduced greenhouse gas emissions, DSM and EE are strategies that are known to achieve environmental and/or social objectives.
(iii) Enhancing and/or averting electricity network problems by reducing demand in ways that sustain system stability.
(iv) Short term responses to electricity conditions (demand response), in particularly by reducing high market load periods triggered by reduced generation or capability of the network.

2.9.3. Challenges of demand side management

As summarised by [72], [73], to implement effective EE and DR is challenging in the sense that there is: (i) lack of knowledge and understanding EE, (ii) lack of communication between the consumer and the supplier, (iii) fear that EE will disrupt production or work process, (iv) lack of confidence in investing in EE programmes, (v) lack of investment in enabling DR technologies, (vi) lack of consumer engagement and (vii) poor consumer segmentation with regard to DR implementation.

2.10. Demand side management in South Africa

There had been mitigating measures that were implemented by the utility. Those included the implementation of demand response activities, techniques through direct and indirect control of large energy users such as the mine. Also included in the initiatives is the South African efficient lighting initiative. Among those activities and techniques implemented were the Time of Use tariffs, virtual power stations, demand market participation, load shifting, peak clipping, electricity pricing, national treasury tax incentives and Integrated Demand Management.

2.10.1. Policy framework

(i) Demand side management: Supply Side

Responding to Energy Act ,34 of 2008, the government licenced the fourteen renewable projects (driven by IPPs) for delivering power through Eskom`s main power grid so as to alleviate the energy crisis faced by the country. These projects consisted of wind and solar programmes providing more than 700 MW of energy.

In response to Integrated Energy Plan of 2003, Eskom uses the Integrated Strategic Electricity Planning (ISEP) to analyse usage patterns, growth trends and match these performance features of various generation technologies. ISEP concluded on options includes the return of mothballed coal fired stations (Camden, Komati and Grootvlei) that increased capacity with 3720 MW in 2006. The following table shows the mitigation by means of importing the electricity from neighbour countries, implementing the DSM programmes, purchasing from IPPs and the contribution of its own wind farm (Sere) as suggested by IRP2010.

Table 2.3: Mitigation measures: Supply Side. Source: [74]

Capacity (MW) and Capacity Margins (%) at Annual Peak													
Year	Annual Peak Demand Eskom	Eskom Installed Capacity	Import Capacity Firm	Total Eskom Installed Capacity plus Imports	Eskom Purchases Excl. RE	Renewable (RE) Incl. Sere	Other non-Eskom capacity	Total Country Capacity	Demand Marker Participation (DMP)	EE & DSM (MYDT)	Eskom Reserve Margin (Excl.RE & other purchases)	Eskom Reserve Margin (Inc. Imports, RE & Other)
	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	%	%
2008	35139	38844	1138	39982	0	0	0	39982	590	916	10.63	10.63
2009	35910	40544	1138	41682	0	0	0	41682	590	372	16.07	16.07
2010	36970	40981	1138	42119	517	0	0	42636	467	289	13.93	15.33
2011	36212	21201	1138	42339	862	0	0	43201	590	301	16.92	19.30
2012	35895	41695	1500	43196	1142	0	0	44338	651	447	20.34	23.52
2013	34979	41975	1500	43475	1327	0	1593	46395	3108	379	24.29	32.64
2014	34590	42308	1500	43808	13	1716	1500	47037	1737	294	26.65	35.98
2015	32985	42308	1500	43808	1162	2242	1500	48712	-	187	32.81	47.68
2016	34484	44034	1500	45534	1167	3253	1834	54788	-	196	32.04	50.18
2017	35324	45474	1500	46974	0	3912	1005	51891	-	-	32.98	46.90

The electricity power station capacity is being expanded by building the coal fired power stations (Kusile and Medupi) with capacity of 4800 MW each. The first unit of Kusile with capacity of 1588 MW will be operational and its commission date is expected to be September 2022. Unit 5 and 9 of Medupi has been commissioned and its operational as of 2020.

(ii) Demand side management: Consumer Side

To achieve the set strategy of reducing electricity consumption by 12%, the NEES initiated some programmes and regulations as follows:

- Appliance standards and labelling regulations were put in place with a sole purpose of ensuring that consumers are informed about the relative energy efficiency of an appliance during the purchase process.
- Minimum Energy Performance Standards (MEPS) (MEPS not voluntary but compulsory legal requirement) define the minimum level of energy performance that an appliance must meet or exceed before it can be sold. MEPS regulators have been put to protect consumers from purchasing appliances that are wasteful in terms of energy. MEPS are mandated by the Department of Trade & Industry (DTI) and enforced by National Regulator for Compulsory Standards (NRCS). The South Africa Bureau of Standards (SABS) is responsible for setting and publishing standards which manufacturers must meet.
- Energy Efficiency income tax allows the deductions in respect to energy efficiency. The provision came into effect on 1 November 2013. It allows taxpayers to claim deductions of 95% per KW equivalent, of energy efficiency saving made against the baseline measures at the start of each assessment year.
- Conditional grant was also put in place to assist the selected distributors with high load centres and electricity saving potential, so as to implement the energy DSM programs with the aim of reducing electricity consumption and mitigate the risk of load shedding and supply interruptions. The programmes solely focus not only on retrofitting the existing lighting technologies with efficient technologies but also the roll out of solar water heaters within selected areas.
- Government introduced energy and power restriction programmes including power conservation programmes. Energy power conservation scheme encourages large electricity customers to achieve energy efficiency by setting energy reduction targets. The users would receive an annual energy

allocation based on historical usage pattern. Exceeding this level would incur in stiff penalties and less usage would generate credits.

- In 2010 NERSA approved Incline Block Tariff (IBT) for Eskom and Municipalities. IBT divides the electricity price into several steps or blocks. As more energy is consumed, the blocks raise the price. Within this ambit, by just purchasing the electricity they will use during the month, consumers can save money. As a result, the implementation of IBT was an important step towards the effective use of electricity.

2.10.2. Technological mitigation measures

From demand side the smart grid initiatives which have direct impact on consumers to meet the goal of energy management and enable the consumers to be active participants in electricity system are as follows:

(i) Advanced metering system (AMI)

Responding to Electricity Regulation Act, 2006, Eskom initiated the rollout of the advanced metering infrastructure (AMI) commonly referred to as smart meter that measure energy in the time of use periods and manage the selected appliances through a control device. The appliance that might be switched off during peak periods, when implementing this initiative are geysers, swimming pool pumps, underfloor heating and air conditioners. It consists of meter with two bidirectional communication capabilities.

(ii) Dynamic pricing and demand response incentives

The use of dynamic pricing and demand response strategies have emerged as powerful DSM tools to optimise the energy consumption pattern of consumers and simultaneously improve the overall efficiency within the energy market [70]. However, in order to achieve these benefits from DR programmes, a certain level of automation is required both for uncertainty in consumer response to price signals and complexity for consumer to react to fluctuating daily electricity price [75].

In one study, optimisation-based Automatic Demand Response (ADR) controller was implemented in home energy management system to optimally co-ordinate the operation of different types of domestic appliance in response to dynamic pricing [75]. The proposed ADR was designed to find the best schedule in controlling appliances across a finite time zone in a day. This was done so as to minimise the daily bill below the consumer’s willingness to pay whilst achieving maximum satisfaction level. The energy payment reduction of up to 68% was observed and peak demand reduced below 4 kw threshold in 57% of the cases. The authors in [70] maximised peak load reduction for residential and commercial sector by 10% and 5% respectively by applying game theory to model price based demand response on three pricing models (real time pricing, time of use and day night pricing). Also, authors in [6] proposed the scheduling of appliances according to their category. A multi agent system (MAS) was integrated into the smart meter to alter the shape of residential load curve. The user preference was considered by designing a model with a direct load control. The simulation results showed that up to 58% of total residential energy consumption was saved during high power demand. More to that, the model predictive control (MPC) is an optional control technique that, at each time step, uses measurement of state and mathematical model of the system in order to predict the system evolution [76]. MPC has been applied in most research work because of its capability to determine the future behaviour of the system, considering the uncertainties in demand forecast, particularly driven by weather forecast and renewable energy generation forecast [77]. The central hub controller in centralised energy control system (CEMS) as suggested in [77] is executed with MPC core in its decision making. This is done by updating the inputs from the forecast values. MPC approach allows errors in forecasting methods to be identified and update the response in real time. It is proved that when using MPC considerable energy bill and savings of energy of about 17% and 18% respectively is realised over a day. The mathematical model used in each building incorporates parameter settings, external information and user preferences. The combination of air conditioning (A/C) use with operation on time-shiftable appliances has been investigated in [78]**.** A centralised model predictive control (MPC) scheme minimised the peak A/C energy use by altering the thermostat set points in individual homes and simultaneously scheduling the operation of time-shiftable appliances to further reduce the community peak load. The results showed that there was a minimisation of daily peak load 25,5 %.

The incorporation of artificial intelligence (AI) also referred to as Soft Computing Systems (SCAs) to make intelligent decisions in energy management has been studied and has yielded good results without the interaction of the consumer in controlling the appliances. Soft computing is basically optimisation techniques used to find solutions to problems which are very hard to answer and is based on techniques such as fuzzy logic (FL), artificial neural networks (ANNs) and genetic algorithm (GA). The evolution of SCAs dates way back as the 1940s, and till today the algorithms are still drawing the attention of the researchers globally. SCAs can be employed individually or in conjunction with each other to create a numerical or analytical model to solve engineering problems. On one hand, ANNs and GA are data driven optimisation techniques that are not restricted to the constraints of mathematical functions. FL, on the other hand, employs verbal statements in solving problems [79]. As an example, it has been shown in [67] that up to 20% of energy consumption can be realised by using multi-agent system (MAS) for the distributed control system that aims to address the peak load problem with the cyber-physical systems. The control decision process of the system implements an Artificial Neural Network Algorithm to determine the state of consumption of any controlled device connected to the smart grid.

Further example as demonstrated by [80], artificial intelligence technologies approaches, using sensors, was incorporated to make intelligent decisions based on the occupant`s pattern and preference changes. In this study the results showed that there was a 33.95% improvement in energy reduction. In this study, the authors integrated the rule based algorithm to the programmable communicating thermostats (PCTs) so that they can adapt the occupant`s pattern and preference changes. Set of rules [IF-THEN] is use in to design an intelligent algorithm PCTs to facilitates the interaction between device and user in order to change or adjust set values of a day as a solution in response to changes in environmental conditions such as ambient temperature, electricity price or user pattern.

(iii) Home energy management system (HEMS)

HEMS is a technology platform comprising of both hardware and software that allows the user to monitor the energy usage and production, and manually control and/or automate the use of energy within a household. Homes today are equipped with many appliances and electricity devices that consume a significant amount of energy daily. HEMS enable households to effectively centralise the management of services in the house, providing them with a round of functions for internal information exchange and help to keep them in contact with outside world [81]. The HEMS manage the consumption by communicating with household appliances and receive the information such as tariff prices from the utility through the smart meter [82]. Such wireless sensor network technologies provide the home appliances with a link to communicate with the outside world. For instance, [83] reports in one of his work that 18% of energy saving was obtained by using the HEM when it incorporated Wi-Fi technology for data transmission inside home and GSM technology for external communication. The authors considered the activity state (occupancy) of home residents and controlled the operation of home appliances in line with space state requirements. As important tool for DR, HEMS shift and limit the household appliances energy consumption with a view of improving the energy efficiency [84]. Apart from using HEMS alone, recent literature has also shown that HEMS can be integrated with AI to provide an automated energy control based on a learning profile of appliances in any home. For instance, the use of artificial intelligence for load scheduling in HEMS has been investigated. Authors in [85] proposed a HEMS that used the Wi-Fi for communication between controlling nodes, IOT for internal data exchange and fuzzy logic for performing the load and battery management. They simulation results demonstrated the energy reduction of 35% a day.

2.11. Summary

The outlook and background of energy particularly the electrical energy and its challenges has been outlined in this chapter. We further elaborated on the undergoing mitigating measures towards energy consumption. Particularly, this chapter emphasised on policy driven measures and technology driven measures. The focus was to alert the reader to different means that are applied in demand side management of energy consumption.

Chapter 3: Application of fuzzy logic in energy management

3.1 Introduction

Fuzzy logic concept and the mathematics behind the fuzzy logic are presented in this chapter. This chapter concludes with the related work on the application of fuzzy logic in energy management.

3.2 Fuzzy logic concept

Professor L.A. Zaden introduced the idea of fuzzy logic in 1965 to formalise the mathematical approach to deal with complex decisions. In contrast to classical or discreet values of either 0 or 1 (true or false), fuzzy systems are useful into two general contexts, in the form of several value logics in which true values of the variables can be real numbers between 0 and 1. The use of fuzzy systems is beneficial in following:

(i) in a situation involving highly complex system whose response is not well known and whose conduct is not well understood, and

(ii) in a case where it is necessary, but the quick solution is warranted.

These systems, however, are defined as shallow models in the sense that they are mainly used in reasoning which are deductive, the reasoning where we infer the particular from general [86].

Fuzzy logic operates on a principle based on assumptions and on the basic of sets to determine the output. The linguistic variable defining the possible output state is represented by each set. Depending on which output is expected, any possible state of input and degrees of change of the state are part of set. Using membership functions, the fuzzy sets are graphically represented and the output is determined on basis of degree of each membership in each part of the function. The IF-ELSE logic determines the membership of set. The set variables are the state of inputs and the degree of changes of the input and output membership depends on the logic of AND function of the input state and input change rate. The variables can also be different inputs for multi-input system and output can be the product of AND operation between variables.

The fuzzy logic system is made up of four elements namely fuzzifier, fuzzy rules, inference and the defuzzifier and three stages (input, processing and output) as shown in Figure 3.1.

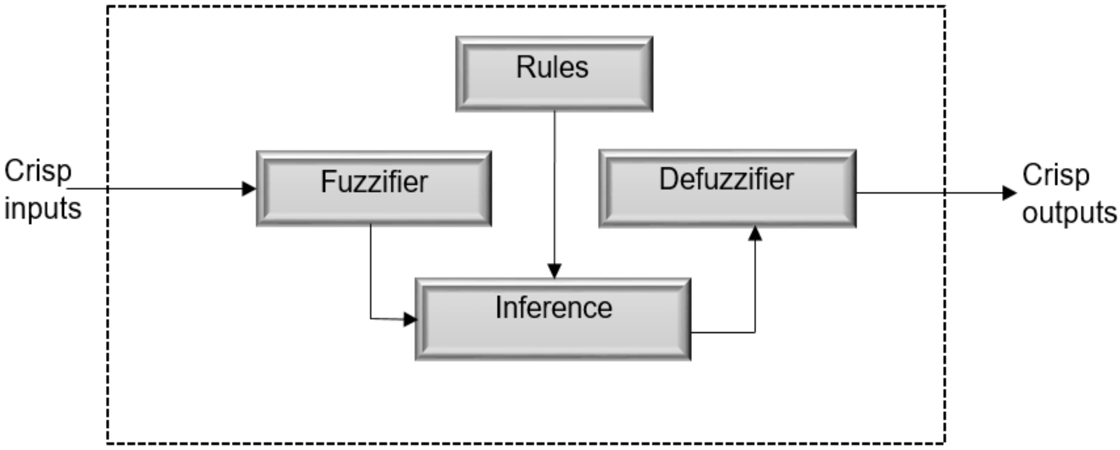


Figure 3.1: Fuzzy logic components

The input stage maps input (like from sensors and switches) to suitable membership sets, functions and truth values. In order to produce results for each inference, the processing stage invokes each appropriate rule and then incorporates the results and rules. The output stage turns the cumulative outcomes back into a particular control output.

There are three key sections of a fuzzy system: linguistic variables, membership functions and rules. The input in FLS which are linguistic and are in form of words or sentences from natural language are mapped by sets of membership function. The process of converting the input crisp values to fuzzy values is called fuzzification. Given the mapping of input crisp values to fuzzy membership functions and truth tables, the rules are made for what actions are to be taken based on predetermined set of rules. These rules are designed in order to control the variable at the output. A fuzzy rule with a condition and conclusion, is a simple IF-THEN rule. The steps in reasoning of FLS is referred to as inference, and which is the part of taking decision by combining the rules and input crisp of the system to generate the fuzzy output crisp. The ultimate outcome after inference is a fuzzy value that is then defuzzified to obtain final crisp output.

3.3. Mathematical and graphical concept of fuzzy logic

Fuzzy logic starts with the universal information which is the collection set of all-natural number system, the set of alphabets that is discrete and finite or continuous and infinite. These universal sets are denoted as follows:

$$A = \{ \frac{\mu_A(x_1)}{x_1} + \frac{\mu_A(x_2)}{x_2} + \ \ldots\ldots\ldots \}$$

$$A = \{\sum_{i=1}^{n} \frac{\mu_A(x_1)}{x_1} \quad (3.1)$$

And when universal information is continuous or infinite:

$$A = \{\int \frac{\mu_A(x)}{x}\} \quad (3.2)$$

Where A is the subset of the universe set, $x_1, x_2, \ldots$ ...are the members of A and $\mu_A(x)$ is the membership function of x in A.

3.3.1. Fuzzy sets

The fundamental concept of fuzzy logic is a fuzzy set. For example, let $\boldsymbol{X}$ be the universal set (universe of discourse) that contains all possible elements having in nature or property under consideration. The rule helps us to decide whether or not any unique element of universal set belongs to a determined set. Any set is the subset of universal set. The set is denoted by capital letters such as A**, B, C** and members or elements by small letters e.g., $\boldsymbol{a, b, c, x}$. To denote if the element is the member of set or not, certain notation functions are used. For example, if $\boldsymbol{x}$ is the member of A, can be mathematically denoted as: $\boldsymbol{x} \in A$

whereas $\boldsymbol{x}$ is not the member of A, $\boldsymbol{x} \notin A$

and A is the subset of universal set $A \subset \boldsymbol{X}$

Crisp set is classical set where member can be either in set or outside the set while fuzzy set member can be particularly in the set. For crisp set, the value is assigned 0 or 1 (true or false) since it follows the binary system of the universe. Classical mapping is defined *characteristic function*, for given set A, this function assigns the value:

$\mu_{\boldsymbol{A}}(\boldsymbol{x})$ to every $\boldsymbol{x} \in \boldsymbol{X}$

using Boolean function, we have a true or false (1 or 0).

$$\mu_{\boldsymbol{A}}(\boldsymbol{x}) = \begin{cases} \mathbf{1}, & \boldsymbol{x} \in \boldsymbol{X} \\ \mathbf{0}, & \boldsymbol{x} \notin \boldsymbol{X} \end{cases}$$

and this function is referred toas *discrimination function* since it discriminates between the elements of the universal set that belongs to a set and those which do not belong, i.e.: $\mu_{\boldsymbol{A}} : \boldsymbol{X} \rightarrow [\mathbf{0}; \mathbf{1}]$

A membership function is the curve that specifies how each point in a point is mapped (or degree of membership) between 0 and 1 and is denoted as:

$$A = \{(\boldsymbol{x}, \mu_{\boldsymbol{A}}(\boldsymbol{x}) \mid \boldsymbol{x} \in \boldsymbol{X}\} \quad (3.3)$$

In this case let X be the set of universal

Where A is the subset of the set of the universe, x_1, is the member of A and $\mu_A(x)$ is the membership function of x in A.

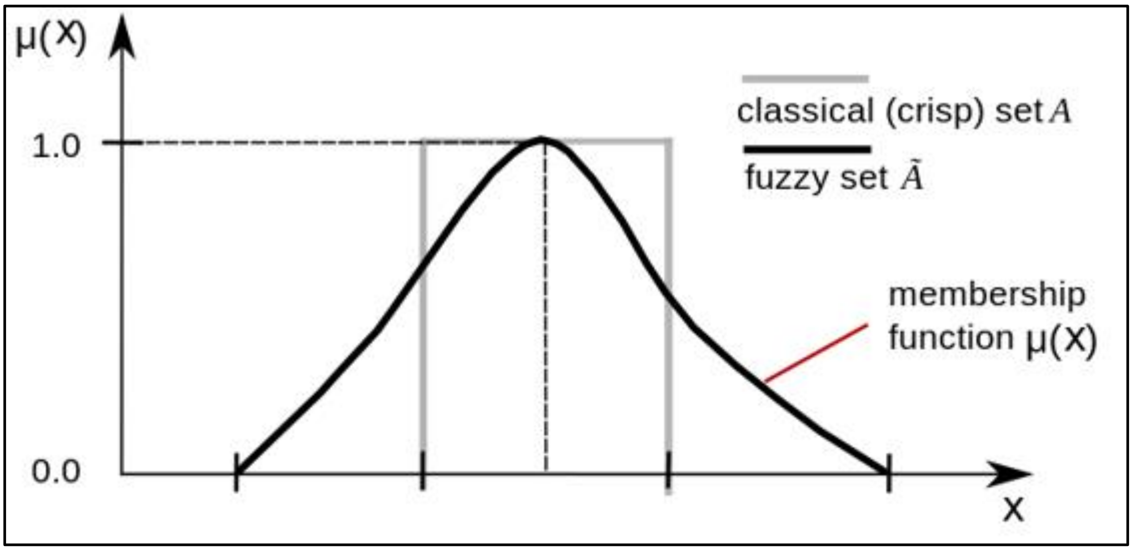


Figure 3.2: Membership function of fuzzy Set

The membership function which represents a fuzzy set A is usually denoted by μA. For element $\boldsymbol{x}$ of $\boldsymbol{X}$ is $\mu_{\boldsymbol{A}}(\boldsymbol{x})$ as presented in Figure 3.2. The core of membership function for any fuzzy set A, is the region in the universe that is defined by complete membership in the set and includes of all elements $\boldsymbol{x}$ of information such that, $\mu_{\boldsymbol{A}}(\boldsymbol{x})$= 1 as shown in Figure 3.2. Even though there are several membership function shapes in fuzzy systems, the most commonly used shapes are triangular, trapezoidal and gaussian. The triangular function is described by lower limit **a**, an upper limit **b** and value of **m** where **a<m<b** as shown in Figure 3.3 and equation 3.4.

$$\mu_A(x) = \begin{cases} 0 & x \leq a \\ \frac{x-a}{m-b} & a < x \leq m \\ \frac{b-x}{b-m} & m < x < b \\ 0 & x \geq b \end{cases} \qquad (3.4)$$

Where $\mu_A(x)$ is the membership function of element x, a denotes the lower limit, b the upper limit and the value of m where $a < m < b$.

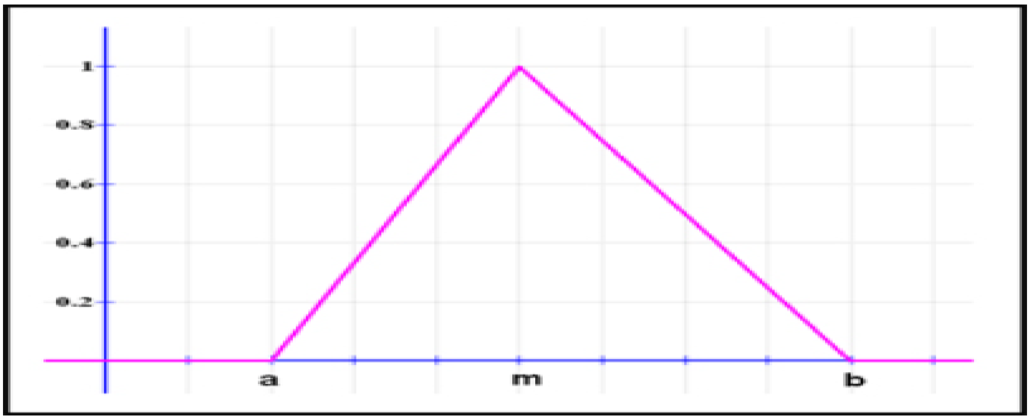


Figure 3.3: Triangular membership function

Trapezoidal function is defined by the lower limit **a**, an upper limit **d**, a lower support limit **b** and the upper support limit **c** where **a<b<c<d** as shown in Figure 3.4. The trapezoidal membership function is mathematically expressed by the following equation.

$$\mu_A(x) = \begin{cases} 0 & (x < a) or\ x > d \\ \frac{x-a}{b-a} & a \le x \le b \\ 1 & b \le x \le c \\ \frac{d-x}{d-c} & c \le x \le d \end{cases} \quad (3.5)$$

a is the lower limit, b is the lower support limit, c is the upper support limit and d is the upper limit where $a < b < c < d$.

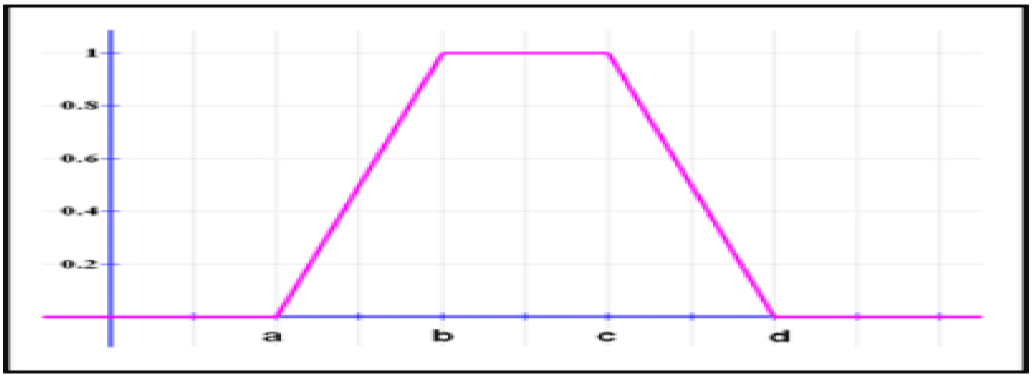


Figure 3.4: Trapezoidal membership function

Gaussian function is defined by the central value of **m** and standard deviation **k>0**. The smaller the **k** is, the narrower the “bell” is. The function is mathematically expressed as follows.

$$\mu_A i(x) = e^{-\frac{(x-m_i)^2}{2k^2}} \quad (3.6)$$

Where m_i and k_i are the centre and width of the i^{th} fuzzy set A^i respectively.

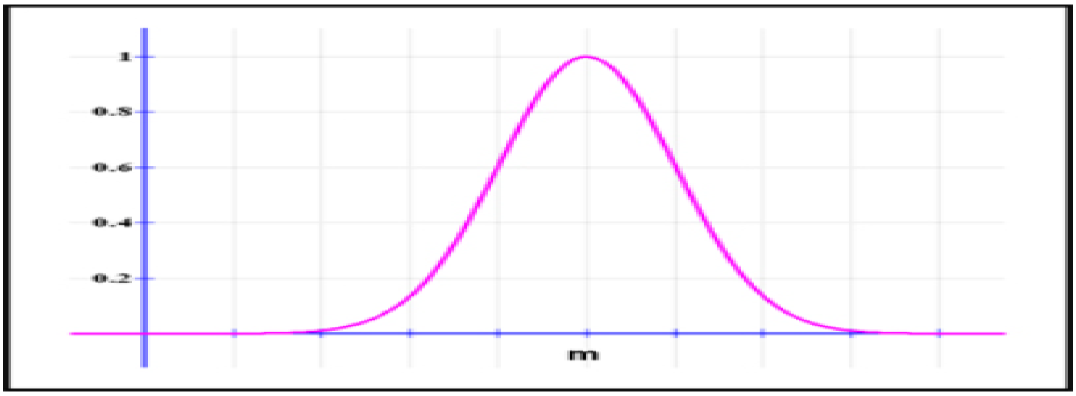


Figure 3.5: Gaussian membership function

Supporting the membership function for any fuzzy set A, is the area of the universe that is defined by nonzero membership in the set. The centre therefore consists of all elements $\boldsymbol{x}$ such that, $\mu_{\boldsymbol{A}}(\boldsymbol{x}) > 0$

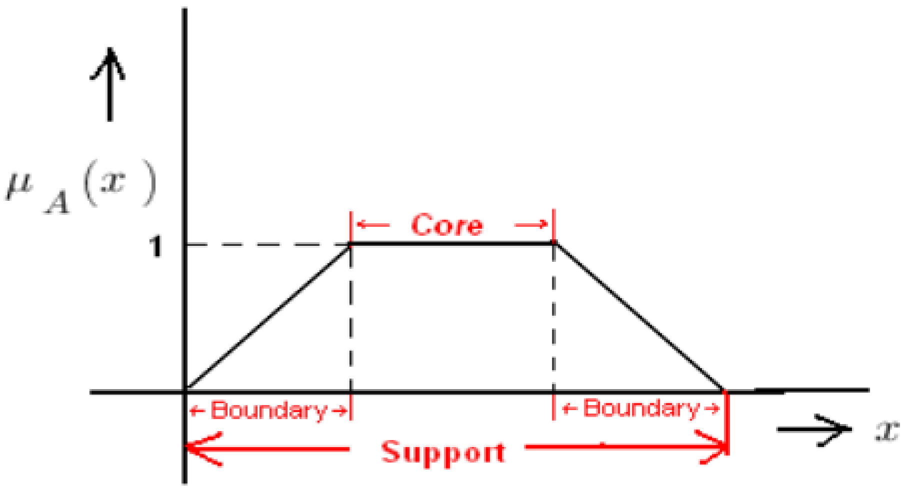


Figure 3.6: Features of membership function.

For any fuzzy set A, the boundary of membership function is the region of the universe that is characterised by a non-zero but incomplete membership function. Hence, core values consist of all elements of $\boldsymbol{x}$ of information such that,

$$1 > \mu_{\boldsymbol{A}}(\boldsymbol{x}) > 0$$

3.3.2 Fuzzy rules and decision making

A rule base consists of a collection of linguistic statements known as rules that are invoked to combine the inputs and outputs. These rules are IF antecedent and the

THEN consequent. The output of the fuzzy set can be single fuzzy set or union of two or more fuzzy sets.

Let fuzzy set with n-rules

R_1: if $\boldsymbol{x_1}$ is A_1 then y = B_1

R_2: if $\boldsymbol{x_2}$ is A_2 then y = B_2

R_n: if $\boldsymbol{x_n}$ is A_n then y = B_n

The case for output y is possibly be $\boldsymbol{B} = \boldsymbol{B_1} \cup \boldsymbol{B_2} \ldots \boldsymbol{B_n}$

For t-input-1 output fuzzy system with rules:

$\boldsymbol{R^i}$: IF $\boldsymbol{x_1}$ is $\boldsymbol{S_1^i}$ AND $\boldsymbol{x_2}$ is $\boldsymbol{S_2^i}$ …AND $\boldsymbol{x_t}$ is $\boldsymbol{S_t^i}$ THEN $\boldsymbol{y}$ is $\boldsymbol{A^i}$

Where $\boldsymbol{x_1}, \boldsymbol{x_2} \ldots \boldsymbol{x_t}$ is applied, the degree of firing can be determined by:

$$\mu_{S_1^i}(\boldsymbol{x_1}) * \mu_{S_2^i} * \ldots \mu_{S_t^i}(\boldsymbol{x_t}) = \boldsymbol{T}_{l=1}^{t} \mu_{S_l^i} \quad (3.7)$$

Where $\boldsymbol{S}$ and $\boldsymbol{T}$ denotes the operation applied to the fuzzy sets.

3.3.3. Operations of fuzzy sets

Since the membership function specifies fuzzy set, the operations should work with the membership function.

For example, if A and B are sets, and if there is a universe of information $\boldsymbol{X}$ and an element $\boldsymbol{x}$, the relation expresses the union (or disjunction), intersection (or conjunction) and compliment of fuzzy set. In making the fuzzy rule the concept of "**and**", "**or**" and sometimes "**not**" is used. The combination operators are also referred to as T-norms.

(i) Intersection/ Fuzzy "AND"

The intersection of set A and B is denoted as follows:

$$\mu_{A \cap B} = T\,(\mu_{\boldsymbol{A}}(\boldsymbol{x})\ ;\ \mu_{\boldsymbol{B}}(\boldsymbol{x})) \quad (3.8)$$

The two most common techniques to compute the "and "are:

- Zadeh – min ($\mu_A(\boldsymbol{x})$; $\mu_{\boldsymbol{B}}(\boldsymbol{x})$) computes the "and" by taking minimum of two (or more) membership values.
- Product - $\mu_{\boldsymbol{A}}(\boldsymbol{x})$; $\mu_{\boldsymbol{B}}(\boldsymbol{x})$ computes the "and" by multiplying two membership values.

Both techniques have the following properties.

T (0; 0) = Ta 0 =T (0; a) = 0

T (a; 1) = Ta 1 = a

The fuzzy "and" is the extension of Boolean "and" to numbers that are not just 0 or 1 but between 0 and 1.

Table 3.1: Fuzzy "AND" truth table

Input 1 (A)	Input 2 (B)	Output A "and" B
0	0	0
0	1	0
1	0	0
1	1	1

Figure 3.7 represents the minimum operation.

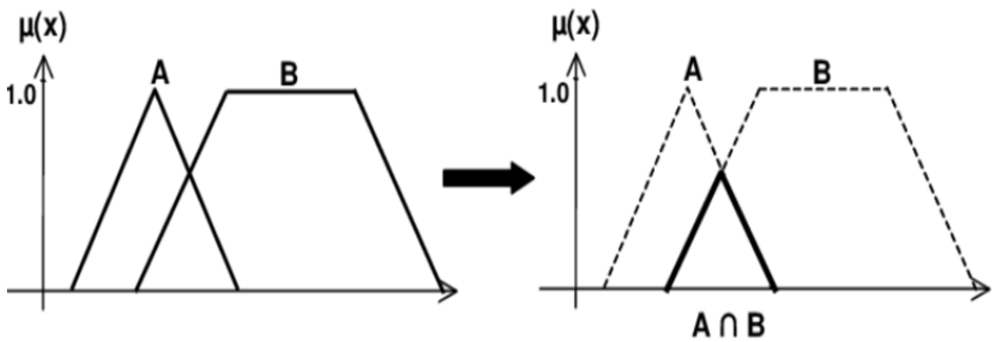


Figure 3.7: Intersection / Fuzzy "AND" operation

(ii) Union / Fuzzy "OR"

The union of A and B is $\mu_{A \cup B}$ = T $(\mu_A(x); \mu_B(x))$ (3.9)

Similar to fuzzy "and" there two most common techniques to compute the "or "

- Zadeh – max $(\mu_A(x); \mu_B(x))$ (3.10)

By taking up to two (or more) membership values, technique computes the fuzzy "or" and is the most common method of computing fuzzy "or".

- Product - $\mu_A(x) + \mu_B(x) - \mu_A(x) . \mu_A(x)$ (3.11)

The difference between the sum of the two or more membership values and product of the membership values is used this technique.

Both strategies have following characteristics:

T (a; 0) = T (0; a) = a

T (a; 1) = T (1; a) = 1

The fuzzy "or" is the extension of Boolean "or" that are not just 0 or 1 but between 0 and 1.

Table 3.2: Fuzzy "OR" truth table

Input 1(A)	Input 2 (B)	Output A "or" B
0	0	0
0	1	1
1	0	1
1	1	1

Figure 3.8. represents the maximum operation of fuzzy sets.

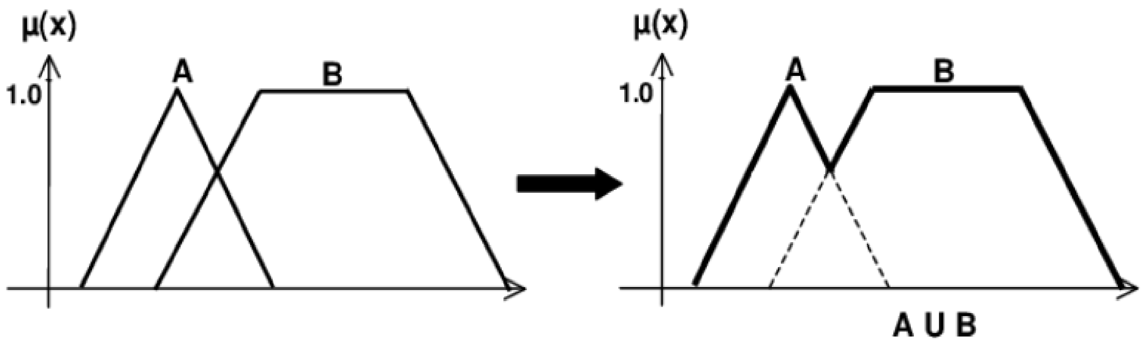


Figure 3.8: Union /Fuzzy "OR" operation

(iii) Complement/ Fuzzy "NOT"

A complement of fuzzy set A has a membership that is pointwise described for all $x \in X$ by:

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x) \quad (3.12)$$

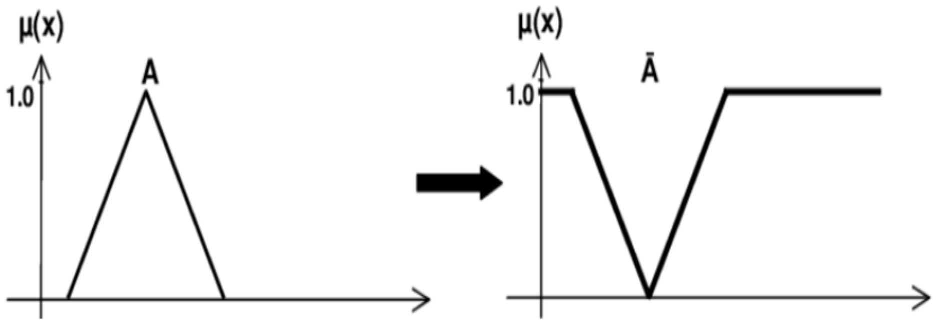


Figure 3.9: Complement/Fuzzy "NOT" operation

3.3.4 Defuzzification

It is necessary to defuzzify the result so that it must be converted to a crisp result. The process of defuzzification is often called "rounding it off" mathematically. There are several methods of defuzzification but the most popularly used are centroid method and mean of maximum. The basic principle of center of gravity (COG) is to find a point of $\boldsymbol{x}$ coordinates (x^*) in which the sum will be cut into two equal masses by vertical line. It is possible to mathematically express COG as follows:

$$X^* = \frac{\int \mu_A(\boldsymbol{x})\boldsymbol{x}\, \boldsymbol{dx}}{\int \mu_A(\boldsymbol{x})\boldsymbol{dx}} \tag{3.13}$$

Where: X^* is the $\boldsymbol{x}$ coordinates of center of gravity and denoted by:

$$\frac{\sum_{i=1}^{n} \mu_A(x_i)x_i}{\sum_{n=1}^{n} \mu_A(x_i)} \tag{3.14}$$

And $\int \mu_A\,(\boldsymbol{x})\boldsymbol{dx}$ denotes the area of region bounded by the curve μ_A.

Graphically COG is expressed as follows,

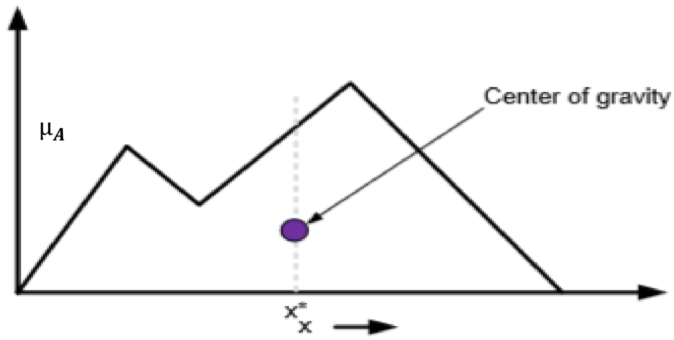


Figure 3.10: Center of Gravity Defuzzification

Maximum of mean (MoM) is also known as the middle of the maxima. The outcome reflects the mean value of all activities whose membership functions reach the maximum and is given by:

$$X^* = \sum_{i=1}^{n} \frac{x_i}{n} \tag{3.15}$$

And graphically expressed by:

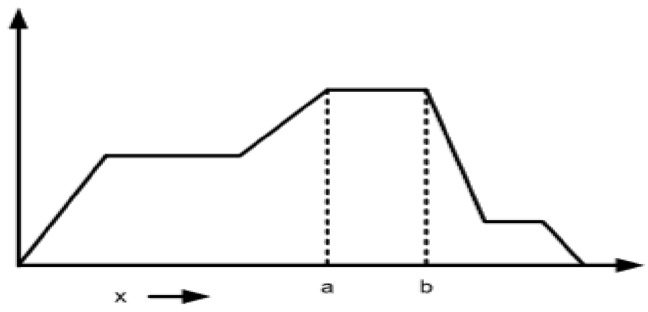


Figure 3.11: Maximum of Mean Defuzzification

3.4. Fuzzy logic in energy management

The increasing energy demand, increasing energy price and imbalance between the energy demand and supply demonstrate the need and importance of energy management. Load forecast/prediction, load shifting/scheduling, consumer behaviour modelling, thermal and illumination control and hybrids can assist with better optimisation methods in energy management and energy efficiency. Among many optimisation techniques in literature, fuzzy logic has expressed best results through its capabilities to reduce the uncertainty in measurement of nonlinear input variables.

Table 3.3: Application of fuzzy logic in energy management

Technique	Area of research	References
FIS	Load forecast Hybrid	[80], [81], [82], [85], [86], [87]
Fuzzy, CBA	Load forecast	[95]
FIS	Load shifting	[83], [84]
FIS-AG_0	Load shifting	[88]
AFLL	Thermal /illumination control	[89]
ANFIS, CG, EMPC, HMM	Occupant behaviour modelling	[93], [94]
FIS- IoT	Thermal illumination control	[90]
FLS, FLDC, FLID	Hybrid	[92]
FIS, Cuckoo Search	Hybrid	[95]
FIS, HGA	Hybrid	[97],[98]

3.4.1. Load forecasting and prediction

It is important for building owners and independent power producers to forecast the energy management and higher prediction accuracy that can significantly lower energy consumption in buildings in order to incorporate different building energy output and energy efficiency, such as demand response [87]. Moreover, the load forecasting in buildings offers the advantages to determine the energy behaviour, load pattern and trends. Several occupant behaviours, load forecast using fuzzy techniques models have been developed in literature. Extant literature such as in [88] used fuzzy logic to forecast day to day electricity usage in individual housing by implementing short term load consumption (STLC). Their model was based on effective and feasible of storage system management by turning on/off appliances to conserve energy and by extension reduce the cost of electricity usage. Their model was able to manage the electricity consumption and reshaped the load profile. Authors in [89] proposed a fuzzy logic procedure-based approach, with energy consumption modelling to derive rules from input variables and provide long term annual forecast of electricity demand. The study used the population of a country and the GDP of the country as variables. The results were compared with official projections and %age mean error of 1.46% was produced by the model.

It is necessary to understand the typical trend and energy usage of the target household when designing an efficient energy generation system. There is a probability of simulating potential energy demand, to schedule initiative to manage energy and to design appropriate techniques [89] on bases of traditional appliance patterns for each household. In addition, the simulation of consumer behaviour and habits also add an advantage in demand prediction by reducing the inherent risk in the implementation of strategies for demand side management [90]. The application of fuzzy inference system (FIS) was presented in [91], in modelling the occupancy behaviour and habits of domestic electricity use based on the size of the photovoltaic (PV). They modelled the likelihood of each appliance being connected to the grid and this was used as the FIS output. With electricity demand data recorded over a duration of a year in twelve buildings, the model was validated. The results correctly sized the PV plant according to the cost benefit analysis (CBA). Introduction of an ex-ante assessment of the benefits of the energy management (EM) method in residential scenario was presented in [92]. The model used to measure the EM benefits, consisted of the precise fuzzy modelling and cost benefit analysis to determine the actual economic benefits of load shifting analysis. The relevant consumer sensibility to a fair use of energy is taken into account in this model. To set an upper limit for the particular household EM equipment expense, the model used the analysis process. The CBA was carried out for various sizes of PV plants and different number of loads to be shifted in order to determine the economic convenience for PV system and load shifting policies. The core of the model considered the intelligent load shifting to minimise energy payment and maximise the PV self-consumption. The shifting of residential electricity demand from PV production during off peak hours to on peak production maximised savings. The results showed the efficacy of load shifting interventions quantifying users' savings both for new and existing PV installations. Moreover, the CBA reported that the economic convenience all PV systems sizes is closely linked to the matching of output and consumption pattern.

Authors in [93] built the bottom-up approach FIS model using the patterns of occupancy and domestic habits. The FIS model gave the starting probability of each appliance in order to create a minimum resolution of electricity demand data. The model demonstrated good performance in the simulating of energy behaviour of household. Actually, the results had less than 18% root mean square error (RMSE). Moreover, 9% of daytime duration allows for its use for demand response planning and energy management systems. Authors in [94] presented fuzzy logic customer response prediction model to forecast the customer`s knowledge of the concept of real time pricing, their flexibility in changing their consumption pattern and the degree of incentive provided by utility provider in terms of price adjustment. The focus of their study was on predicting how different consumers will act their level of awareness, versatility and added incentive in real time pricing, which in turn will form the overall future demand. The best results were obtained when the level of versatility and understanding among customers was highest and the level of motivation needed to impact the customer was generally low. This was the great benefit for the utility. The results also demonstrated that the high levels of flexibility and understanding are crucial to effective implementation for dynamic pricing to work. However, more effort was needed in terms of sensitisation so as to market the dynamic pricing schemes to ordinary people.

Based on practice and theory, energy policies are, mostly, formulated on a traditional view of human decisions. The decisions concerning the energy are influenced by the consumer economic concept and consumer energy behaviour which then can serve as the basis in policy making. Fuzzy logic has been used to integrate the behavioural economic concept to residential energy behaviour modelling for the purpose of policy making in [95]. In the sense of residential cooling energy consumption, their model characterised and predicted consumer energy efficiency and curtailment behaviour taking into account monetary, personal comfort and environmental responsibility to determine purchase and use behaviour of air conditioning predictions. The finding of their model may be of interest to decision makers since they have shown that reducing cooling energy would significantly reduce energy consumption by 30%.

It is possible to evaluate the peaks and valleys influencing the performance power systems through load curves. Overall, such oscillations are the result of shifts in consumer behaviour [90]. The application of fuzzy was presented in [90] simulating the behaviour of residential sector in terms of energising the appliances and lights in home. At given time of the day, their approach yielded the curves showing the activation profiles of appliances and lights. The authors built the residential load curve based on home appliances. With primary focus on appliances that led to the formation of load peaks in the overall curve, the authors analysed the load curves for each appliance. Their finding showed that most f of curve peaks and valleys are formed by residential sector.

3.4.2. Load shifting / scheduling

The increase in number of automated electrical appliances may result in an increase in inefficient energy use in the buildings. To encourage the load reduction during peak hours, the utilities may introduce incentive driven pricing schemes like RTP and ToU. Note withstanding the above schemes it is, however, difficult for users to manually respond to such incentive-based schemes. The integration of wireless sensors, artificial intelligent technologies like fuzzy logic to make intelligent decisions has contributed significantly in energy management of systems. For load reduction in residential HVAC system, the fuzzy logic approach (FLA) utilising wireless sensors and smart grid incentives was presented in [96]. The FLA was embedded into PCTs for intelligent decision in load reduction while maintaining the thermal comfort considering price, outdoor temperature and occupancy. In order to apply suitable fuzzy rule(s) for load reduction, the model constantly tested the initialised set point of HVAC along with the data from sensors and smart grid. A possible saving of approximately 478 kWh was shown by the one-month energy consumption using FLA, where all sensors and smart grid incentives were activated. Authors in [97] presented an adaptable local control and intelligent decision making for a home automation using multi-agent techniques. Each agent used fuzzy logic controller to manage consumer`s energy consumption. The study considered all kinds of residential load and it executed a scheduling policy algorithm using AG_0 that made joint decisions with respect to the user comfort and desire. The developed AG_0-FLC successfully altered the load curve shape and results showed an energy saving of up to 58% of the total residential energy consumption in period of when the utility had high power demand.

3.4.3. Occupant behaviour modelling

Modelling the occupant behaviour with respect to energy consumption in building mainly aims to reveal the interaction between humanity and energy use. Most of the studies investigated have used a techno-economic analysis of user behaviour and expenditure. For example, the integration of adaptive neuro fuzzy inference system (ANFIS), cost generator (CG), economic model predictive controller (EMPC) and Hidden Markov Model have been investigated in [98] to model behaviour and compute the sum of personalised cost, time of use charges prediction from load curve and fixed energy of heat, ventilation and air conditioning (HVAC) in their personalised energy management system (PEMS). The EMPC optimises the energy consumption using the classical constrained optimisation model that specifies comfort margins of an occupant. In order to predict the occupant behaviour, ANFIS behaviour model uses the forecast information on temperature, humidity, prediction on occupancy from HMM information on current hour of a day, historical activity information and type of the day. The PEMS report showed a 9.7%-25% reduction in energy consumption and 8%-18.2% cost reduction.

3.4.4. Thermal and illumination control

Controlling and predicting thermal comfort in buildings is essential considering the fact that the ambient temperature in households fluctuates. Usually, it is much easier to design the thermal comfort of fewer households and people. However, it becomes more complicated to design the thermal comfort for more people and more buildings as the personal experience or perception differs from one person to another. The need for automation in thermal comfort is important concerning the energy management that becomes an integral part of our daily lives. Adopting the revised models of thermal comfort takes the designers one step further towards energy efficiency in design of the building and relates indoor temperatures to occupants and their activities within the building as well as to the broader building environmental context [99]. It is also important to know whether or not the occupant is in controlled space and when the building is occupied, for the control system to function differently on providing thermal and illumination comfort.

The integration of fuzzy logic, sensors and IoT has been considered in [100] to control the specific temperature of specific room taking into account the outdoor conditions and humidity to obtain the outdoor temperatures. They authors automated the thermal comfort system using fuzzy rules considering the outdoor temperature. The model collected the data from sensors and IoT platforms. Fuzzy was used to perfume inferences. From the degree of truth table of each linguistic variable, the centre of the gravity was selected in order to take input of the next step. Model of fuzzy approach achieved around 40% energy saving. Also, the authors in [101] further considered the integration of supervised fuzzy logic learning (SFLL), wireless sensors abilities and dynamic pricing to control the HVAC in a residential building. In case the user overrides the made autonomous decisions, the adaptive fuzzy logic model (AFLM) was incorporated to the system to detect, learn and adapt the new user's preferences. The results of SFLL simulation coupled with thermostat for load reduction with respect to energy saving for one-month was around 21.3% where no user interaction was required. In case that the user overrode the initialised set points the AFLM was capable to learn and adapt new preferences and it demonstrated 1.03% reduction. Notwithstanding the above, authors in [102] integrated fuzzy logic in their energy management system to control the illumination. The sensors of their system used to detect the environment conditions for outdoor light user occupancy, indoor lighting and electricity price to the illumination controller. The fuzzy logic was used to adjust set points of illumination considering the sensor inputs. There were two modes of lighting system operation: manual and autonomous mode. Set points of illumination were set manually by user in manual mode, while fuzzy logic was used to set illumination in autonomous mode. The effects of input parameters were studied within the 24-hour period and the results showed that the energy consumption without supervised fuzzy logic learning (SFLL) was less than where SFLL was used in isolation. In addition, the consumption with price excluded was more than consumption with price included.

3.4.5. Hybrid

Renewable energies have gained the opportunity in energy market due to the steady decrease of fossil fuels used in energy production and consumption, the environmental concerns, global warming green gas emissions and global concern in rapid energy demand growth. Renewables sustain the operation of power source which are used to extract the maximum power either from solar PV, wind and hybrid systems. The advancement of technology has made it possible to integrate the renewable energy systems into the grid for energy sustainability. Extant literature has shown that fuzzy logic has been investigated in hybrid systems. For instance, an intelligent control system strategy based on fuzzy logic was introduced in [103]. The study, facilitated the improvement of electrical network stability on an active standalone generator. The generator controller provided for continuous generator by changing the grid voltage and frequency to maintain the continuous supply load in event of grid failure. The controller had three components: The first was the fuzzy logic supervisor (FLS) which managed the power flow to keep the direct current (DC) bus voltage constant in order to deal with load, wind power variations and grid fluctuations by maintaining batteries and super capacitors (SC). The second was the fuzzy logic drop control (FLDC) which was used to control the transferred active and reactive powers with grid thus, ensuring its stability. Lastly the fuzzy islanding detection (FLID) which ensured the transition between the grid to its guaranteed stability. The simulation results showed the validity of the intelligent control strategy proposed. The authors in [104] presented a study of using a hybrid system generator, PV and energy storage system (ESS) instead of standalone generator. The study considered the cost of electricity (COE) and carbon gas (CO_2) emission. The novel model was designed to control and operate a hybrid system. The fuzzy logic control (FLC) system was able to ensure that any renewable energy available was completely stored or utilised while reducing the run time of the generator while preserving the balance between supply and load demand all times. The control was handled by fuzzy control and its output was generated on set of fuzzy values from several fuzzy memberships with two inputs of SC and solar irradiance. The performance of system was evaluated using MATLAB/Simulink and the results showed a significant reduction of COE and CO_2 emission reduction as compared to standalone generator system of 12.7 % and 25% respectively. The authors in [105] optimised fuzzy logic in operating standalone hybrid system that consisted of PV array, diesel generator and power bank based on cuckoo search algorithm. Fuzzy logic was incorporated to monitor the hybrid system configured as power system for typical remote residential area. Batteries that provided the net power flow were FLC inputs and ratings of the batteries, PV and diesel generator were FLC outputs. Weekly solar irradiation data, ambient temperature and load profiles that were used by cuckoo search algorithm to tune the controller. The optimisation model was simulated using cuckoo search algorithm to obtain the optimal control of hybrid power system that used a loss of power supply probability (LPSP), excess energy (EE) and levelised energy cost (LEC) techniques. The FLC was able to minimise the LPSP, EE and LEC. Moreover, the results of CS optimisation compared with particle swarm optimisation (PSO) for fuzzy logic demonstrated better results. Authors in [106] presented a decision making for micro grid power flow management designed with renewable energy sources and energy storage system aimed at optimising the monetary benefit main grid trading. The focus was on the application of Hierarchical Genetic Algorithm (HGA) for turning the rule base of fuzzy inference system (FIS) and in trying to minimise the fuzzy rule set as core inference engine of an energy management system. The performance comparison performed well with an approach based on classic fuzzy –HGA scheme where FIS parameters and rule weights were tuned, while number of fuzzy rules was fixed in advance. The experiment showed that the fuzzy-HGA adopted the synthesis of controller outperformed fuzzy-GA schemes increased monetary profit by 67%.

3.5. Summary

In this chapter, we discussed the fuzzy logic concepts and mathematics behind fuzzy. The four main stages in fuzzy operation were discussed. The defuzzification of inferred rules were explained and the graphical and mathematical expression of defuzzification methods were presented. The chapter concluded with the application of fuzzy logic in energy management.

Chapter 4: Research methodology and design

4.1. Introduction

In this chapter the detailed methodology and system design is discussed. The arrangement of conditions and activities that were performed to collect the information that aims to combine the relevance to the research purpose are presented. This chapter determines the fuzzy logic controller functionality and its architecture and explains in details how it has been designed and developed to control and enhance the electrical energy consumption.

4.2. Design science research methodology

Design science research methodology (DSRM) is the methodology that not only describe, explain and predict the problem but develops the artefact that can assist individuals to meet their needs, resolve their difficulties and seize new opportunities [11]. In [12] DSR is explained as the paradigm with basic knowledge theory, understanding of design problem and its solution obtained in construction and application of artefacts. Artefact is the man-made object with purpose of being able to use it to solve the practical problem [11].

4.3. Design science research methodology (DSRM) process

The main objective of the design science research methodology is to consolidate the existing knowledge in design science to aid the exploration and design and resolving problem. It seeks to overcome the dichotomy that exists in the field between theory and practise to enable researchers to find solution to problem [107]. Therefore, to establish a widely agreed paradigm based on the concepts of design science. The broad principles of design science are conceptual principles which define what research in design science research is, the rules of practise in design science research and processes involved [108]. The framework resulted in process with six steps processes to be followed when conducting DSRM.

The sequential order process of DRSM is described in Figure 4.1 as adapted from [109] and [110].

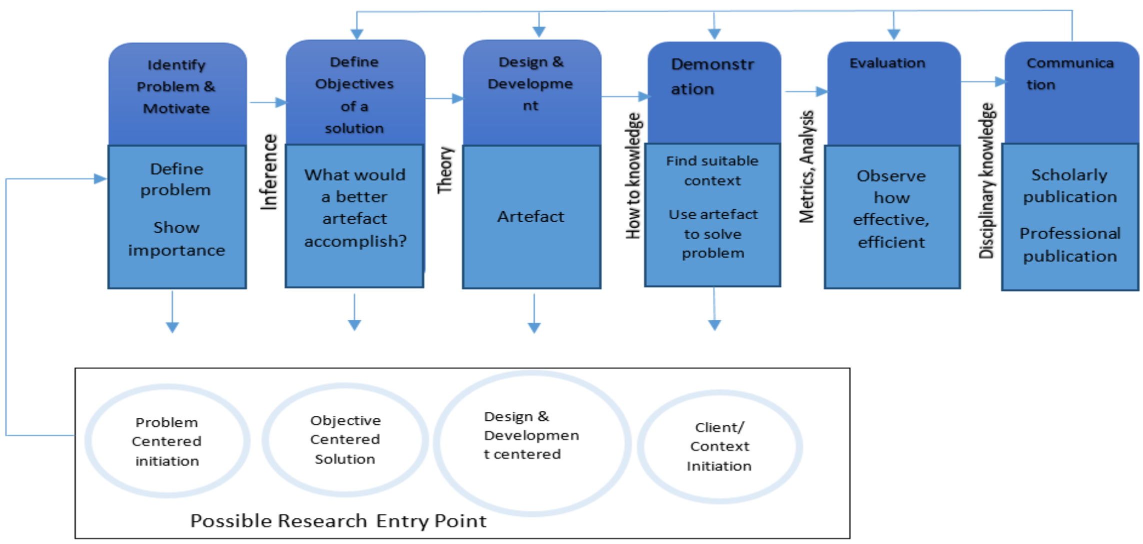


Figure 4.1: Design science research methodology process [109], [110]

(i) Problem identification and motivation

Define the particular problem of the study and explain the importance of the solution. Since the description of problem can be used to develop a realistic and a factual solution, it may be beneficial to conceptually atomize the problem so that the solution can capture the complexity of problem. Knowledge of the state of the issue and the relevance of the solution are the tools needed for this operation. With regard to this study research problem and suggested solution is: Even though, there have been number of mitigating measures put in place that includes government policy and framework, demand side strategies (demand response) to motivate the consumers to adjust their patterns in electricity consumption, South Africa is still facing the challenge of high demand and increasing cost of electricity. Therefore, the study seeks to integrate the artificial intelligence system that will be able to make intelligent decisions without interaction of the consumer. The proposed solution is the development of fuzzy enabled intelligent system for intelligent decisions in controlling the residential end users considering the dynamic pricing.

(ii) Objectives of a solution

Infer a solution`s goals from the description of the problem Objectives may be objectives like terms where the desired solution will be better than the existing ones or quantitative, e.g., where it is assumed that have not been discussed before. From the problem definition, the targets should be inferred rationally. Awareness of the status of the issues and existing proposals and their effectiveness are the tools needed for this. The objectives of this study are to:

- Design the fuzzy logic enabled system that will be able to manage the amount of electricity as desired by the consumer for the given time frame.
- Use fuzzy logic to enhance the electricity consumption scheduling of household appliances in response to the ToU tariffs.
- Design the fuzzy logic rules that will switch off the appliances in an orderly manner to achieve objective (i) and (ii).

(iii) Design and development

Creating the solution using the artefact. Such artefacts are potentially, with each defined broadly, constructs, models, methods, or instantiations [11]. The task involves deciding desired functionality of the artefact and its layout and designing the actual artefact afterwards. Resources needed to shift from objectives to development and implementation include theoretical information that can be brought to bear as a solution. In this study the MISO heuristic ruled based fuzzy logic controller is designed to control and reduce the residential electricity consumption and cost.

(iv) Demonstration

Demonstrate the use of artefact to address one or more situations. This could involve its use in experiment, simulations, case study and proofs. Resource required for demonstration is the knowledge of how to use the artefact to solve problem. The LabVIEW VI 2019 was used to develop the fuzzy logic controller and real time simulation experiments.

(v) Evaluation

Observe and assess how well the artefact supports a solution to the problem. This practice includes contrasting the expectations of a solution to real outcome found in the demonstration of the artefact. Knowledge of appropriate metrics and techniques for analysis is required. Technology skills and knowledge are not only demonstrated by the research, but it is also necessary to analyse, explain and evaluate the artefacts [15]**.** Part of DSR process is to analyse the performance of the designed artefact in order and understand the artefact, the qualitative or quantitative methods obtain the opportunity to be utilised [14]**.** The study followed the quantitative method to rigour the demonstration and evaluation of artefact results. The results were presented descriptively in form of tables and graphs.

(vi) Communication.

It requires the knowledge of the disciplinary culture to convey the problem and its significance, the artefact, its usefulness and novelty, the rigor of its design, and its effectiveness to researchers and other applicable audiences through scholarly research publications. The finding of this study will be communicated through the dissertation and the scholarly publications.

The DSR is structured in a sequential order with 4 entry points corresponding to the main steps however there is no expectation that the researcher would always actually proceed in sequence.

- Problem centered initiation – approach is the nominal sequence if the idea is from the observation of problem or suggested future research from previous work.
- Objective centered solution- could be by product of consulting experience
- Design and development centered initiation- approach result on existence of artefact that has not been formally thought through.
- Client/Context initiation- might result in design science solution if researcher work backward to apply rigor to process.

The mapping of this study with design science research is summarised in Figure 4.2

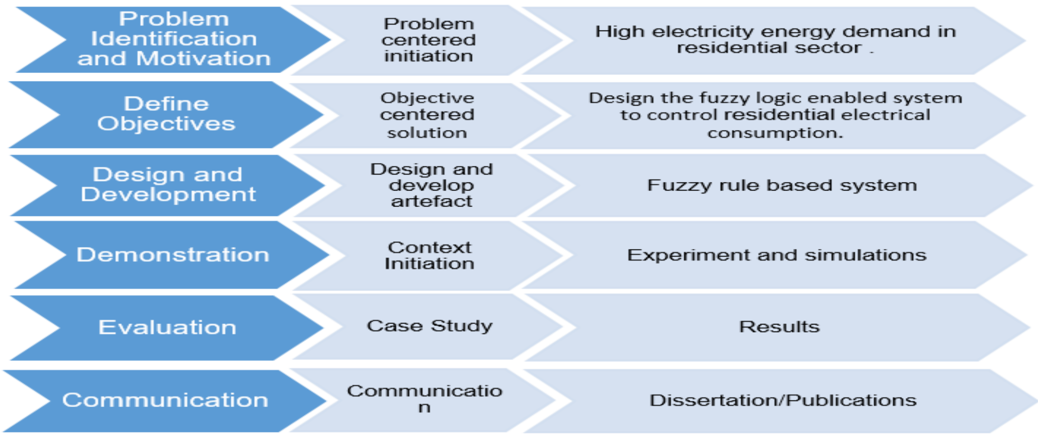


Figure 4.2. Design process flow of fuzzy rule based system

4.4. Research design and development

The study used Multi-Input-Single-Output (MISO) heuristic rule based fuzzy logic controller simulation. The simulator was implemented using Laboratory Visual Instrument Engineering Workbench (LabVIEW) 2019. LabVIEW is National Instruments ` system design platform and development environment for language of visual programming. LabVIEW has the advantage of being the development environment for developing the measurements, automation, test and control system. Its graphical programming language has visual instruments that consist of front panel and block diagram. For this study LabVIEW was used to control the energy consumption, cost of various input parameters considering the demand side management activities such as ToU tariffs.

4.4.1. Fuzzy inference of rule-based controller

Fuzzy inference is the method by which the mapping is formulated from given input to an output. Then the mapping provides the basis from which the option can be made or patterns descend. The fuzzy inference process involves all parts defined in membership function, logical operation IF…THEN rules.

Fuzzy inference process comprises of five parts as shown in Figure 4.3

(i) Fuzzification of the input variables

The first step is to take the inputs and determine the degree to which they belong to each of appropriate fuzzy sets through membership function.

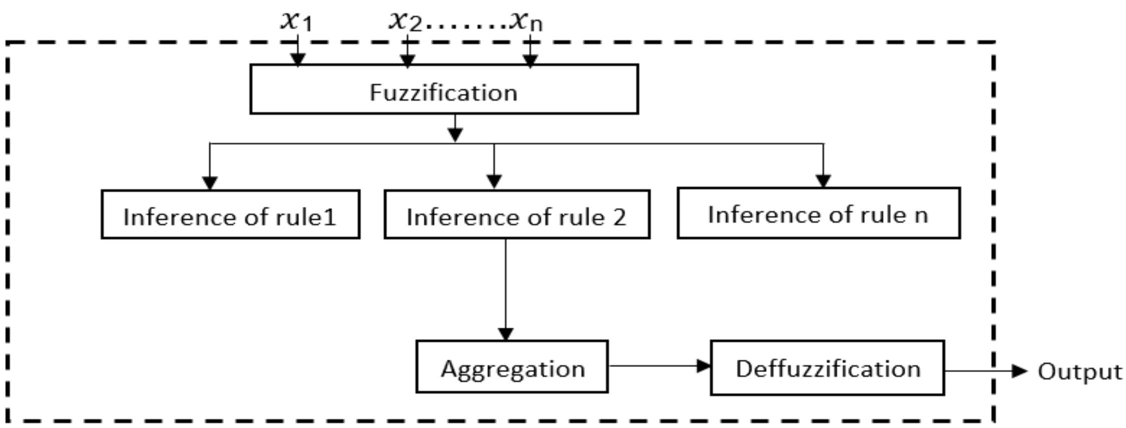


Figure 4.3: Fuzzy inference of fuzzy rule based controller

(ii) Application of fuzzy operation (AND or OR) in antecedents

After inputs are fuzzified and the degree is known then a certain part of antecedent is satisfied for each rule. If antecedent of fuzzy has more than one part, the fuzzy operator is applied to obtain one number that represents the result of antecedent. In fuzzy toolbox, there are two built in AND methods: the min(minimum) and prod (product) methods. Two built in OR methods are also supported: max(maximum) and probabilistic OR method (probo). The general state evaluation fuzzy rule in case of Multi- Input-Single-Output is in form of:

$R{:}\, IF\ x_1 = B_1 \ldots .AND\ x_n = B_n, THEN\ Z\ is\ C_1,$ and

$R{:}\, IF\ x_1 = B_1 \ldots .OR\ x_n = B_2, THEN\ Z_1\ is\ C_1\ OR\ Z_2\ is\ C_2$ for Multi-Input-Multi-Output

Where x_1 and x_n are the linguistic variables representing the process state and control variable(inputs), respectively the B_1 and B_n are the linguistic values of the control variables. Z is the linguistic variable of the output with the value C_1.

In this type of fuzzy control more than one rule may fire at the same time.

(iii) Application from the antecedent to consequents

The weight of each rule (a number from 0 through 1) is added to the number specified by the antecedent. The application method is applied after proper weighting has been allocated. The outcome is reshaped by the feature associated with the context (a single number). The input is the single number given by the antecedent for application method, and the output is a fuzzy set.

(iv) Aggregation of the consequents across the rules

Since the decisions are focused on testing, it is important to combine all rules of fuzzy inference in some way. Aggregation is the method by which the fuzzy sets representing each rule`s outputs are combined into a single fuzzy set. For each output variable that is before the final defuzzification stage, aggregation occurs only once. The input of the aggregation process is the list of compressed output functions returned by the implication process for each rule. One fuzzy set for each output variable is the output of the aggregation process.

(v) Deffuzzification

The fuzzy set (the aggregate fuzzy set) is the input for deffuzzification process and the output is a single number. As much as fuzziness assists the rule assessment during the intermediate stages, a single number is normally the final desired output for each variable. However, fuzzy set aggregate encompasses a number of output values, so that a single output derived from the set must be defuzzified.

4.4.2. Designing the MISO rule based fuzzy logic residential energy controller

With the objective of enhancing the residential electrical energy consumption, the fuzzy rule-based controller was designed to switch off and on the appliances in household considering the dynamic pricing and remaining desired daily electricity limit. With given amount of electricity and desired number of days the daily electricity limit is calculated. To design the controller, the four steps were followed:

(1) Identification of input and output variables

The performance of fuzzy controller depends on the correct choice of the parameters and proper membership functions being specified. In this study, the parameters that directly relate to the electricity control were considered and taken into account as the inputs. These parameters are load consumption, electricity price and remaining daily electricity limit. The load status is only the output that controls the load to switch ON or OFF.

(ii) Creating and labelling the membership functions (MFs)

The membership function shape does not really have impact in the fuzzy controller performance. Instead of choosing the shape of membership function, setting the intervals and number of membership functions are very important [111]. The only condition of membership function that must be really satisfied is that it must vary between 0 and 1. The triangular membership function has been chosen for its simplicity and fast in computation. All inputs of the controller have three membership function and output has only two membership functions.

- Input Load Consumption

The consumption of the load has been identified as one of the variables that has an impact in high energy and the increase of the energy cost in households. The input control was sampled to total consumption of 15 kw/h. The consumption amount is converted to %age in respect to remaining daily limit using the following equation.

$$Load\ consumption\ \% = \frac{load\ consumption}{remaining\ daily\ limit}\ X\ 100 \qquad (4.1)$$

The membership function parameters of the consumption were sampled as shown in Figure 4.4 within a range from 0 to 100%

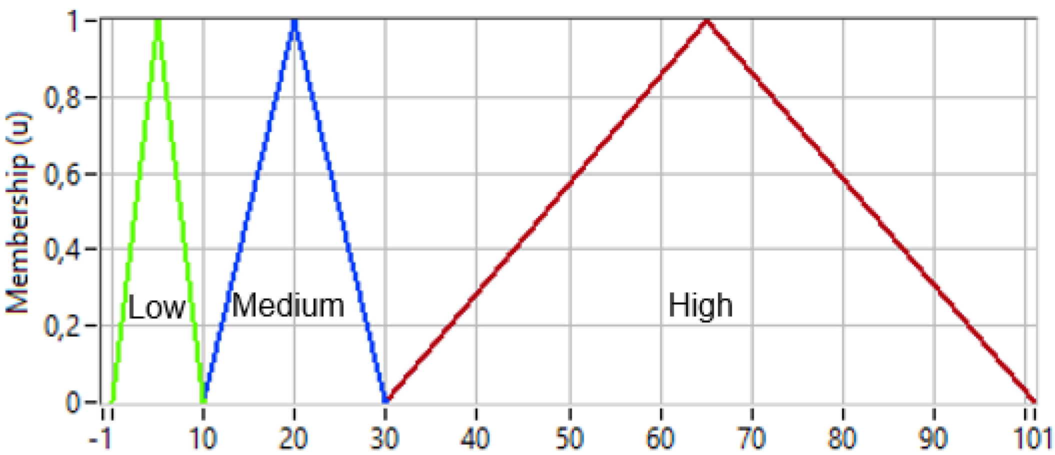


Figure 4.4: Appliance load consumption membership functions (kw in %age)

It is possible to state the mathematical equations of the membership functions shown in Figure 4.4 as follows:

$$\mu(C)_{Low} = \begin{cases} 0 & C \leq 0 \\ \frac{C-0}{5-0} & 0 < C < 5 \\ \frac{10-C}{10-5} & 5 < C < 10 \\ 0 & C \geq 10 \end{cases} \quad (4.2)$$

$$\mu(C)_{Medium} = \begin{cases} 0 & C \leq 10 \\ \frac{C-10}{20-10} & 10 < C < 20 \\ \frac{30-C}{30-20} & 20 < C < 30 \\ 0 & C \geq 30 \end{cases} \quad (4.3)$$

$$\mu(C)_{High} = \begin{cases} 0 & C \leq 30 \\ \frac{C-30}{65-30} & 30 < C < 65 \\ \frac{100-C}{100-65} & 65 < C < 100 \\ 0 & C \geq 100 \end{cases} \quad (4.4)$$

where C is the load consumption in %age

- Input Electricity Price (P) in cents

Advanced meter infrastructure normally known as smart meters has an advantage of supplying the customers with the real time energy usage, energy cost data to assist the customers on how can they effectively manage their consumption. Reducing consumption during peak periods can result in cost and high demand reduction. In this study to facilitate the two-way communication that AMI is capable of, Figure 4.5 illustrates the electricity price membership functions read from the smart meter during peak, standard and off-peak periods. The prices are fixed in cents for each period and charged per second.

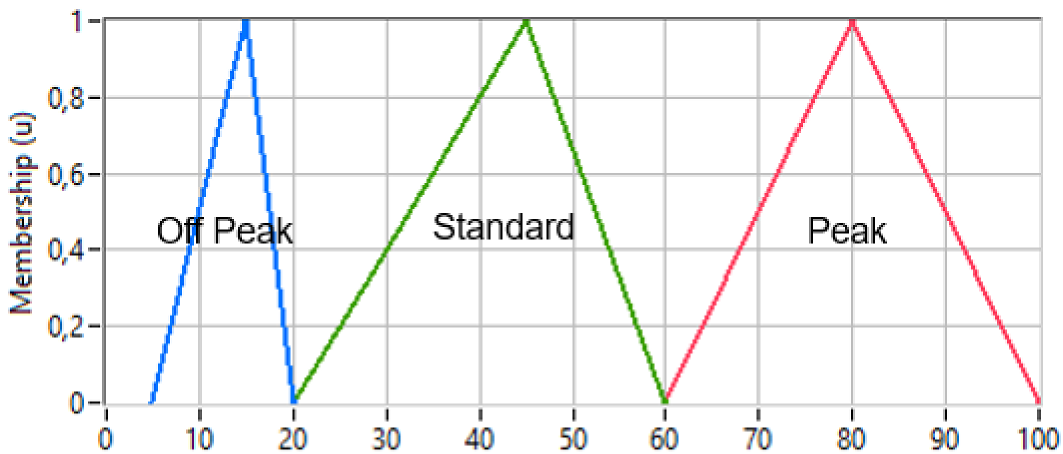


Figure 4.5: Electricity price membership functions in cents

Three membership functions in Figure 4.5 were designed to separate the demand response tariffs namely off peak that cost 15c, standard that costs 45c, and peak that cost 80c.

$$\mu(P)_{offpeak} = \begin{cases} 0 & P \leq 5 \\ \frac{P-5}{15-5} & 5 < P < 15 \\ \frac{20-P}{20-15} & 15 < P < 20 \\ 0 & P \geq 20 \end{cases} \quad (4.5)$$

$$\mu(P)_{standard} = \begin{cases} 0 & P \leq 20 \\ \frac{P-20}{45-20} & 20 < P < 45 \\ \frac{60-P}{60-45} & 45 < P < 60 \\ 0 & P \geq 60 \end{cases} \quad (4.6)$$

$$\mu(P)_{peak} = \begin{cases} 0 & P \leq 60 \\ \frac{P-60}{80-60} & 60 < P < 80 \\ \frac{100-P}{100-80} & 80 < P < 100 \\ 0 & P \geq 100 \end{cases} \quad (4.7)$$

- Input remaining daily electricity limit (RDL)

The prepaid smart meter was chosen for the study with user`s desired amount of electricity. The remaining electricity daily limit was then calculated by subtracting the used electricity from the initial daily limit. The remaining daily limit in %age was then the input of fuzzy controller with three triangular membership functions (less, enough and adequate) as shown in Figure 4.6.

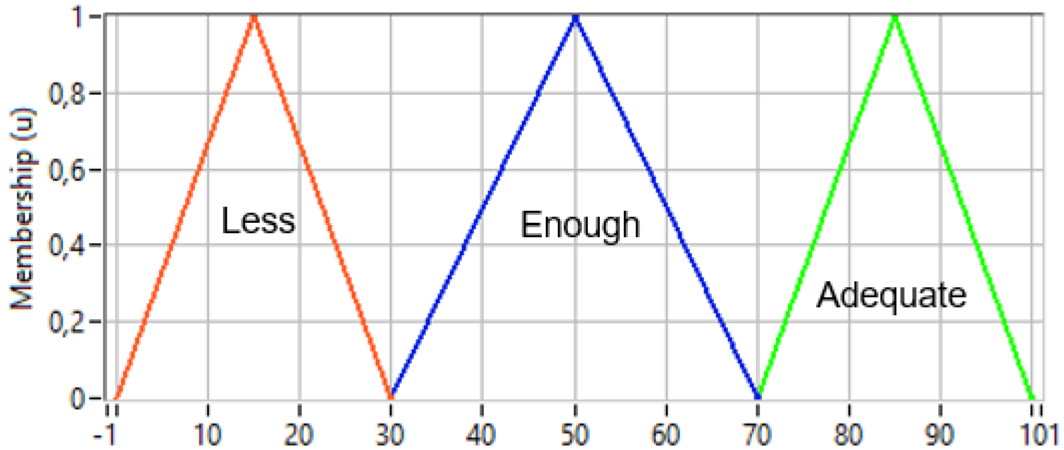


Figure 4.6: Remaining electricity daily limit membership functions (kw in %age)

The triangular membership functions of the available electricity are mathematically expressed by the following equations:

$$\mu(RDL)_{Less} = \begin{cases} 0 & RDL \leq 0 \\ \frac{RDL-0}{15-0} & 0 < RDL < 15 \\ \frac{30-RDL}{30-15} & 15 < RDL < 30 \\ 0 & RDL \geq 30 \end{cases} \quad (4.8)$$

$$\mu(RDL)_{Enough} = \begin{cases} 0 & RDL \leq 30 \\ \frac{RDL-30}{50-30} & 30 < RDL < 50 \\ \frac{70-RDL}{70-50} & 50 < RDL < 70 \\ 0 & RDL \geq 70 \end{cases} \quad (4.9)$$

$$\mu(RDL)_{Adequate} = \begin{cases} 0 & RDL \leq 70 \\ \frac{RDL-70}{85-70} & 70 < RDL < 85 \\ \frac{100-RDL}{100-85} & 85 < RDL < 100 \\ 0 & RDL \geq 100 \end{cases} \quad (4.10)$$

- Output load status (LS)

Load status was the only output of the controller. Figure 4.7 shows the system output membership function. The defuzzified output value determines whether, during specific time, the appliance should be ON or OFF on basis of the outputs aggregation from all rules specified. For presentation purposes in this study the ON and OFF values were converted to %age.

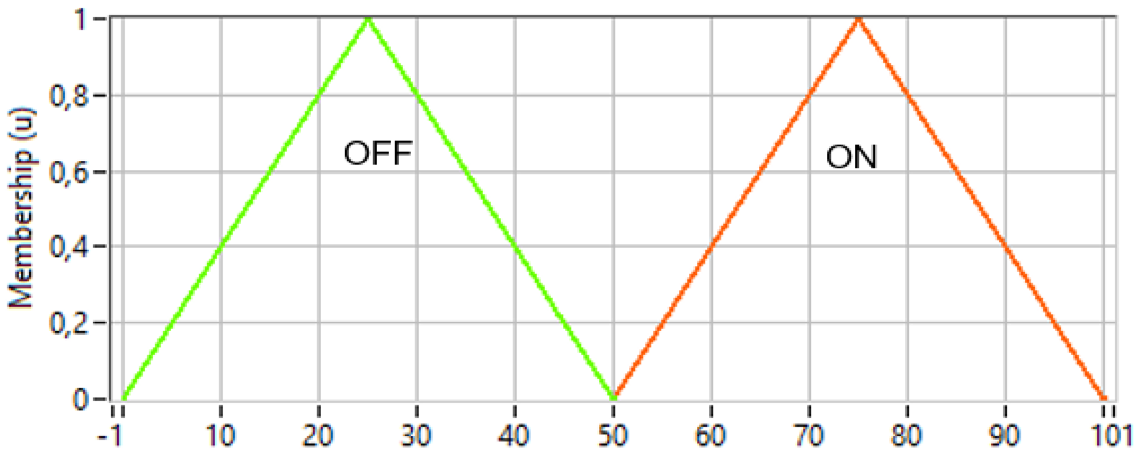


Figure 4.7: Load status of the appliance membership functions in %age)

Mathematical expression of Figure 4.7 is:

$$\mu(LS)_{off} = \begin{cases} 0 & LS \leq 0 \\ \frac{LS-0}{25-0} & 0 < LS < 25 \\ \frac{50-LS}{50-25} & 25 < LS < 50 \\ 0 & LS \geq 50 \end{cases} \quad (4.11)$$

$$\mu(LS)_{on} = \begin{cases} 0 & LS \leq 50 \\ \frac{LS-50}{75-50} & 50 < LS < 75 \\ \frac{100-LS}{100-75} & 75 < LS < 100 \\ 0 & LS \geq 100 \end{cases} \quad (4.12)$$

(iii) Building fuzzy rules

Fuzzy rules are important to map the input and output variables. They are a series linguistic statements that describe how the decisions are made by the fuzzy controller. The state of the rule fulfilled to certain degree in fuzzy logic and each rule will affect the outcome of the collection according to the grade of fulfilment [112]. The state evaluation fuzzy rules in this study were derived using the heuristic method in which the collection of rules was formed by analysing the behaviour of the controlled process. The summary of designed rules in this study are tabulated as follows.

Table 4.1: Summary of designed fuzzy logic controller rules

Rule	Load consumption	Price	Remaining daily limit	Load Status(output)
1	Low			ON
2	Medium	Off-Peak	Adequate	ON
3	Medium	Off-Peak	Enough	ON
4	Medium	Off-Peak	Less	OFF
5	Medium	Standard	Adequate	ON
6	Medium	Standard	Enough	ON
7	Medium	Standard	Less	OFF
8	Medium	Peak	Adequate	OFF
9	Medium	Peak	Enough	OFF
10	Medium	Peak	Less	OFF
11	High	Off-Peak	Adequate	ON
12	High	Off-Peak	Enough	ON
13	High	Off-Peak	Less	OFF
14	High	Standard	Adequate	ON
15	High	Standard	Enough	ON
16	High	Standard	Less	OFF
17	High	Peak	Adequate	OFF
18	High	Peak	Enough	OFF
19	High	Peak	Less	OFF

The objective considered when designing the rules was the residential electrical energy control and consumption enhancement. There are many variables that can fulfil this objective but for this study only the price of electricity, load consumption, remaining electricity for the day and consumer desired number of days to use given amount of electricity for period of time were investigated. The rules were fired using the min-max method (AND) where the minimum value of the antecedents was taken to enable the controller to fire more than one rule condition at the same time but with varied strengths. The rules were structured as follows:

Rule 2: IF Consumption is "Medium" AND Price is "Off-peak" AND Available Electricity is "Adequate" THEN Load Status is "ON"

(iv) Choosing deffuzzification method

The final control in the fuzzy controller relies not only on the rule base but also on the chosen inference mechanism chosen [113]. Choosing the appropriate defuzzification method of the fuzzy controller plays an important performance factor. There are many defuzzification methods that can be used by the fuzzy controller but the accuracy of the method depends on the control application. Most used methods are the centroids methods and maximum of mean method. Extant literature as put forward by [114] suggested the criteria to choose the defuzzification method that has a continuity, plausibility, computational complexity and disambiguate. Center of gravity also known as the center of area or centroids method was chosen as the suitable method for the controller in this study. The center of gravity as proven by studies provides stability and accuracy to the controller. This is proven by its capabilities of:

- No resulting large change in output with the small change in input.
- The defuzzified output was in the center of the resulting membership function1s support and had a high degree of membership function.

In essence the center of gravity calculates the area under the scaled membership functions within the range of the output variable using the following equation.

$$\text{CoA}=\frac{\int_{x_{min}}^{x_{max}} f(x).x\,dx}{\int_{x_{min}}^{x_{max}} f(x)dx} \qquad (4.13)$$

where x is the value of linguistic variables and x_{min}, x_{max} represent the range of linguistic variable.

(v) Simulation (Rule testing) of the fuzzy controller

The final step in designing the fuzzy controller is to test the rules if they meet the objective of the system. The test system command on was used to test the relationship between the input and output variables. The input variables were set manually, and the controller calculated the weight of input variables to assign the output value as shown in form of 3D plots. The test system was able to display the invoked rule. The validity of the system was tested by varying the two inputs (electricity price and remaining daily limit) and one (load consumption) was kept constant.

- **Simulation 1: Testing low load consumption rule**

For low load consumption, only one rule was designed, that was Rule 1 which invoked on the following condition:

IF Consumption is "Low" Load Status is "ON

Table 4.2 shows the input and output values used to test the fuzzy rules.

Table 4.2: Simulation 1 input and output values

	Load consumption (%)	Price (cents)	Remaining daily limit (%)	COG output value
RULE 1	9	15	90	74.9828
	9	45	50	74.9828
	9	80	20	78.9828

The output value was calculated by the fuzzy controller during its deffuzzification stage using equation 4.13. For this study every output greater or equal to 50% was true, that is the appliance was ON else condition was false. The rule testing values tabulated in Table 4.2 were presented by 3D plots shown in following Figure 4.8

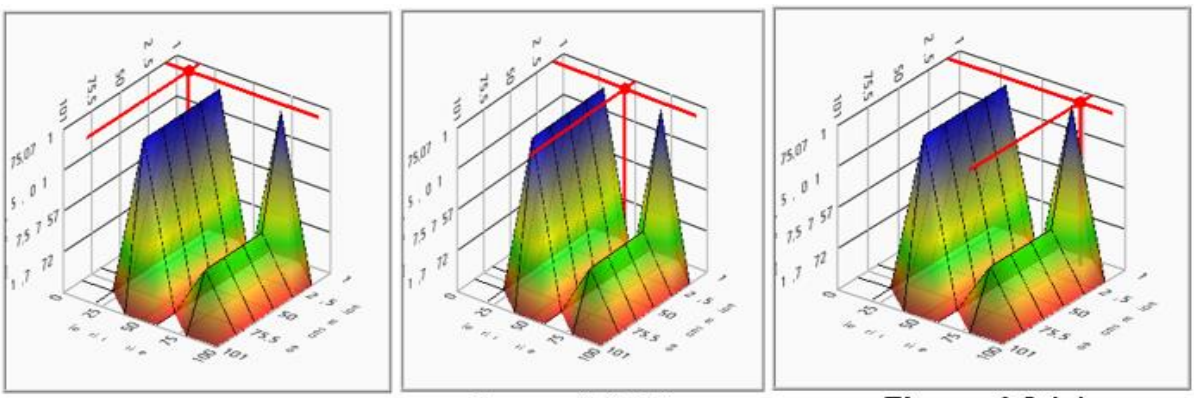


Figure 4.8 (a) Figure 4.8 (b) Figure 4.8 (c)

Figure 4.8: Low consumption invoked rules

Figure 4.8 (a) shows the response of the low consumption set to 9% with off peak price (15c), and adequate remaining daily electricity daily (90%). Figure 4.8 (b) is the standard price (45c), enough daily electricity limit (50%) and lastly Figure 4.8 (c) is the result of peak price (80c), and less daily electricity limit (20%). It is observed that there is no condition that can switch off appliance with low load consumption.

- **Simulation 2: Testing medium load consumption rules**

The consumption was set to 25% of remaining daily limit, the test parameters for the medium consumption to invoke the rules in Table 4.3 are summarised in Table 4.4.

Table 4.3 Rules designed for medium load consumption

Rule	Load consumption	Electricity Price	Remaining daily limit	Load Status (output)
2	Medium	Off-Peak	Adequate	ON
3	Medium	Off-Peak	Enough	ON
4	Medium	Off-Peak	Less	OFF
5	Medium	Standard	Adequate	ON
6	Medium	Standard	Enough	ON
7	Medium	Standard	Less	OFF
8	Medium	Peak	Adequate	OFF
9	Medium	Peak	Enough	OFF
10	Medium	Peak	Less	OFF

Table 4.4:Simulation 2 input and output values

Rule	Load consumption (kw/h)	Price (R)	Available Electricity (kw)	COG output value
2	25	15	90	75.0185
3	25	15	50	75.0185
4	25	15	20	24.9995
5	25	45	90	75.0185
6	25	45	50	75.0185
7	25	45	20	24.9995
8	25	80	90	24.9995
9	25	80	50	24.9995
10	25	80	20	24.9995

The following Figures (i.e. Figure 4.9 a up to h) present the output of the controller as designed in Table 4.3 and Table 4.4

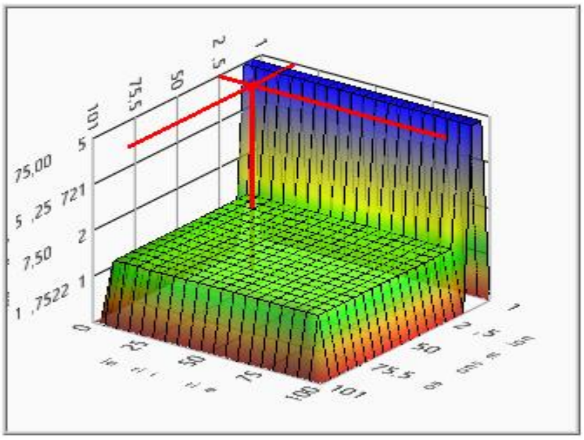


Figure 4.9 (a): Rule 2

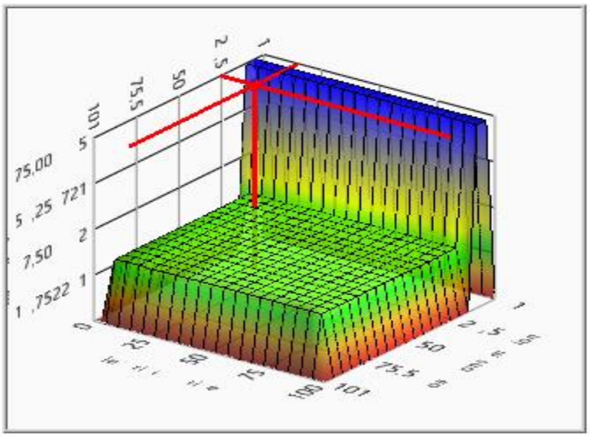


Figure 4.9 (b): Rule 3

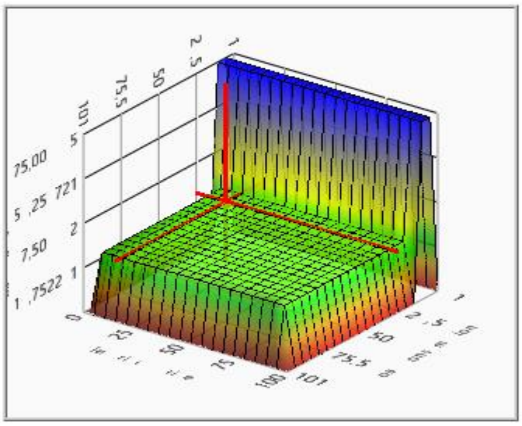


Figure 4.9 (c): Rule 4

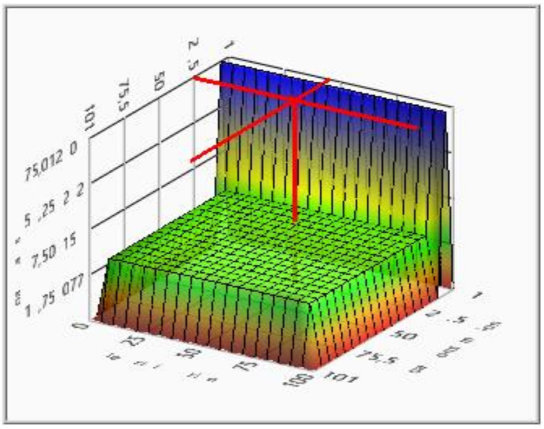


Figure 4.9 (d): Rule 5

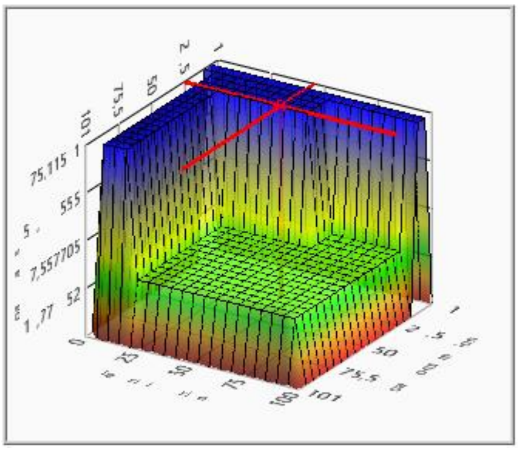


Figure 4.9 (e): Rule 6

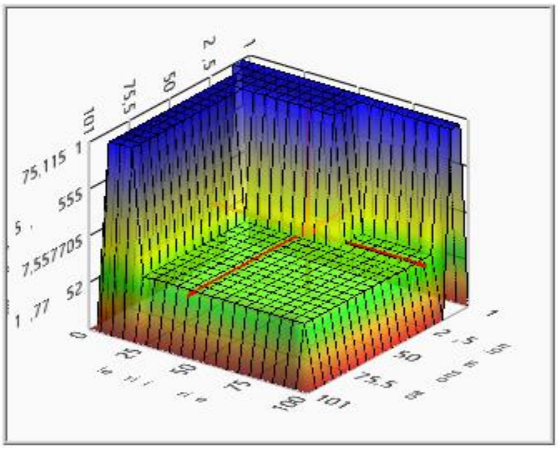
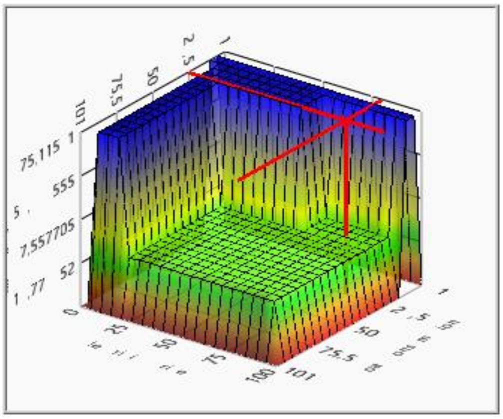


Figure 4.9 (f): Rule 7



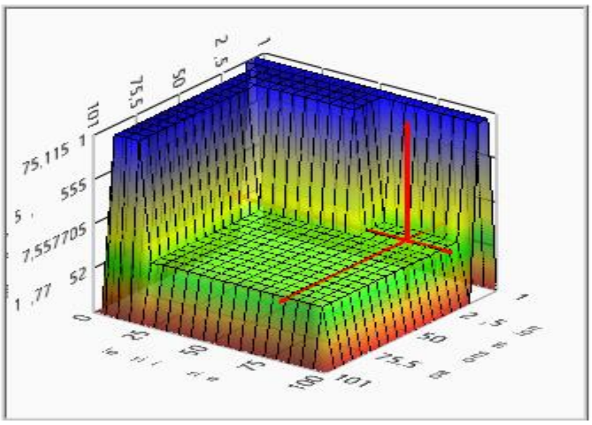


Figure 4.9 (g): Rule 8 **Figure 4.9 (h): Rule 9**

- **Simulation 3: Testing high load consumption rules**

For this simulation the load consumption was set contant at 70%. The price, number of days and the available electricity were varied considering the designed rules expressed in Table 4.5. The test parameters are tabulated in Table 4.6.

Table 4.5: Rules designed for high load consumption

Rule	Load consumption	Electricity Price	Remaining daily limit	Load Status (output)
11	High	Off-Peak	Adequate	ON
12	High	Off-Peak	Enough	ON
13	High	Off-Peak	Less	OFF
14	High	Standard	Adequate	ON
15	High	Standard	Enough	ON
16	High	Standard	Less	OFF
17	High	Peak	Adequate	OFF
18	High	Peak	Enough	OFF
19	High	Peak	Less	OFF

Table 4.6 Simulation 3 input and output values

Rule	Load consumption	Electricity Price	Remaining daily limit	COG output value
11	70	15	80	75.0155
12	70	15	60	75.0155
13	70	15	25	24.9995

14	70	45	80	75.0155
15	70	45	60	75.0155
16	70	45	25	24.9995
17	70	80	80	24.9995
18	70	80	60	24.9995
19	70	80	25	24.9995

Rule firing for simulation 3 as tabulated in Tables 4.5 and 4.6 are presented in following figures.

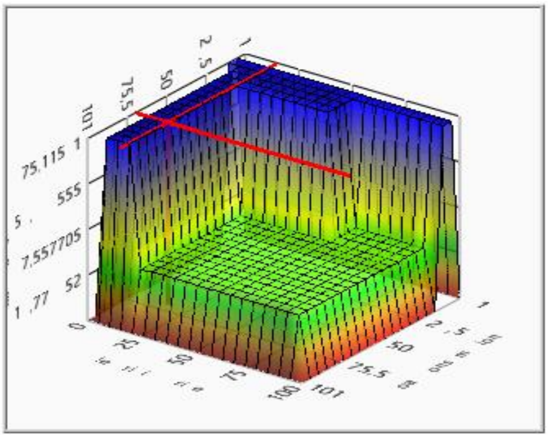


Figure 4.10 (a): Rule 11

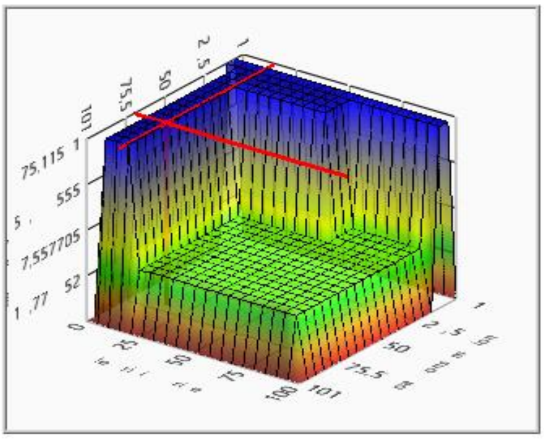


Figure 4.10 (b): Rule 12

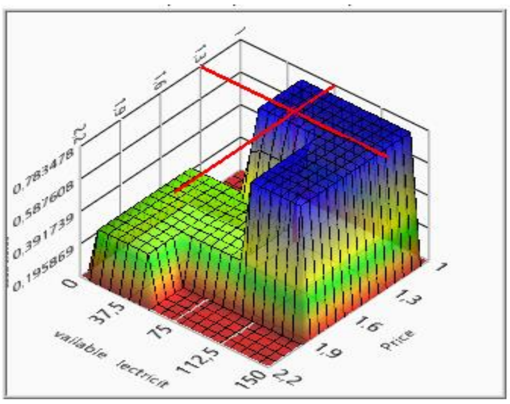


Figure 4.10 (c): Rule 13

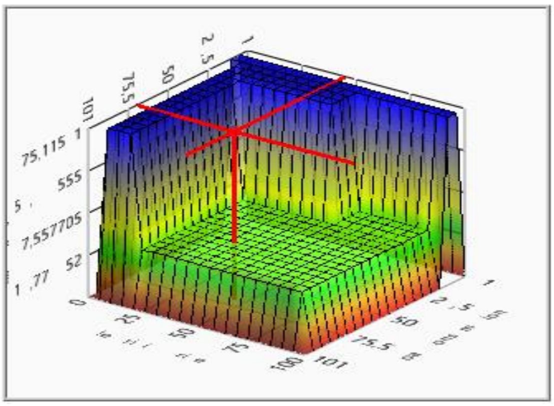
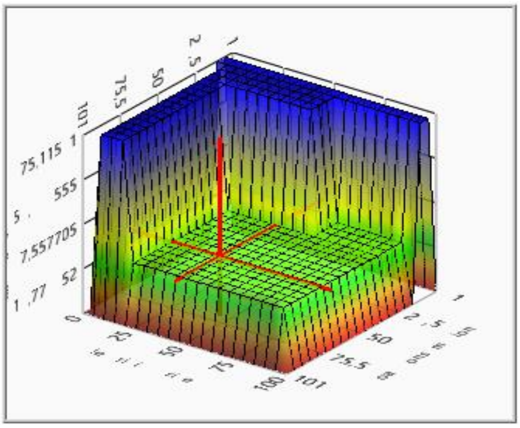


Figure 4.10 (d): Rule 14



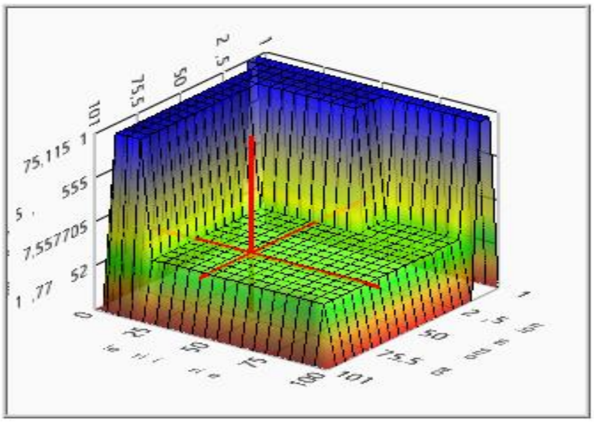
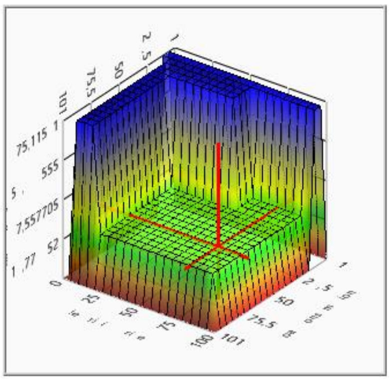
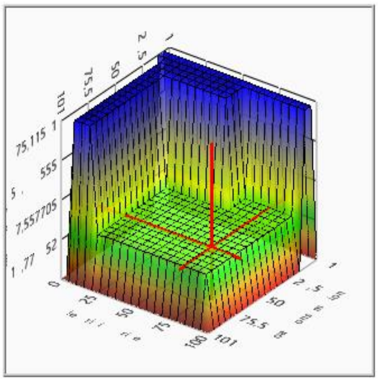


Figure 4.10 (e): Rule 15

Figure4.10 (f): Rule 16





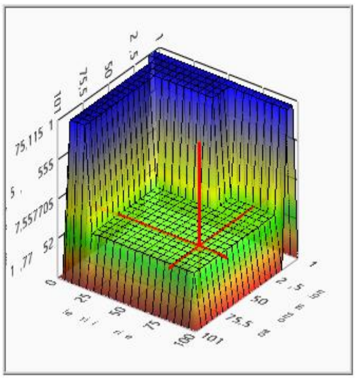


Figure 4.10 (g): Rule 17

Figure 4.10 (h): Rule 18

Figure 4.10 (i): Rule 19

4.4.3. Real time simulation

LabVIEW was designed to test the accuracy of the system in real time. The visual instrument has the two panels: front panel and block diagram. The front panel has controls and indicators that are visual tools and interactive inputs and outputs terminals, respectively. Controls and indicators mounted on front panel are placed on block diagram automatically.

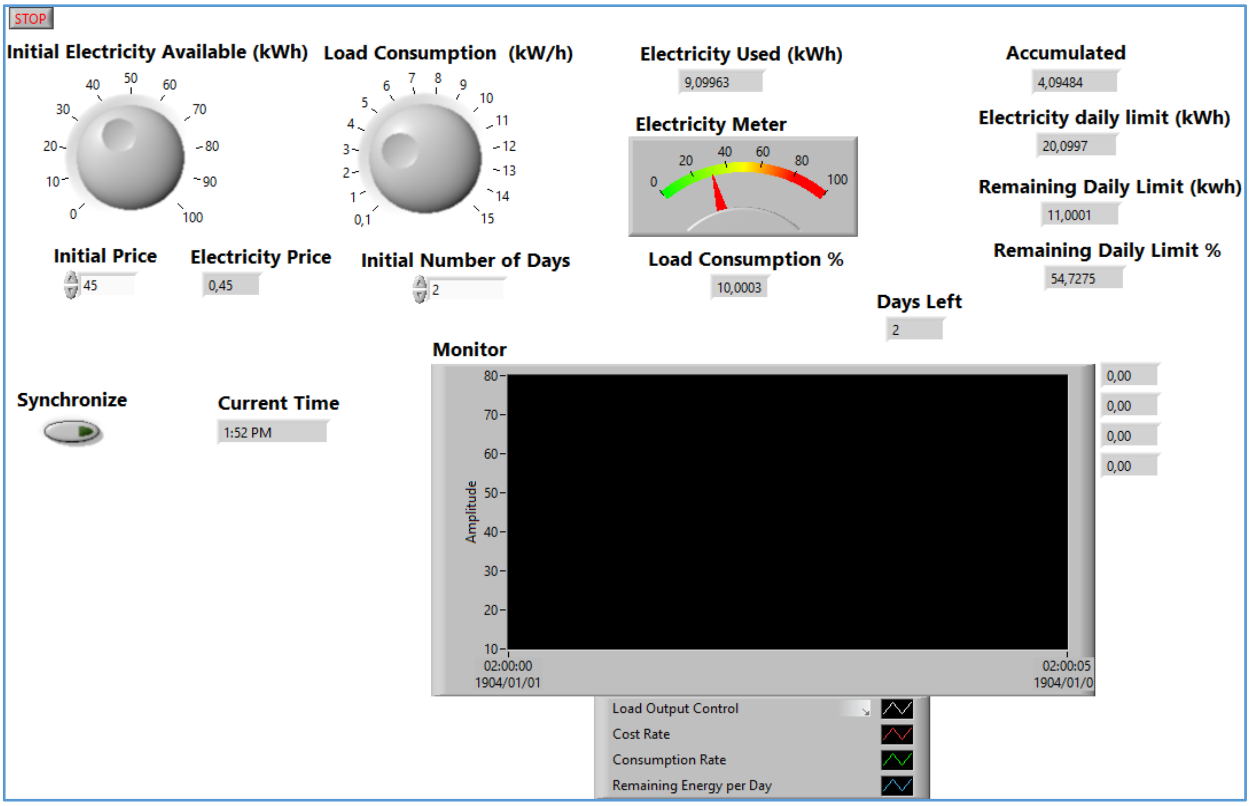


Figure 4.11: LabVIEW fuzzy logic system front panel

The block diagram includes the graphical source code of the LabVIEW program, the terminals, the functions, the constants, the structures and the wires that transfer data among other. On block diagram, terminal represents the changes made to their corresponding front panel.

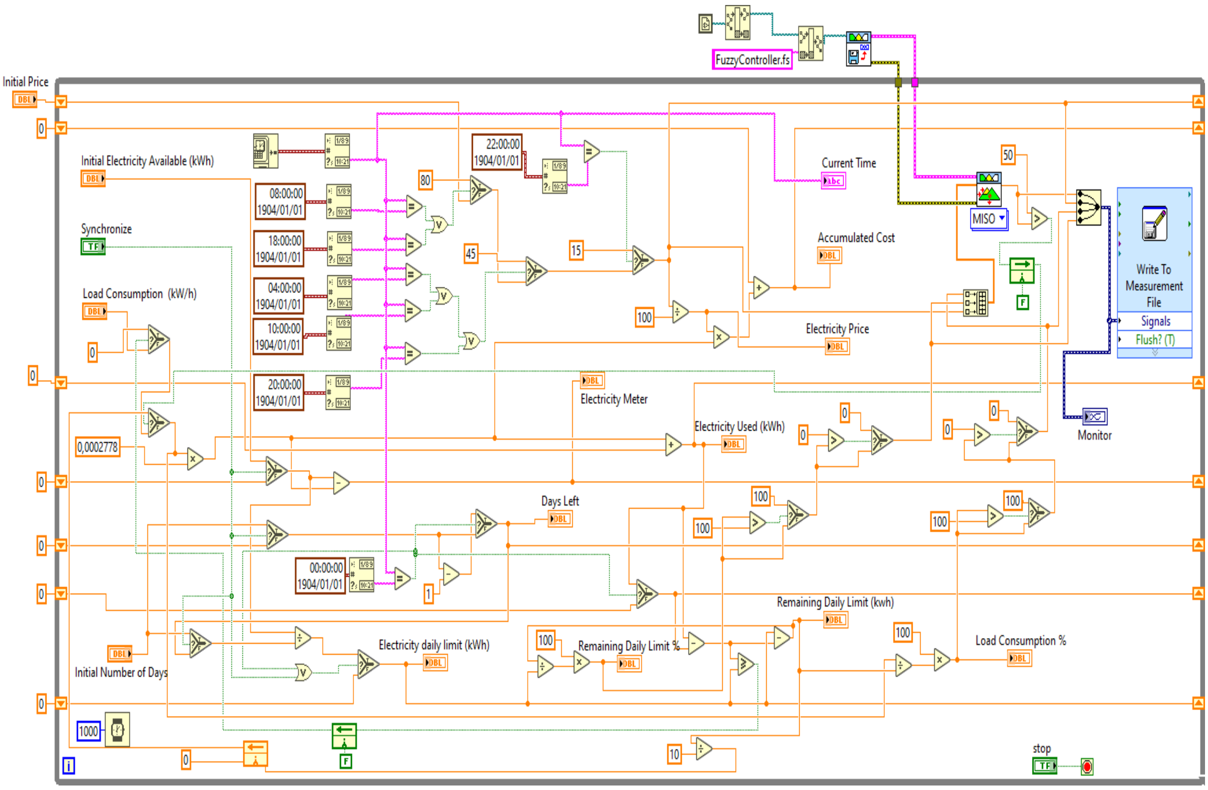


Figure 4.12: Fuzzy logic system block diagram

The available initial electricity was set at desired amount of electricity for desired number of days. The electricity daily limit for first day was calculated in respect to the available electricity and number of desired days using the equation 4.14.

$$Electricity\ daily\ limit = \frac{initial\ electricity\ available}{initial\ number\ of\ days} \qquad (4.14)$$

The electricity meter value initially equal to the initial available electricity and then updated as the electricity used continuously until the electricity is finished. The number of days were automatically changed at 00:00 AM. The electricity daily limit from the second day was calculated for everyday at 00:00 AM in respect to available electricity as read from the meter and number of days left with equation 4.15.

$$Electricity\ daily\ limit = \frac{available\ electrity\ on\ meter}{Days\ left} \qquad (4.15)$$

As the electricity used during the day the remaining daily limit was calculated and displayed in form of kwh and the %age in respect to the daily limit. The equation to calculate the remaining daily electricity is:

$$Remaining\ daily\ limit = electricity\ daily\ limit - used\ electricity \qquad (4.16)$$

To accommodate the different possible initial available electricity, the remaining daily limit was sampled from electricity daily limit in %age using the equation 4.17:

$$Remaining\ daily\ limit\% = \frac{remaining\ daily\ limit}{electricity\ daily\ limiy} * 100 \qquad (4.17)$$

If the remaining daily limit is equal or less than 30% of the daily limit the fuzzy controller will only allow the consumption that is equal or less than 10% of the initial daily limit. For every electricity not used for the day was recurred and new daily limit for numbers of days calculated.

The initial price was manually initialised depending to the time of the day when the system started to synchronise and the electricity price is detected. The day (24 hour) was sampled with three pricing tariffs, off peak, standard and peak as tabulated in Figure 4.7. The price tariffs were fixed at 15c for off peak, 45c for standard and 80c for peak periods. These tariffs were fixed prices for kw/second.

Table 4.7: Price tariff schedule

Off Peak	Standard	Peak
22:00- 07:00	07:00-08:00 10:00-18:00 20:00-22:00	08:00-10:00 18:00-20:00

The only manual controller is the load consumption. The normal total load consumption per household was set to 15 kw/h. The controller was sampled to 15 kw/h. The input of the controller was the load consumption in %age calculated from the remaining daily electricity as shown in equation 4.1. To calculate the accumulated cost and used electricity, the load consumption in kw/h was converted to kw/s by:

$$\frac{consumption\ in\ kw\ per\ hour}{3600} = 0.0002778 * consumption\ in\ kw\ per\ hour \qquad (4.18)$$

4.4.4. Reliability of the model

In order to test the reliability of the controller, simulations were conducted on full model with several scenarios such as varying the price tariffs, load consumption and electricity daily limit available for the day for 24 hours. Simulation of the model helped in monitoring of the energy consumption and enhancement considering the different scenarios of the controller input.

4.4. Summary

The methodology and the design followed in this study was explained in detail in this chapter. We further explained the steps followed to design the fuzzy logic controller. The membership functions of inputs and output parameters and ranges were graphically designed and presented. The designed rules were tabulated, tested for validity and presented using 3D plots. The operation of the model and equations that were sampled in the model to give the specific output were presented.

Chapter 5: Presentation of results and analysis

5.1. Introduction

This chapter involves the comparing the objectives of the study to actual observed results from the designed fuzzy logic enabled system .The main objective of this study was to design fuzzy logic enabled demand side management system for residential electrical energy control. The prime objectives were to:

(i) Design the fuzzy enabled system that will be able to manage the amount of electricity as desired by the consumer for the given time frame.

(ii) Use fuzzy logic to enhance the electricity consumption by scheduling the household appliances in response to the ToU.

(iii) Design fuzzy logic rules that will switch off the appliances in an orderly manner to achieve objective (i) and (ii).

The results are presented descriptively in the form of tables and graphs. This chapter concludes with analysing, justifying and evaluating the results.

5.2. Simulation scenario 1: Off peak price and adequate electricity

Fuzzy logic enabled system to manage the available amount of electricity as desired by the consumer for the given time frame and enhance the electricity consumption by scheduling the household appliancces in response to the ToU tariffs .

The three parameters for the time of use tariffs and load consumption used in this study are tabulated in Table 5.1.

Table 5.1: Parameters for the price tariffs

Price	Time	Parameters in cents
Off Peak	22:00-07:00	15
Medium Peak	07:00-08:00 10:00-18:00 20:00-22:00	45
Peak	08:00-10:00 18:00-20:00	80

The simulation was run on the 18th December 2019 from 04:49 in the morning during off peak period as shown in the following table with starting amount of electricity equal to 7.7 kwh desired to to be consumed for 2 days. The following tables were categorised from from the 24 hour simulation. Figure 5.1 shows the simulation for the offpeak period with the adequate daily electricity limit.

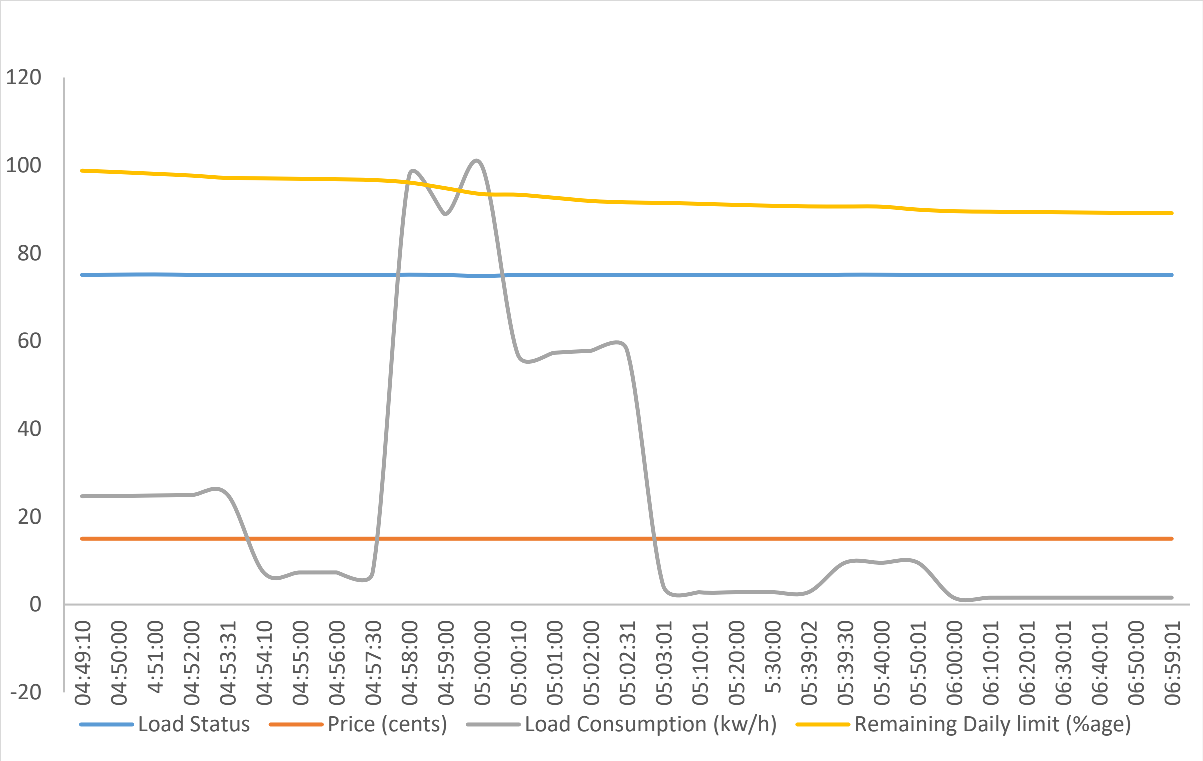


Figure 5.1: Offpeak price(cents) and adequate electricity(kw in %age)

Low, medium and high load consumption were sampled between 04:49 and 06:59 and the load status was on. This implies that fuzzy logic was able to invoke Rule1,2 and 11 which were summarised based on the load consumption being low or medium or high, while the price was off peak and the remaining daily limit was adequate. In this case the load status was on.

5.3. Simulation scenario 2: Standard price and adequate electricity

This simulation evalutes how fuzzy logic perfomed when controlling the load consumption given that the price tariff was standard and the remaining daily limit of electricity was still adequate. As shown in Figure 5.2 the price changed from 15 cents to 45 cents at 07:00 t until 08:00.

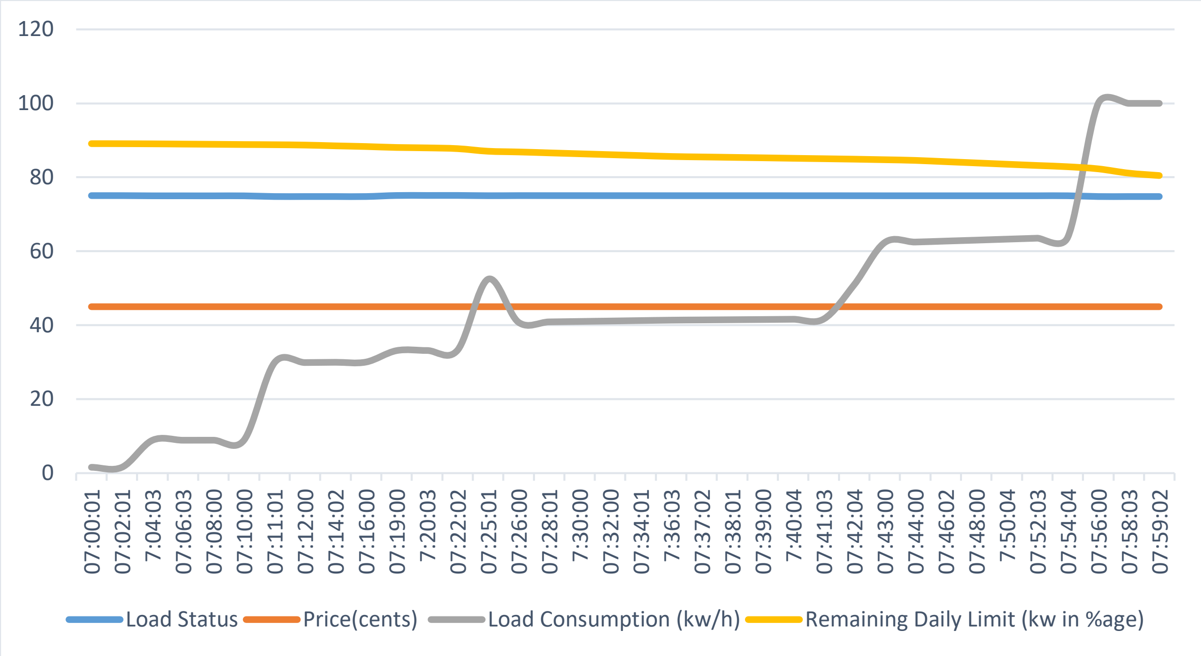


Figure 5.2: Standard price(cents) and dequate electricity(kw in %age)

Also during this period the on status of the different load consumption were observed since the remaining daily electricity was still adequate. Rule 1 was sampled between 07:00 and 07:10 with low load consumption. Rule 5 was in invoked between 07:11 and 07:16 with medium load consumption while rule 14 of high load consumption was invoked from 07:19 to 07:59.

5.4. Simulation scenario 3: Peak price and adequate electricity

Fuzzy rules were obseved during peak period and adequate remaining daily electricity limit.

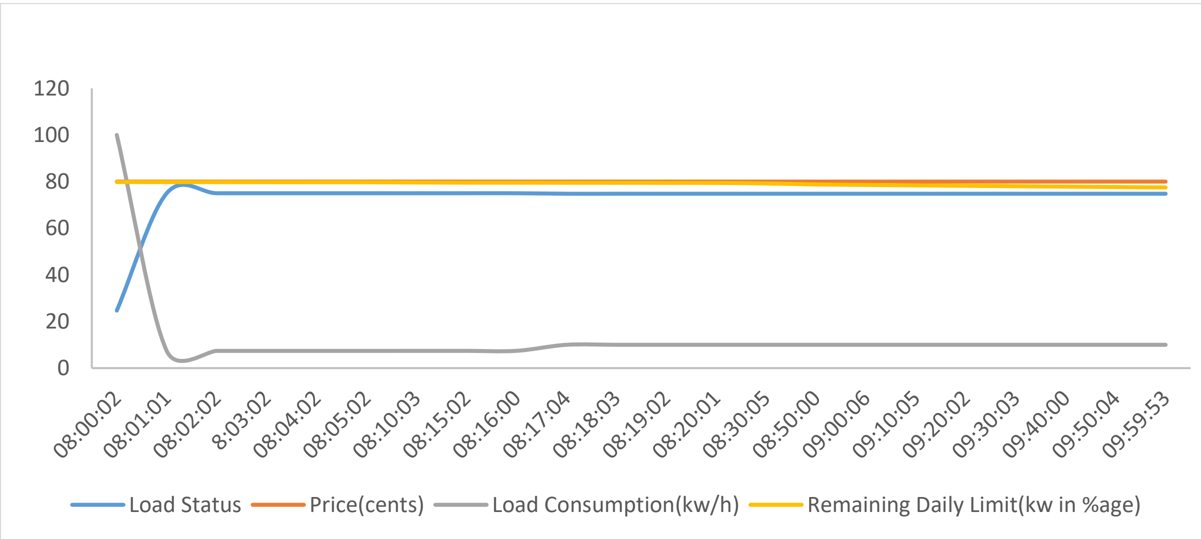


Figure 5.3: Peak price(cents) and adequate electricity (kw in %age)

The load cunsumption was high at 80% by 08:00 as shown in Figure 5.3 and the load status was off for a minute. The fuzzy logic invoked Rule 8 and 17 showing that if load consumption is medium or high and the price is peak or price is adequate, then load status was OFF. At 08:01 to 09:59 during the peak period the fuzzy logic invoked rule 1 for allowing only low consumption ON on status.

5.5. Simulation scenario 4: Standard price and enough electricity

At 10:50 the electricity started to be enough that is less than 70% and greater than 30% as shown in Figure 5.4 which meant that the remaining daily electricity limit was no longer adequate but enough. The load status remained ON from 10:50 to 15:30 as fuzzy logic invoked rule 1,6 and 15 that allowed low, medium and high load consumption to be ON if the price is standard and remaining daily limit is enough.

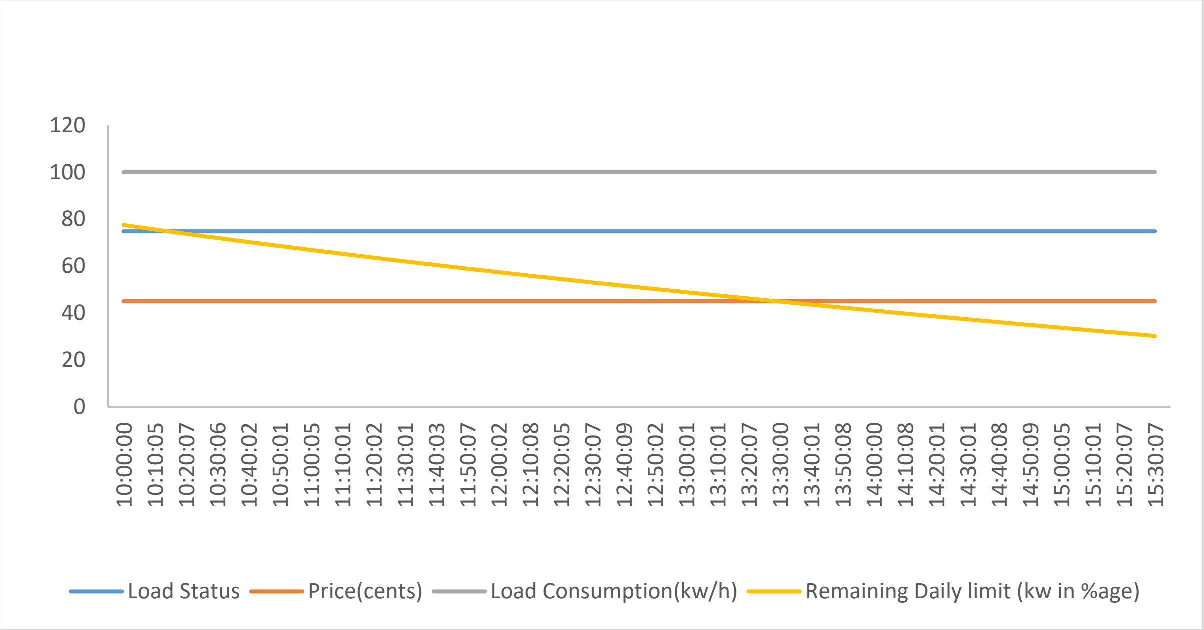


Figure 5.4: Standard electricity(cents) and enough electricity (kw in age%)

5.6. Simulation scenario 5: Standard, peak price and less electricity

Between 15:32 and 17: 59 the price was standard and the remaining daily limit was less with load consumption at 100% of the remaining daily limit and the load was switched OFF as per rule 7 and 16. The only allowed load was the load that was equal to 10% and less (low load consumption). At 18:00 the price changed to peak with less remaining daily limit also from this period to 23:59 only 10% of remaining daily limit was abled. Figure 5.5 shows the simulation scenario 5.

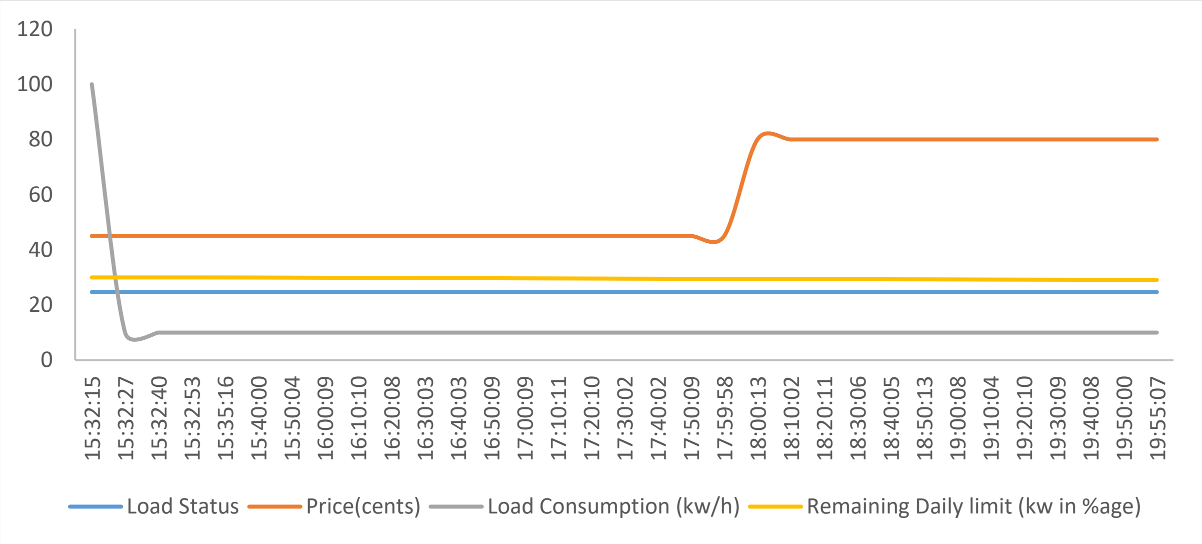


Figure 5.5: Standard(cents), peak price(cents) and less electricity(kw in %age)

5.7. Simulation scenario 6: Day change and recalculation of daily limit

At 23:58 the remaining daily limit for the 18th was 28% as shown in Table 5.7. The system changed the day at 23:59 and the remaining daily limit was resetted by calculating the new daily limit with response to the available electricity on the smart meter and the new daily limit was allocated for the following day that was the 19 th of December 2019 as shown in Table 5.2.

Table 5.2: Day change and recalculation of remaining daily limit

Time	Load Status	Price(cents)	Load Consumption (kw/h)	Remaining Daily Limit (kw in %age)
12/18/2019 23:58:49	24,673469	15	10,000278	28,409166
12/18/2019 23:59:07	75,021572	15	2,470659	100
12/18/2019 23:59:27	74,800141	15	76,571366	99,978733
12/19/2019 00:00:05	74,800141	15	76,603956	99,936199
12/19/2019 00:10:05	74,906073	15	77,129189	99,255655

Figure 5.6 shows the overall simulation results for 24 hours.

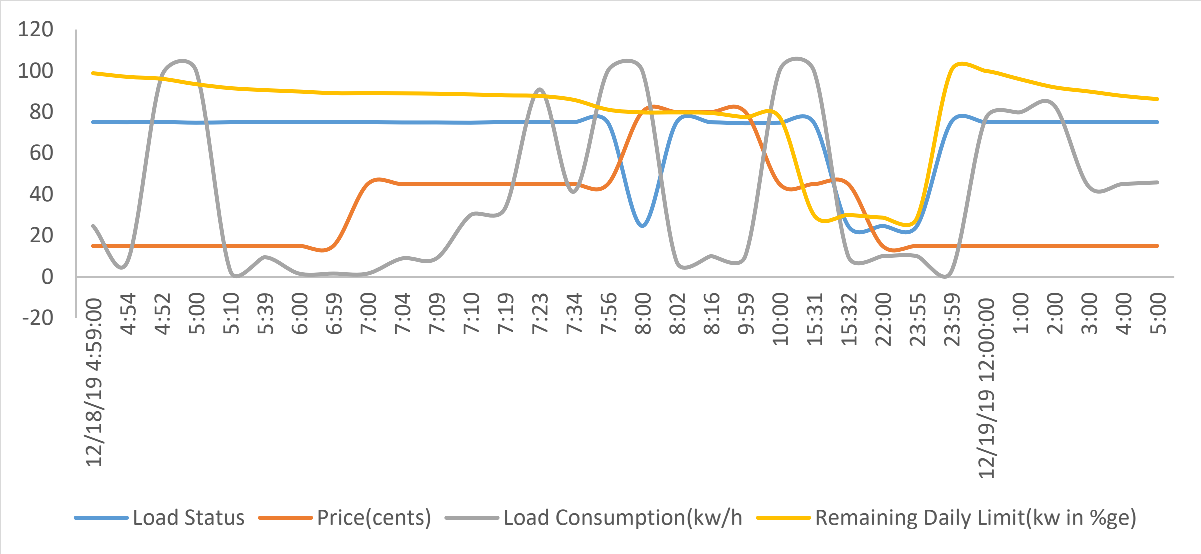


Figure 5.6: Overall 24-hour simulation scenarios

5.8. Simulation scenario 7: Fuzzy logic rule testing

Fuzzy logic rules designed to switch OFF the appliances in orderly manner to manage electricity amount of electricity for given time frame and enhance the household appliance scheduling in response to the ToU tariffs.The fuzzy logic rules tabulated in Table 5.3 were designed to switch off the appliances in orderly manner to manage electricity consumption .

Table 5.3: Fuzzy logic Rules designed to switch OFF the appliances

Rule	Load consumption	Electricity price	Remaining daily limit	Load Status(output)
4	Medium	Off-Peak	Less	OFF
7	Medium	Standard	Less	OFF
8	Medium	Peak	Adequate	OFF
9	Medium	Peak	Enough	OFF
10	Medium	Peak	Less	OFF
13	High	Off- Peak	Less	OFF
16	High	Standard	Less	OFF
17	High	Peak	Adequate	OFF
18	High	Peak	Enough	OFF
19	High	Peak	Less	OFF

The OFF load status was classified in output membership functions in Figure 4.7 as any range from 0 to 50%. The rules to switch off the appliances were designed and tested before real time simulation. The following Figures shows the rule testing for selected rules of the fuzzy logic to switch off the appliances. Medium load consumption at off peak price with less remaining daily limit of electricity. The load status was OFF as invoked by rule 4 and showed in Figure 5.7.

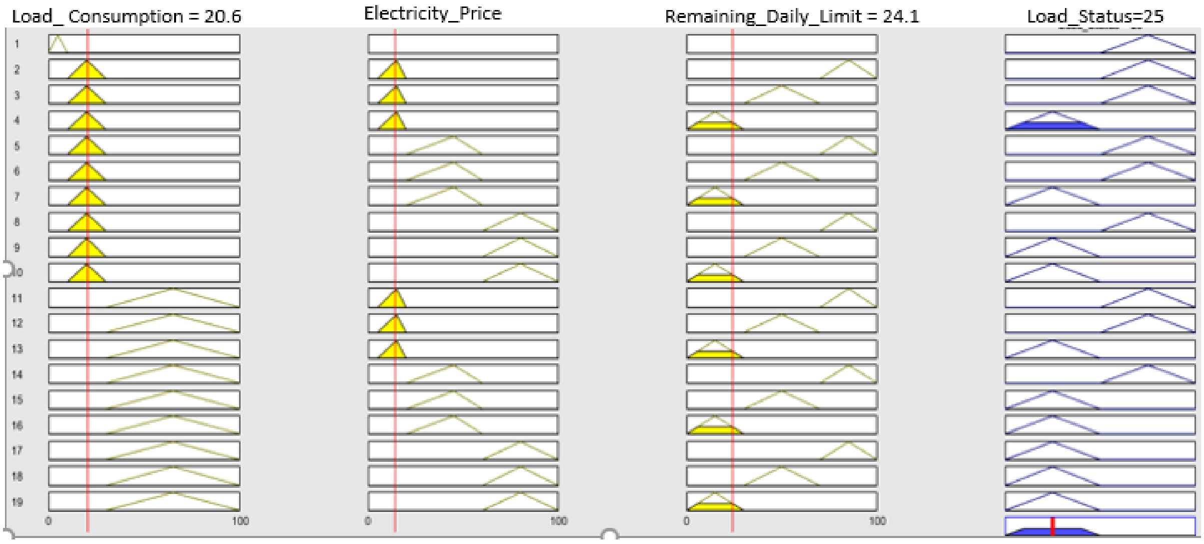


Figure 5.7: Rule 4 invoked

Rule 7 was invoked and shown in the following figure when medium load consumption was switched OFF during the standard price tariff and less remaining daily limit of electricity.

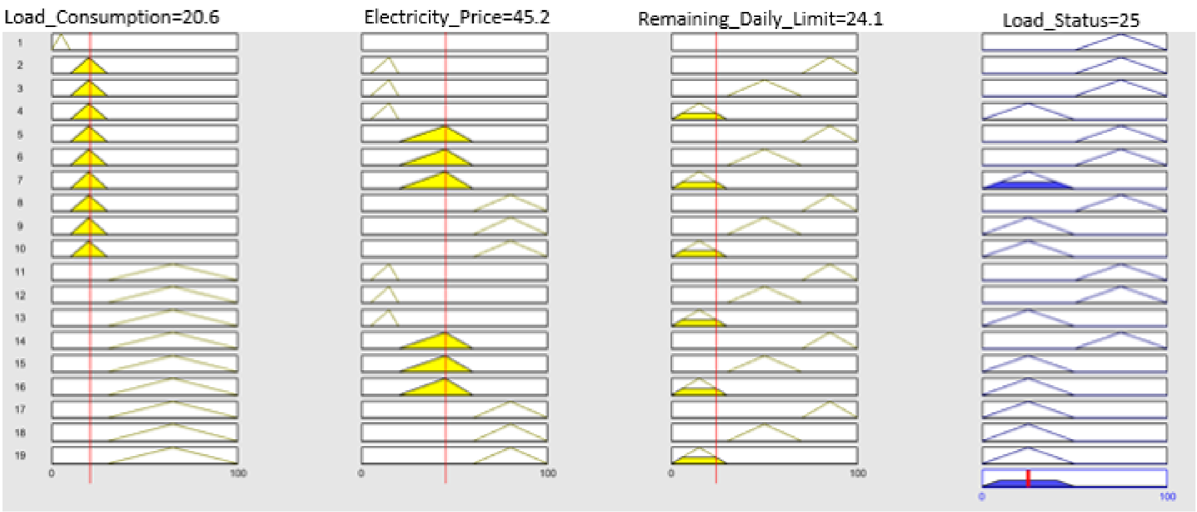


Figure 5.8: Rule 7 invoked

Figure 5.9 shows the sampled high load consumption at off peak price tariff with less remaining daily limit of electricity. Rule 13 was invoked to switch OFF the load.

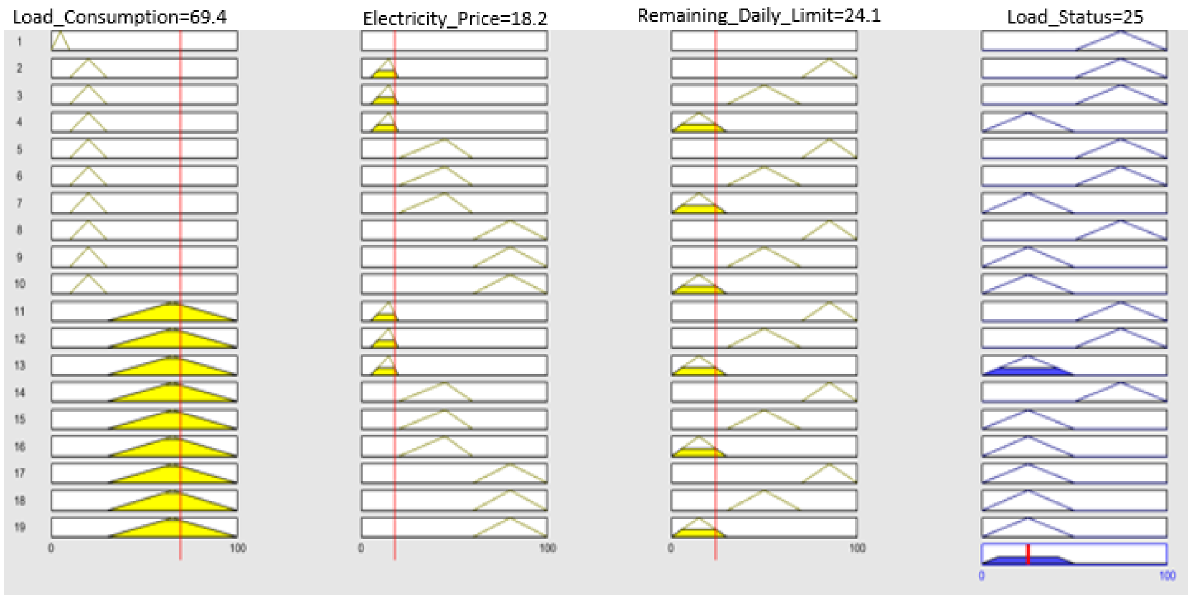


Figure 5.9: Rule 13 invoked

Rule 18 was invoked for high load consumption during peak price tariff with enough remaining daily limit. The Off-load status was shown in Figure 5.10.

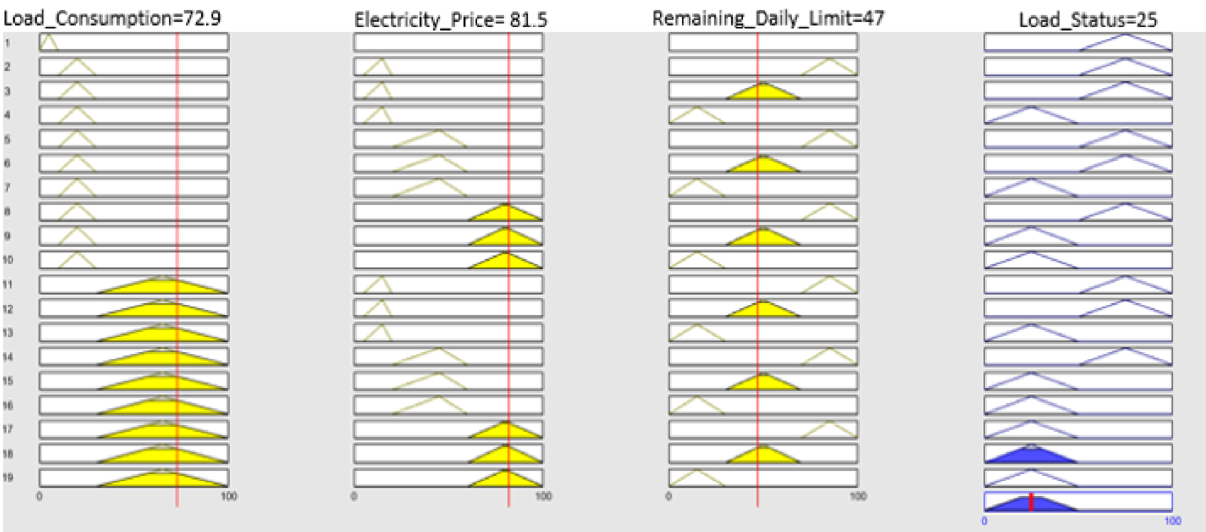


Figure 5.10: Rule 18 invoked

The following figures shows the Surface view Z-output for the inputs and output.

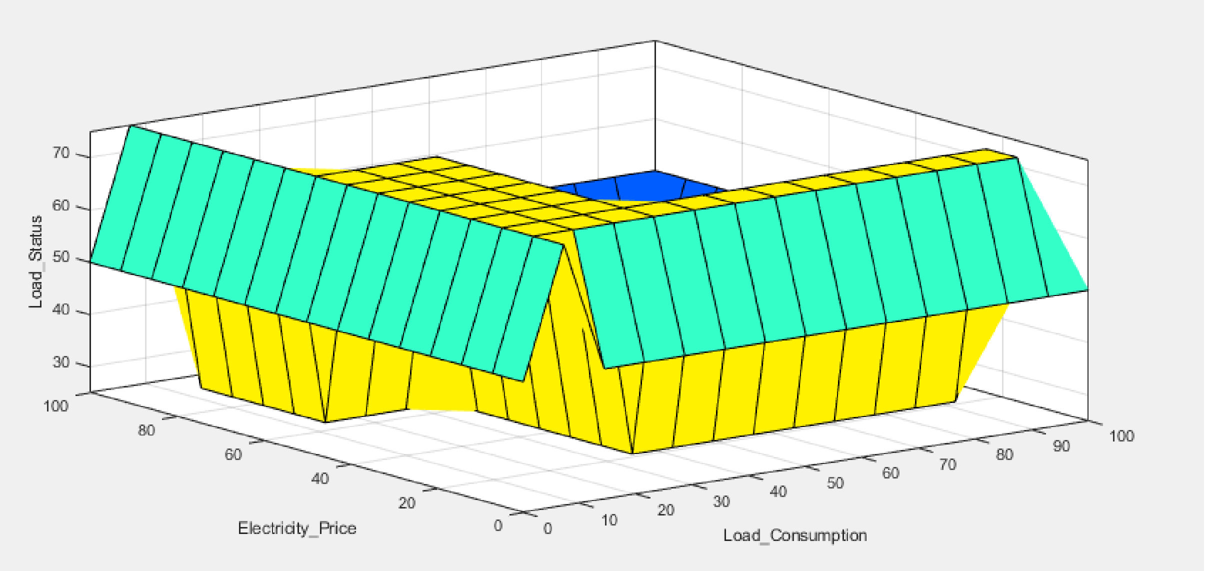


Figure 5.11: Surface view Z-output of electricity price (y-input) and load consumption (x-input)

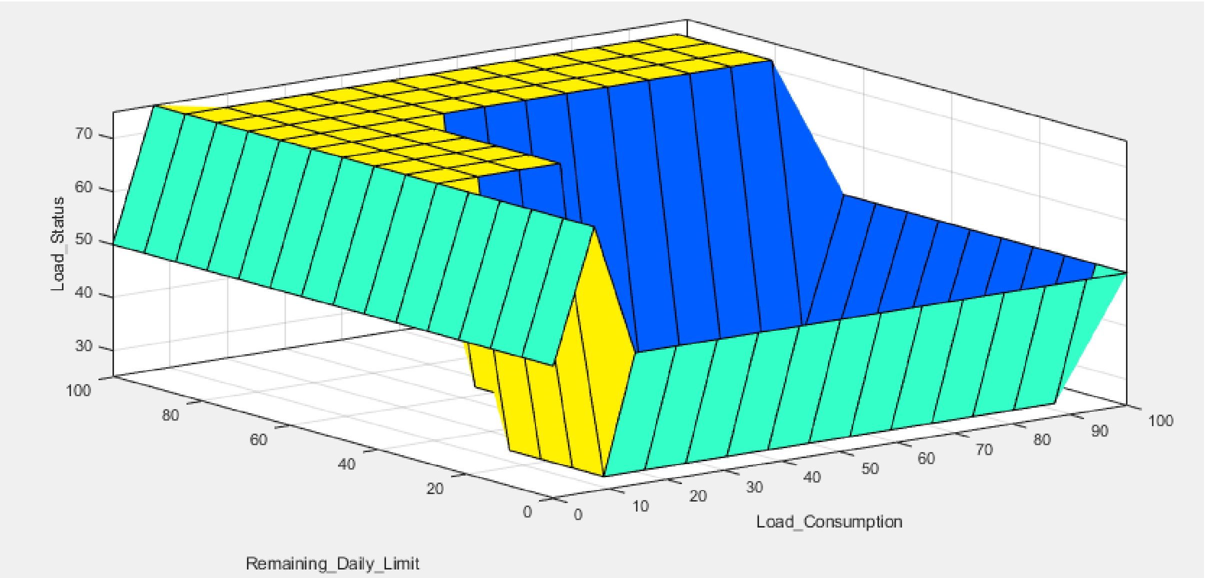


Figure 5.12: Surface view Z-output of remaining daily limit (y-input) and load consumption (x-input)

For rule 1,2,3,4 and 5 to be invoked the load consumption should be anything between 0 and 30 % of the remaining daily limit thus low and medium load consumption to be ON. The surface view Z output for the load consumption was as shown in Figure 5.13.

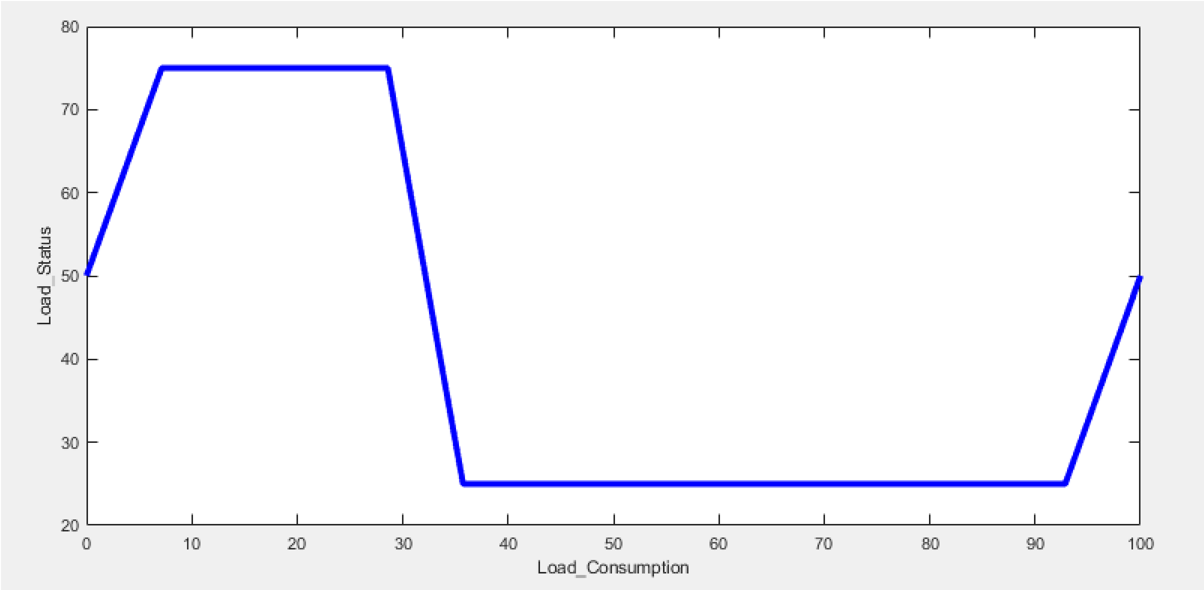


Figure 5.13: Load Status(kw/h) surface view Z output

When electricity price is off peak, the load status is more likely to be ON for the load consumption as shown in Figure 5.14.

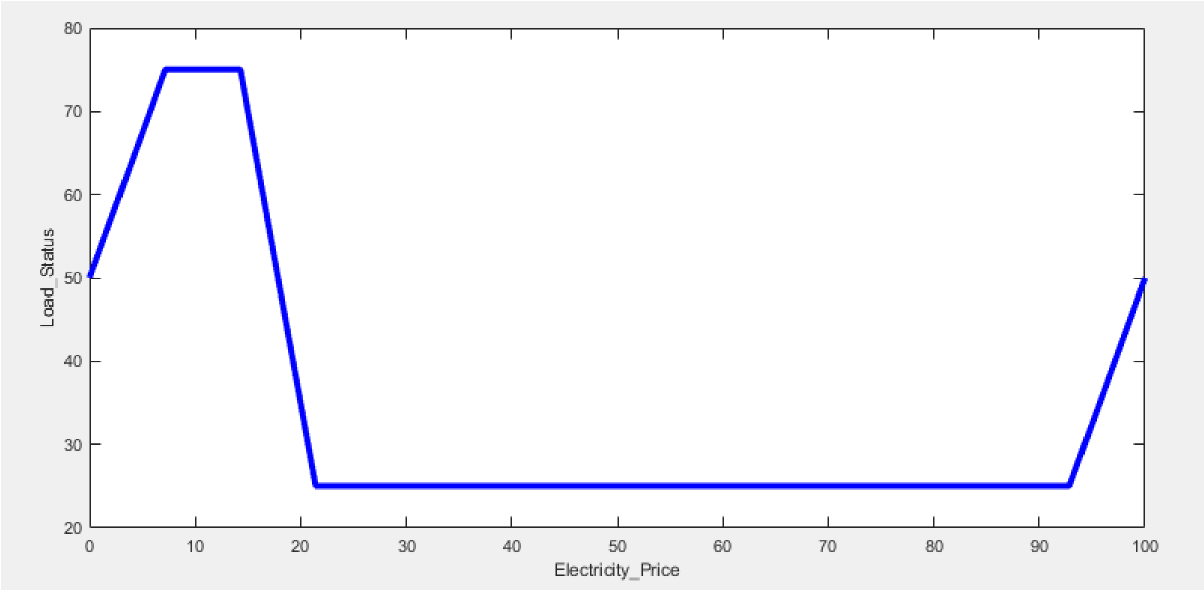


Figure 5.14: Electricity Price(cents)surface view Z output

On status was invoked mostly when the remaining daily limit was more than 60% of the electricity daily limit. The z surface view for the remaining daily limit was as shown in Figure 5.15.

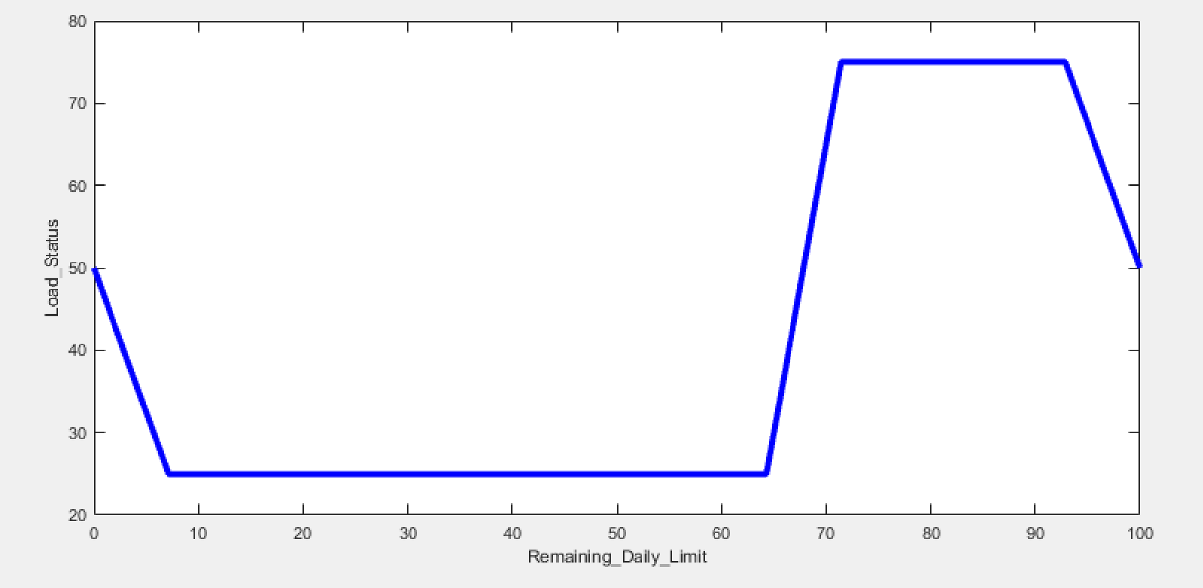


Figure 5.15: Remaining daily limit (kw in %age) surface view Z output

5.9. Summary

This chapter presented the results of this study which was investigated using fuzzy logic controller. The vey basic aim was to control the consumption and cost of the electricity considering the price tarrifs, load consumption and remaining electricity daily limit as inputs and load status as the only output. For true condition of the output (≥ 50%), the system was able to calculate the amount of electricity used for that particular time of operation and subtract it from the initial calculated daily limit electricity. Fuzzy logic enabled system was simulated to manage the available amount of electricity as desired by the consumer for the given time frame and enhance the electricity consumption by scheduling the household appliances in response to the ToU tariffs. The simulation was run for 24 hours and results were categorized by the price and the remaining daily limit of the electricity.

Lastly the simulation scenario 7 tested the designed fuzzy logic controller rules to switch off the household appliance to enhance the electricity consumption by schedulling the household appliances in response to the Time of Use tarrifs. The results were presented by the z surface view for every input with respect to the output.

Chapter 6: Findings, implications, recommendations and conclusion

6.1. Introduction

This chapter summarise the study and its motivation, findings and the implications are discussed in this chapter. The chapter further sumarised the study, its contribution recommendations of investigations that might worth to be studied in future and the conclusion.

6.2. Findings

The main objective of this study was to design the fuzzy logic enabled system to control the residential electricity consumption.

The primary objectives are to:

(iv) Design the fuzzy logic enabled system that will be able to manage the amount of electricity as desired by the consumer for the given time frame.

(v) Use fuzzy logic to enhance the electricity consumption by scheduling the household appliances in response to the ToU tariffs.

(vi) Design the fuzzy logic rules that will switch off the appliances in an orderly manner to achieve objective (i) and (ii).

The results per objective are discussed below.

- The results showed that designed fuzzy logic system managed to control the amount of electricity as desired by the consumer. The fuzzy logic rules managed to lock the high and medium load consumption and allow the only 10% or less (low) consumption of the daily limit when there was only 30% of remaining daily limit. To manage the time frame the system unlocked the following day starting with adequate remaining daily limit.
- The system switched off the high and medium load consumption appliances when the price is high(peak period) and only low load consumption was enabled.
- The designed fuzzy logic rules managed the amount of electricity for desired time frame and enhanced the electricity consumption by switching off the medium and high load consumption when price tariff is peak, switching high and load consumption when the remaining daily electricity limit is less.

6.3. Implications

The fuzzy logic and demand side management initiatives, in particular dynamic pricing that includes the time of use tariffs and load scheduling that was investigated in this study provides the evidence that fuzzy logic can control the electricity consumption without the interaction of the consumer and enhance the scheduling of appliances in orderly manner so as to manage electricity consumption. However, the design that manages the amount electricity for the given time frame, that is it only allows 10% of the electricity to be used, when the remaining daily limit is less than 30% of the daily limit, could compromise the consumer`s comfort because of the amount of electricity that could be brought forward for the following day. This, in essence, could have been used by the consumer for particular day. The completely switching off of high and medium load consumption during peak hours with less remaining daily limit could also compromise the consumer`s comfort.

6.4. Recommendations

Possible further improvement of fuzzy logic approach for potential manual operation when there is a need by the consumer to increase load consumption considering the time left for the day is recommended after this study. Furthermore, the investigation on how the system could manage the load consumption for defined time period instead of completely switching off will add advantage to the comfort and preferences of the consumer.

6.5. Summary of the study

The increasing residential energy demand in South Africa has resulted in renewal of energy policy documents and legislatives. Apart from energy polices, the utility further introduced demand side management initiatives such as demand response (incentive based and price based) to encourage the load reduction, in particular, during peak hours. However, managing the peak hour consumption may have a negative impact on load diversity which might potentially result in new peaks at a least price. Furthermore, it is difficult for the users to manually respond to the offered incentives and price-based tariffs.

To address the above-mentioned issues the system developed herein enabled demand side management system for residential electrical energy control" with the aim to manage the amount of electricity as desired by the consumer for the given time frame and to enhance the electricity consumption by scheduling the household appliances in response to the ToU tariffs was proposed.

6.5. Conclusion

In section 1.7 the contribution of the study was briefly stated. Below this dissertation puts up concluding remarks of the study contribution and research efforts. In chapter 4, a fuzzy logic controller system was developed and implemented in LabVIEW VI 2019. The simulator enabled the researcher to address the objectives, as set out in chapter 1, using the scheduling of load consumption to save electricity consumption and costs under different scenarios. Time of Use tariff and daily limit were applied. The 24-hour period was simulated to demonstrate the control of electricity consumption considering the price and amount of electricity remaining for the day. The collected results showed that the system, based on fuzzy logic, was able to able control the residential load consumption by scheduling the household appliances as desired by the consumer considering the time of use tariffs and amount of remaining electricity.

References

[1] J. Bohlmann," An analysis of residential sector energy consumption in South Africa," in Conf. ESSA, South Africa: University of Pretoria, 2017.

[2] Statistics South Africa. (2017, July,10). Electricity: big business for municipalities [online]. Available: www.statssa.gov.za/?p=10186

[3] A. Keshkar, "Development of adaptive fuzzy logic systems for energy management in residential building, "Ph.D. Thesis, School of Mechatronic Systems Engineering, Simon Fraser University,2015

[4] I. Laicane, D. Blumberga, A. Blumberga, M. Rosa, "Reducing household electricity consumption through demand side management: the role of home appliance scheduling and peak load reduction," Energy Procedia, vol. 72, pp. 222-229, 2015.

[5] A. Keshtkar, S. Arzanpour, F. Keshtkar, P. Ahmadi," Smart residential load reduction via fuzzy logic, wireless sensors, and smart grid incentives," Energy and Building, vol. 104, pp.165-180, 2015. http://dx.doi.org/10.1016/j.enbuild.2015.06.068

[6] A**.** Garrab, A. Bouallegue, R. Bouallegue, "An agent fuzzy control for smart home energy management in smart grid environment," International Journal of Renewable energy research, vol.2, no.2, pp. 600-612, 2017.

[7] S. Bissey, S, Jacques, J.-C Le Bunetel," A Relevant fuzzy logic algorithm to better optimise electricity consumption in individual housing," in Conf. Renewable Energies and power quality, Malaga, Spain, 2017, pp. 103-107.

[8] R. Khalid, N. Javaid, M.H. Rahim, S. Aslam, A. Sher," Fuzzy logic management controller and scheduler for smart home," Sustainable Computing: Informatics and Systems, vol. 21 pp. 103-118, 2019.

[9] A. Keshtkar, S. Arzanpour," An adaptive fuzzy logic system for residential energy management in smart grid environment," Applied Energy, vol. 186 pp. 68-81,2017.

[10] J. Liu, W. Zhang, X. Chu, Y. Liu," Fuzzy logic controller for energy saving in smart LED lighting system considering lighting comfort and daylight," Energy and Building, vol. 127, pp. 95-104, 2016. http://dx.doi/10.1016/j.enbuild.2016.05.066

[11] P. Johannesson, E. Perjons," *An introduction to design science*" Switzerland: Springer International Publishing, 2014

[12] A. Henver, S. March, J. Park, S. Ram," Design Science research in information systems research, MIS Quarterly vol. 28, no. 1, pp .75-105, 2004.

[13] K. Peffers, T. Tuunamen, C.E. Gengler, M. Rassi, W. Hui, V. Virtanen, J. Bragge," The design research process: A model for producing and presenting information system research," Clermont: Desrist, 2006.
[14] R. Botes, R. Goede, I. Smit, "Demonstrating on interpretive data collection and analysis process for DSR project," Czen Institute of Academic Education, Prague: Creator of CD, 2014.
[15] B.J. Oates," Researching information systems and computing," London: SAGE Publications Ltd, 2006.
[16] R. Nembahle, K. Rantshomo, "South African Energy Sector Report Directorate: Energy Data Collection, Management and Analysis," DoE., Pretoria, South Africa, 2018.
[17] L. Ganta,Y.Chetty, T.Zulu, "Annual Performance Plan 2017/18," DoE., Pretoria, South Africa, 2018.
[18] I.Cronshaw, "World Energy outlook 2014 projections to 2040: natural gas and coal trade, and role of China," Australian Journal of Agriculture and Resource Economics vol. 59, pp. 571-585 https://onlinelibrary.wiley.com/doi/full/10.1111/1467-8489.12120
[19] R. Skimmer, "World energy trends: recent developments and their implications for Arab countries," Oxford Institute of Energy studies, 2006.
[20] International Energy Agency. (2014). "World Energy Outlook," [online]. Available: http://webstore.iea.org/download/summary/412?.filename=English-WEO-2014-ES.pdf
[21] EXXON Mobil. (2017). "Outlook *for Energy*: A view to 2040 [online]. Available: https://cdn.exxonmobil.com/~/media/global/files/outlook-for-energy/2017/2017-outlook-for-energy.pdf.
[22] EIA. (2015). "South Africa International energy data and analysis," EIA., US Energy information. [online]. Available: https://www.eia.gov/international/content/analysis/countries_long/South_Africa/south_africa.pdf
[23] DoE., "Annual Report 2015/16," DoE., Pretoria, South Africa, Rep.334, 2016.
[24] SARS. (2016). Annual report South African Revenue Services 2015-2016 [online].Available: www.gov.za
[25] T.R. Masetlana, M. Ikaneng, R. Motsie, L. Malebo, M. Machaka, P. Mwape, "South African mineral industry 2016/2017 (SAMI)," DMR., Pretoria, South Africa, 2017.

[26] Chamber of mines of South Africa. (2016). Integrated Annual Review 2016 [online]. Available: https://www.mineralscouncil.org.za/reports/2016/#home

[27] Eskom. (n.d.). Electricity Sector in South Africa [online]. Available: https://en.wikipedia.org/wiki/Electricity_sector_in_South_Africa

[28] South African Government. (2019, Feb.07). President Cyril Ramaphosa: 2019 State of the Nation Address [Online]. Available: https://www.gov.za/speeches/president-cyril-ramaphosa-2019-state-nation-address-7-feb-2019-0000

[29] Eskom Holdings. (2018). Eskom generation mix [online]. Available: www.eskom.co.za.Y2018

[30] World Energy. (2016). World energy resources [online]. Available: https://www.worldenergy.org/publications/2016/world-energy-resources-2016/

[31] Eskom. (2016, May.15). Eskom's generation plant mix [online]. Available: http://www.eskom.co.za/news/Pages/May15.aspx

[32] DoE. (n.d.). Nuclear Energy in Every Life Sunnyside, Pretoria [online]. Available: http://www.energy.gov.za/files/media/Pub/NuclearEnergyInEverydayLife_Booklet.pdf

[33] D.M. Moller," Assessment of willingness to pay and determinants influencing the large consumers` perspectives regarding the supply of premium green electricity in South Africa," Ph.D. thesis, Faculty of Economic and Management Sciences, University of Stellenbosch, South Africa, 2018.

[34] Eskom Holdings. (2017). Eskom Demand Side management [online]. Available: www.eskomdsm.co.za

[35] Eskom. (2015). Eskom heritage sites [online]. Available: www.eskom.co.za/sites/heritage/Documents

[36] D, Peters, B. Thompson, "Survey of energy to related behaviour and perception in South Africa," DoE. Pretoria. South Africa, 2012.

[37] DoE, "Non grid electrification policy guideline" DoE., Pretoria, South Africa, 2018.

[38] Statistics South Africa. (2018, Nov. 9). Four facts about indigent households[online]. Available: www.statssa.gov.za/?p=11722

[39] DoE, "Strategic National Grid Vision for the South African Electricity Supply Industry," DoE., Pretoria, South Africa, 2017.

[40] R. Madlener, Y. Sunak, (2011) Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management? Sustainable Cities and Society, vol.1, no.1, pp.45-53, 2011.

[41] Economic Report on Africa. (2017). An overview of urbanisation and structural transformation in Africa [online]. Available: https://www.uneca.org/sites/default/files/uploaded-documents/ERA/ERA2017/chap3_03.pdf

[42] SEA. (2014, September). Tackling urban energy poverty in South Africa [online]. Available: https://www.sustainable.org.za/upload/files/file75.pdf.

[43] Y. Omorogbe, A.O. Ordor, "Ending Africa`s energy deficit and law achieving sustainable energy for all in Africa," United States of Kingdom: Oxford University Express, 2018.

[44] D. Geldeblom, P. Kok, "Urbanisation South Africa`s challenge Volume 1. Dynamics," Pretoria: HSRC Publishers, 1994.

[45] A.A. Eberhard, C. van Horen, "Poverty and Power: Energy in South African State,". London: Pluto Press, Cape Town: UCT,1995.

[46] Eskom. (2015). Consumption load profile [online]. Available: http://twitter.com/Eskom_SA

[47] Z. Maury, R.D. Redondo, A.F. Vilas, "Reducing Energy consumption through the use of home energy management systems (HEM) and gamification" American Journal of Engineering Research (AJER) vol.6, no. 9, pp. 117-125, 2017.

[48] DoE, "South African energy efficiency label appliance sales training for retail sector learner," DoE., Pretoria, South Africa, February 2018.

[49] J.T. Cousins, "*Using the time of use (ToU) tariffs in industrial commercial and residential applications effectivel*y," TLC Engineering Solutions PTY (LTD), Sandton, 2010.

[50] Eskom Holdings. (n.d.). Home flex [online]. Available: eskom.co.za/CustomerCare/TariffsAndCharges/Documents/Eskom%20Booklet.pdf

[51] The Citizens. (2018, April, 19). The Eskom`s coal shortage explained [online]. Available : https://citizen.co.za/news/south-africa/1899435/eskoms-coal-shortage-problems-explained/

[52] News24. (2019, April, 26). State capture enquiry [online]. Available: https://www.news24.com/SouthAfrica/News/state-capture-inquiry-eskom-forced-to-conclude-multibillion-rand-tegeta-coal-supply-deal-in-just-48-hours-20190226

[53] P. Lehohla, "GHS Series Volume. Energy 2002-2012 In-depth analysis of general household survey data. StatsSA., Pretoria, South Africa. Rep. 03-18-04, (2002-2012).

[54] Radio Islam News. (2018, May, 25). Residents of Northern place in Lenesia fed after electricity cuts [online]. Available:
http://www.radioislam.org.za/a/index.php/latest-news/23706-residents-of-northern-place-in-lenasia-fed-up-after-electricity-cuts.html

[55] MyBroadband. (2015, June, 10). The real reasons for power blackouts in South Africa [online]. Available:
https://mybroadband.co.za/news/energy/128942-the-real-reasons-for-power-blackouts-in-south-africa.html

[56] ENW news. (n.d.) Eskom warns of high risk of load shedding due to shortage of capacity [online]. Available: https://ewn.co.za/2019/03/11/eskom-warns-of-high-risk-of-load-shedding-due-to-shortage-of-capacity

[57] Local government (2011). Local government budget and expenditure review 2006/7-2012/13 [online]. Available: www.treasury.gov.za/publications/igfr/2011/lg/02.%202011%20LGBER%20-%20Final%20-%2013%20Sept%202011%20(renumbered).pdf

[58] R. Goebel, Y. Tanaka, W. Wahlster," Artificial intelligence," Switzerland: Springer imprint, 2018.

[59] M. Modiang, R. Nembahle, "South African Energy Price Report.2017. Energy Data, Management and Analysis Directorate," DoE., Pretoria, South Africa, 2017.

[60] Eskom, "Medium –Term System Adequacy Outlook 2017-2022," Eskom, South Africa, 2017.

[61] D. Javor, A. Janjic, "Application of demand side management techniques in successive optimization procedures," CDQM, An Int. J. vol.19, no. 4 pp. 40-51, December 2016.

[62] M.H. Hasheni, M. Maradlou, M. Bogdeli, "Energy management of industrial loads in a smart microgrid using PSO algorithm," in Conf., Optimisation in Science and Engineering, Iran, January 2015.

[63] O.M. Longe, K. Ouahada, H.C. Ferreira, S. Rimer, "Consumer preference electricity usage for demand side management in a smart grid," SAIEE., vol.108 no.4, pp. 174-183, Dec.2017.

[64] A. U. Mahin, M. A. Sakib, M. A. Zaman, M. S. Chowdhury and S. A. Shanto, "Developing demand side management program for residential electricity consumers of Dhaka city," in Conf. *Electrical, Computer and Communication Engineering (ECCE)*, Cox's Bazar, 2017, pp. 743-747.

[65] Government Gazette, "Draft Post -2015 National Energy Efficiency Strategy," DoE., Pretoria, South Africa, Rep. 948, 2015.
[66] Federal Energy Regulatory Commission. (2018, Nov.7). Reports on Demand Response and Advanced Metering [online]. Available: https://www.ferc.gov/industries/electric/indus-act/demand-response/dem-res-adv-metering.asp
[67] D. Lizondo, P. Araujo, A. Will and S. Rodriguez, "Multiagent Model for Distributed Peak Shaving System with Demand-Side Management Approach," *2017 First IEEE* in Conf. Robotic Computing (IRC), Taichung, 2017, pp. 352-357. doi: 10.1109/IRC.2017.50
[68] H.T. Haider, O.H. See, W. Elmenreich, "A review of residential demand response of smart grid," Renewable and Sustainable Energy reviews vol. 59 pp. 166-178, 2016. http://dx.doi.org/10.1016/j.rser.2016.01.016
[69] F. Lobes, H. Coelho, (Eds), "Electricity markets with increasing levels of renewable generation: Structure, operation, agent-based simulation and emerging designers," Switzerland: Springer, 2018.
[70] D. Srinivasan, S. Rajgarhia, B.M. Radhakrishnan, A. Sharma, H.B. Khincha, "Game theory based dynamic pricing strategies for demand side management in smart grid, "Energy, vol.126, pp. 132-143, 2016. http://dx.doi.org/10.1016/j.energy.2016.11.142
[71] Sustainable energy regulations and policy making for Africa. (n.d.) Demand side management, chapter 14 [online]. Available: africa-toolkit.reeep.org/modules/Module14.pdf

[72] N. Maistry, T.M. Mckay, "Promoting energy efficiency in South African university. Journal of Energy in Southern Africa," vol. 27, no. 3, pp. 1-10, 2016.
[73] International risk governance council, Energy Center Cen. (2015). Challenges and opportunities of Demand Response in the context of energy transition [online]. Available: www.irgc.org/wp-content/uploads/2015/04/Challenges-and-Opportunities-of-Demand-Response-IRGC-overview-April2015.pdf
[74] NERSA, "System adequacy outlook," NERSA, South Africa, no. 16: August 2018
[75] S. Althaher, P. Mancarella, J. Mutale, "Automated demand response from home energy management system under dynamic pricing and power and comfort constraints," IEEE Transactions on smart grid, vol. 6, pp. 1874-1883, 2015.

[76] F. Lauro, F. Moretti, F. A. Capozzoli, S. Panzieri, “Model predictive control for building active demand response systems,” Energy Procedia vol.83 pp. 494-503, 2015. Doi:10: 1016/j.egypro.2015.12.167.

[77] I. Sharma, J. Dong, A.A. Malikopoulos, M. Street, J. Ostrowski, T. Kuruganti, R A. Jackson, “Modelling framework for optimal energy management of residential building,” Energy and Building vol.130, pp. 55-63,2016. http://dx.doi.org/10.1016/j.enbuild.2016.08.009

[78] K.X. Peres, M. Baldea, T.F. Edgar, “Integrated HVAC management and optional scheduling of smart appliances for community peak load reduction,” Energy and Building vol.123, pp. 34-40, 2016. http://dx.doi.org/10.1016/j.enbuild.206.04.003

[79] G. Tayfur, “Soft computing in water resources engineering: Artificial neural networks, fuzzy logic and genetic algorithms,” Izmir Institute of Technology Turkey. Boston: Wit Press, 2012.

[80] A. Keshtkar, S. Arzanpour, F. Keshtkar, “Adaptive residential demand side management using rule based techniques in smart grid environment,” Energy and Buildings, vol. 133, pp. 281-294,2016. http://dx.doi.org/10.1016/j.enbuild.2016.19.070

[81] F. Bauhafs, M. Mackay, M. Merabti, “Communication challenges and solutions in smart grid,” London: Springer. 2014.

[82] H. Shareef, M.S. Ahmed, A. Mohamed, E. A. Hassan, “A. Review on home energy management system considering demand response, smart technologies and intelligent controllers,” IEEE Access, vol.6, pp. 24498- 24509, 2019. DOI: 10.1109/Acess.2018.2831917.

[83] B. Mubdir, A. Hindawi, N. Hadi, “Design a smart home energy system for saving energy,” European Scientific Journal vol.12, no.33, pp. 857-7881,2016.

[84] B. Zhou, W. Li, K.W. Chan, Y. Cao, Y. Kwang, X. Liu, Wang, “Smart home energy management system: Concepts, configuration and scheduling strategies,” Renewable and sustainable energy Reviews, vol. 6 pp. 20-40, 2016. http://10.106/j.rser.2016.03.047

[85] P.N. Krishna, S.R. Gupta, P.V. Shankaranarayaman, S. Sidharth, M. Sirphi, “Fuzzy logic based smart home energy management system,” in Conf. Computer, Communication and Network Technologies, Bengaluru, India, 2018.

[86] T.J. Ross, “Fuzzy logic with engineering applications,” The University of New Mexico. United Kingdom: John Wiley & Sons LTD,2010.

[87] T. Ahmad, H. Chen, “Nonlinear autoregressive and random forest approaches to forecasting electricity load for utility energy management systems,” Sustainable Cities and Society, vol. 45, pp. 460-473, 2019.
[88] S. Bissey, S. Jacques, J.C. Le Bunetel, “The fuzzy logic method to efficiently optimise electricity consumption,” Energies, vol.10, pp. 170,2017.
[89] F. C. Torrini, R. C. Souza, F. L. C. Oliveira, J. F. M. Pessanha, “Long term electricity consumption forecast in Brazil: A fuzzy logic approach,” Socio-Economic Planning Sciences, vol.54, pp. 18-27, 2016.
[90] K.V. Zúñiga, I. Castilla, R.M. Aguilar, “Using fuzzy logic to model the behaviour of residential electrical utility customers,” Applied Energy, vol. 115, pp. 384-393, 2014.
[91] L. Ciabattoni, M. Grisostomi, G. Ippoliti, S. Longhi, “Fuzzy logic home energy consumption modelling for residential photovoltaic plant sizing in the new Italian scenario,” Energy, vol. 74, pp. 359-367, 2014.
[92] L. Ciabattoni, F. Ferracuti, M. Grisostomi, G. Ippoliti, S. Longhi,”Fuzzy logic based economic analysis of photovoltaic energy management, “ Neurocomputing, vol. 170, pp. 296-305, 2015.
[93] L. Ciabattoni, M. Grisostomi, G. Ippoliti, L. Longhi, “A fuzzy logic tool for household electrical consumption modelling,” in Conf. Italy, November 2013.
[94] A. Al-Mousa, A. Faza, “A fuzzy-based customer response prediction model for a day-ahead dynamic pricing system,” Sustainable Cities and Society, vol. 44, pp. 265-274, 2019.
[95] C. Spandagos, T. Ling Ng, “Fuzzy model of residential energy decision-making considering behavioural economic concepts,” Applied Energy, vol. 213, 2018, pp. 611-625, 2018.
[96] A. Keshtkar, S. Arzanpour, F. Keshtkar, P. Ahmadi, “Smart residential load reduction via fuzzy logic, wireless sensors and smart grid incentives,” Energy and Buildings, vol.104, pp. 165-180, 2015. http://dx.doi.org/10.1016/j.enbuild.2015.06.068
[97] A. Garrab, A. Bouallegue, R. Bouallegue, “An agent based fuzzy control for smart home energy management in smart grid environment,” International Journal of Renewable energy research, vol. 7, no.2, 2017.
[98] M. Soudari, S. Srinivasan, S. Balasubramanian, J. Vain, U. Kotta, “Learning based personalized energy management systems for residential buildings,” Energy and Buildings, vol. 127, pp. 953-968, 2016.

[99] J. Raish, W. Lang, A. McClain," Thermal Comfort: Designing for people," The University of Texas at Austin, School of Architecture Csd.

[100] D. Meana-Llorián, C. G. García, B.C. P. G-Bustelo, J. M. C. Lovelle, N.G. Fernandez, "IoFClime: The fuzzy logic and the Internet of Things to control indoor temperature regarding the outdoor ambient conditions," Future Generation Computer Systems, vol. 76, pp. 275-284, 2017.

[101] A. Keshtkar, S. Arzanpour, "An adaptive fuzzy logic system for residential energy management in smart grid environment," Applied Energy vol.186, pp. 68-81, 2017.

[102] R. Khalid, S. Abid, A. Yasmeen, Z.A. Khan, U. Qasim, N. Javaid, "Fuzzy energy management controller for smart homes," in Conf. Innovative mobile and internet services in ubiquitous computing, University of Alberta, Edmonton, May 2017.

[103] Y. Krim, D. Abbes, S. Krim, M. F. Mimouni, "Intelligent droop control and power management of active generator for ancillary services under grid instability using fuzzy logic technology," Control Engineering Practice, vol. 81, pp. 215-230,2018.

[104] E-T. Chok, Y. S. Lim, K. H. Chua, "Novel fuzzy-based control strategy for standalone power systems for minimum cost of electricity in rural areas," Sustainable Energy Technologies and Assessments, vol. 31, pp. 199-211, 2019.

[105] S. Berrazouane, K. Mohammedi, "Parameter optimization via cuckoo optimization algorithm of fuzzy controller for energy management of a hybrid power system," Energy Conversion and Management, vol. 78, pp. 652-660, 2014.

[106] E. De Santis, A. Rizzi, A. Sadeghian, "Hierarchical genetic optimization of a fuzzy logic system for energy flows management in microgrid," Applied Soft Computing, vol. 60, pp. 135-149, 2017.

[107] A. Desch, D.P. Lacerda, J. Antunes Jr, V. Antonio, "Design Science Research: A method for science and technology advancement", Springer,2015.

[108] S. Parbanath, "Computer based productivity estimation of academic staff using the fuzzy analytic hierarchy process and fuzzy topsis method," Ph.D. thesis, School of Information Systems and Faculty of Management Studies, University of KwaZulu Natal, South Africa, 2014.

[109] K. Peffers, T. Tuunamen, M.A. Rothenberger, S. Chatterjee, "A design research methodology for information systems research" Journal of Management Information System vol. 24, no 3, pp. 45-78, 2007.

[110] A. Henver, S. Chatterjee, “Design Research in Information Systems: Theory and Practise. New York: Springer Science + Business Media LLC, 2010.

[111] A. Sadollah, “Fuzzy logic based in optimisation and control”, School of mechanical engineering, Sharif University of Technology, Iran, 2018.

[112] H.B. Verbruggen, R. Babuska, “Fuzzy logic control advances in applications”, Singapore: World Scientific Publishing Co. Pte. Ltd. 1999.

[113] N. Siddique, “Intelligence control: A hybrid approach based in fuzzy logic, neural networks and genetic algorithms”, Switzerland: Springer International Publishing,2014.

[114] L. Resnik, “Fuzzy controllers”, Victoria University of Technology, Melbourne, Australia: Newnes,1997.

Appendices

Appendix A: Off peak price and adequate electricity

Time	Load Status	Price (cents)	Load Consumption (kw/	Remaining Daily limit (kw in %age)
12/18/2019 04:49:10	75,060247	15	24,648567	98,788543
12/18/2019 04:50:00	75,115227	15	24,731547	98,457087
12/18/2019 04:51:00	75,15445	15	24,82878	98,071515
12/18/2019 04:52:00	75,075054	15	24,928507	97,679179
12/18/2019 04:53:31	74,996733	15	25,070875	97,124496
12/18/2019 04:54:10	74,998768	15	7,297213	97,032037
12/18/2019 04:55:00	74,999371	15	7,303727	96,945489
12/18/2019 04:56:00	75,000185	15	7,312481	96,829436
12/18/2019 04:57:30	75,001396	15	7,325428	96,658307
12/18/2019 04:58:00	75,109998	15	97,390051	96,093811
12/18/2019 04:59:00	75,022002	15	88,875673	94,791204
12/18/2019 05:00:00	74,800141	15	100	93,465977
12/18/2019 05:00:10	75,032297	15	56,897631	93,306165
12/18/2019 05:01:00	75,022443	15	57,323481	92,613003
12/18/2019 05:02:00	74,998728	15	57,774293	91,890345
12/18/2019 05:02:31	75,006843	15	57,979013	91,565886
12/18/2019 05:03:01	75,009802	15	4,335543	91,449976
12/18/2019 05:10:01	75,005637	15	2,793105	91,240644
12/18/2019 05:20:00	75,006135	15	2,800624	90,99569
12/18/2019 05:30:00	75,006534	15	2,806673	90,799585
12/18/2019 05:39:02	75,006847	15	2,811429	90,645958
12/18/2019 05:39:30	75,107186	15	9,505312	90,624468
12/18/2019 05:40:00	75,105788	15	9,508576	90,593359
12/18/2019 05:50:01	75,070207	15	9,579682	89,920924
12/18/2019 06:00:00	75,044743	15	1,567795	89,545396
12/18/2019 06:10:01	75,044414	15	1,569387	89,454526
12/18/2019 06:20:01	75,044109	15	1,57086	89,370676
12/18/2019 06:30:01	75,043834	15	1,572191	89,295016
12/18/2019 06:40:01	75,043579	15	1,573428	89,224816
12/18/2019 06:50:00	75,043343	15	1,574577	89,159686
12/18/2019 06:59:01	75,043146	15	1,575535	89,105476

Appendix B: Standard price and adequate electricity

Time	Load Status	Price(cents)	Load Consumption (kw/h)	Remaining Daily Limit (kw in %age)
12/18/2019 07:00:01	75,043124	45	1,575638	89,099626
12/18/2019 07:02:01	75,043082	45	1,575845	89,087926
12/18/2019 07:04:03	74,992857	45	8,891839	89,047386
12/18/2019 07:06:03	74,991293	45	8,897994	88,985797
12/18/2019 07:08:00	74,989713	45	8,904156	88,924208
12/18/2019 07:10:00	74,988115	45	8,910328	88,862619
12/18/2019 07:11:01	74,800141	45	29,873036	88,811907
12/18/2019 07:12:00	74,800141	45	29,905299	88,716093
12/18/2019 07:14:02	74,800141	45	29,975025	88,509726
12/18/2019 07:16:00	74,800141	45	30,040063	88,318099
12/18/2019 07:19:00	75,084678	45	33,126983	88,066804
12/18/2019 07:20:03	75,087575	45	33,166662	87,961446
12/18/2019 07:22:02	75,093186	45	33,246306	87,750729
12/18/2019 07:25:01	75,022999	45	52,441043	87,050569
12/18/2019 07:26:00	75,050346	45	40,787878	86,856077
12/18/2019 07:28:01	75,046851	45	40,903747	86,610039
12/18/2019 07:30:00	75,043394	45	41,020276	86,364
12/18/2019 07:32:00	75,039976	45	41,137471	86,117961
12/18/2019 07:34:01	75,036595	45	41,255337	85,871922
12/18/2019 07:36:03	75,033251	45	41,373881	85,625884
12/18/2019 07:37:02	75,031658	45	41,431024	85,507785
12/18/2019 07:38:01	75,030074	45	41,488326	85,389686
12/18/2019 07:39:00	75,028498	45	41,545786	85,271588
12/18/2019 07:40:04	75,0268	45	41,608214	85,143648
12/18/2019 07:41:03	75,025241	45	41,666007	85,025549
12/18/2019 07:42:04	75,018333	45	50,947921	84,9031
12/18/2019 07:43:00	75,011848	45	62,363175	84,751933
12/18/2019 07:44:00	75,012044	45	62,493095	84,575739
12/18/2019 07:46:02	75,012436	45	62,754564	84,223351
12/18/2019 07:48:00	75,011903	45	63,0072	83,885645
12/18/2019 07:50:04	75,010662	45	63,272999	83,533257
12/18/2019 07:52:03	75,009462	45	63,529835	83,195552
12/18/2019 07:54:04	75,011073	45	63,788764	82,857847
12/18/2019 07:56:00	74,800141	45	100	82,28198
12/18/2019 07:58:03	74,800141	45	100	81,120524
12/18/2019 07:59:02	74,800141	45	100	80,47515

Appendix C: Peak price and adequate electricity

Time	Load Status	Price(cents)	Load Consumption(kw/h)	Remaining Daily Limit(kw in %age)
12/18/2019 08:00:02	24,673469	80	100	79,829775
12/18/2019 08:01:01	75,006866	80	7,382888	79,798875
12/18/2019 08:02:02	75,007027	80	7,384554	79,780872
12/18/2019 08:03:02	75,007188	80	7,38622	79,762869
12/18/2019 08:04:02	75,00735	80	7,387888	79,744866
12/18/2019 08:05:02	75,007511	80	7,389556	79,726863
12/18/2019 08:10:03	75,008308	80	7,397757	79,638484
12/18/2019 08:15:02	75,009095	80	7,405823	79,551742
12/18/2019 08:16:00	75,009244	80	7,407347	79,535375
12/18/2019 08:17:04	74,800141	80	10,000278	79,506701
12/18/2019 08:18:03	74,800141	80	10,000278	79,484617
12/18/2019 08:19:02	74,800141	80	10,000278	79,462539
12/18/2019 08:20:01	74,800141	80	10,000278	79,440467
12/18/2019 08:30:05	74,800141	80	10,000278	79,215683
12/18/2019 08:50:00	74,800141	80	10,000278	78,789907
12/18/2019 09:00:06	74,800141	80	10,000278	78,58661
12/18/2019 09:10:05	74,800141	80	10,000278	78,39037
12/18/2019 09:20:02	74,800141	80	10,000278	78,201138
12/18/2019 09:30:03	74,800141	80	10,000278	78,016697
12/18/2019 09:40:00	74,800141	80	10,000278	77,839177
12/18/2019 09:50:04	74,800141	80	10,000278	77,66422
12/18/2019 09:59:53	74,800141	80	10,000278	77,498267

Appendix D: Standard price and enough electricity

Time	Load Status	Price(cents)	Load Consumption(kw/h)	Remaining Daily limit (kw in %age)
12/18/2019 10:00:00	74,800141	45	100	77,473812
12/18/2019 10:10:05	74,800141	45	100	75,590846
12/18/2019 10:20:07	74,800141	45	100	73,756787
12/18/2019 10:30:06	74,800141	45	100	71,971637
12/18/2019 10:40:02	74,800141	45	100	70,235395
12/18/2019 10:50:01	74,800141	45	100	68,523607
12/18/2019 11:00:05	74,800141	45	100	66,836273
12/18/2019 11:10:01	74,800141	45	100	65,197847
12/18/2019 11:20:02	74,800141	45	100	63,583876
12/18/2019 11:30:01	74,800141	45	100	61,994358
12/18/2019 11:40:03	74,800141	45	100	60,429295
12/18/2019 11:50:07	74,800141	45	100	58,888686
12/18/2019 12:00:02	74,800141	45	100	57,396985
12/18/2019 12:10:08	74,800141	45	100	55,905284
12/18/2019 12:20:05	74,800141	45	100	54,462491
12/18/2019 12:30:07	74,800141	45	100	53,019698
12/18/2019 12:40:09	74,800141	45	100	51,60136
12/18/2019 12:50:02	74,800141	45	100	50,231929
12/18/2019 13:00:01	74,800141	45	100	48,862499
12/18/2019 13:10:01	74,800141	45	100	47,517523
12/18/2019 13:20:07	74,800141	45	100	46,172546
12/18/2019 13:30:00	74,800141	45	100	44,876478
12/18/2019 13:40:01	74,800141	45	100	43,58041
12/18/2019 13:50:08	74,800141	45	100	42,284342
12/18/2019 14:00:00	74,800141	45	100	41,037183
12/18/2019 14:10:08	74,800141	45	100	39,765569
12/18/2019 14:20:01	74,800141	45	100	38,542863
12/18/2019 14:30:01	74,800141	45	100	37,320157
12/18/2019 14:40:08	74,800141	45	100	36,097451
12/18/2019 14:50:09	74,800141	45	100	34,8992
12/18/2019 15:00:05	74,800141	45	100	33,725402
12/18/2019 15:10:01	74,800141	45	100	32,551605
12/18/2019 15:20:07	74,800141	45	100	31,377807
12/18/2019 15:30:07	74,800141	45	100	30,228464

Appendix E: Standard, peak price and less electricity

Time	Load Status	Price(cents)	Load Consumption (kw/h)	Remaining Daily limit (kw in %age)
12/18/2019 15:32:15	24,673469	45	100	29,983923
12/18/2019 15:32:27	24,673469	45	10,000278	29,98309
12/18/2019 15:32:40	24,673469	45	10,000278	29,982257
12/18/2019 15:32:53	24,673469	45	10,000278	29,981424
12/18/2019 15:35:16	24,673469	45	10,000278	29,972264
12/18/2019 15:40:00	24,673469	45	10,000278	29,953951
12/18/2019 15:50:04	24,673469	45	10,000278	29,915698
12/18/2019 16:00:09	24,673469	45	10,000278	29,877493
12/18/2019 16:10:10	24,673469	45	10,000278	29,840166
12/18/2019 16:20:08	24,673469	45	10,000278	29,802885
12/18/2019 16:30:03	24,673469	45	10,000278	29,766478
12/18/2019 16:40:03	24,673469	45	10,000278	29,730116
12/18/2019 16:50:09	24,673469	45	10,000278	29,693798
12/18/2019 17:00:09	24,673469	45	10,000278	29,658348
12/18/2019 17:10:11	24,673469	45	10,000278	29,622941
12/18/2019 17:20:10	24,673469	45	10,000278	29,586754
12/18/2019 17:30:02	24,673469	45	10,000278	29,552253
12/18/2019 17:40:02	24,673469	45	10,000278	29,517792
12/18/2019 17:50:09	24,673469	45	10,000278	29,483371
12/18/2019 17:59:58	24,673469	45	10,000278	29,450627
12/18/2019 18:00:13	24,673469	80	10,000278	29,449809
12/18/2019 18:10:02	24,673469	80	10,000278	29,417102
12/18/2019 18:20:11	24,673469	80	10,000278	29,383615
12/18/2019 18:30:06	24,673469	80	10,000278	29,350167
12/18/2019 18:40:05	24,673469	80	10,000278	29,31757
12/18/2019 18:50:13	24,673469	80	10,000278	29,28501
12/18/2019 19:00:08	24,673469	80	10,000278	29,253299
12/18/2019 19:10:04	24,673469	80	10,000278	29,221622
12/18/2019 19:20:10	24,673469	80	10,000278	29,18998
12/18/2019 19:30:09	24,673469	80	10,000278	29,159181
12/18/2019 19:40:08	24,673469	80	10,000278	29,128415
12/18/2019 19:50:00	24,673469	80	10,000278	29,098491
12/18/2019 19:55:07	24,673469	80	10,000278	29,083136

Appendix F: Day change and recalculation of the remaining daily limit

Time	Load Status	Price(cents)	Load Consumption (kw/h)	Remaining Daily Limit (kw in %age)
12/18/2019 23:58:49	24,673469	15	10,000278	28,409166
12/18/2019 23:59:07	75,021572	15	2,470659	100
12/18/2019 23:59:27	74,800141	15	76,571366	99,978733
12/18/2019 23:59:46	74,800141	15	76,587657	99,957466
12/19/2019 00:00:05	74,800141	15	76,603956	99,936199
12/19/2019 00:10:05	74,906073	15	77,129189	99,255655
12/19/2019 00:20:08	75,098459	15	77,661674	98,575111
12/19/2019 00:30:09	75,115378	15	78,201563	97,894567
12/19/2019 00:40:18	75,007443	15	78,749011	97,214023
12/19/2019 00:50:12	75,002735	15	79,28671	96,554746
12/19/2019 01:00:14	75,047784	15	79,831803	95,895469
12/19/2019 01:10:14	75,040611	15	80,384442	95,236192
12/19/2019 01:20:14	75,000378	15	80,944786	94,576915
12/19/2019 01:30:19	75,010695	15	81,512997	93,917638
12/19/2019 01:40:00	75,033168	15	82,070527	93,279627
12/19/2019 01:50:09	75,0227	15	82,654709	92,62035
12/19/2019 02:00:06	75,021815	15	83,228021	91,98234
12/19/2019 02:10:16	74,992166	15	43,154002	91,573397
12/19/2019 02:20:12	74,995671	15	43,309764	91,244058
12/19/2019 02:30:20	74,998446	15	43,466654	90,914718
12/19/2019 02:40:13	75,001103	15	43,619398	90,596357
12/19/2019 02:50:04	75,003735	15	43,77322	90,277995
12/19/2019 03:00:04	75,006344	15	43,928131	89,959633
12/19/2019 03:10:05	75,008929	15	44,084142	89,641272
12/19/2019 03:20:10	75,01149	15	44,241265	89,32291
12/19/2019 03:30:20	75,014029	15	44,399513	89,004549
12/19/2019 03:40:08	75,016458	15	44,553381	88,697165
12/19/2019 03:50:03	75,018866	15	44,708319	88,389782
12/19/2019 04:00:04	75,021253	15	44,864339	88,082398
12/19/2019 04:10:12	75,023621	15	45,021452	87,775014
12/19/2019 04:20:20	75,025967	15	45,179669	87,467631
12/19/2019 04:30:15	75,028212	15	45,333292	87,171225
12/19/2019 04:40:13	75,030438	15	45,487963	86,87482
12/19/2019 04:50:12	75,032645	15	45,643693	86,578414
12/19/2019 05:00:16	75,034835	15	45,800494	86,282008

Appendix G: Overall 24-hour simulation

Time	Load Status	Price(cents)	Load Consumption(kw/h)	Remaining Daily Limit (kw in %age)
12/18/19 4:59:00	75,06	15	24,65	98,79
4:54	74,99	15	7,33	97,03
4:52	75,11	15	97,39	96,09
5:00	74,8	15	100	93,47
5:10	75	15	2,79	91,56
5:39	75,11	15	9,5	90,6
6:00	75,04	15	1,56	89,92
6:59	75,04	15	1,57	89,11
7:00	75,04	45	1,57	89,09
7:04	74,9	45	8,89	89,04
7:09	74,9	45	8,89	88,86
7:10	74,8	45	29,94	88,51
7:19	75,1	45	33,17	88,06
7:23	75,05	45	90,9	87,75
7:34	75,03	45	41,25	85,87
7:56	74,8	45	100	81,12
8:00	24,68	80	100	79,79
8:02	75	80	7,38	79,78
8:16	75	80	10	79,5
9:59	74,5	80	10	77,49
10:00	74,8	45	100	77,47
15:31	74,8	45	100	30,008
15:32	24,67	45	10	29,98
22:00	24,67	15	10	28,72
23:55	24,67	15	10	28,41
23:59	75,02	15	2,47	100
12/19/19 12:00:00	75	15	76,6	99,93
1:00	75,04	15	79,83	95,89
2:00	75,02	15	83,22	91,98
3:00	75	15	43,93	89,95
4:00	75,02	15	45,02	87,77
5:00	75,05	15	45,8	86,25