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UNIVERSITÉ DE TLEMCEN

Pan African University
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Institute of Water and Energy Sciences (Incl. Climate Change)

DEVELOPING A REAL-TIME SMS FEEDBACK TOOL FOR OFF-GRID HOUSEHOLD ELECTRICITY CONSUMPTION

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Date: 06/09/2017

Master in Energy (Engineering Track)

Jury of Examiners

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Academic Year: 2016-2017

This thesis is submitted in partial fulfillment for the award of

Master in Energy Engineering

DECLARATION

I Kukeera Tonny, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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ACKNOWLEDGEMENT

Firstly, I am grateful to God for the good health and well-being that were necessary to complete this thesis. I wish to express my sincere appreciation to PAUWES administration and the management of MicroEnergy International for the support and facilities without which this thesis would not be possible.

I am also grateful to Noara Kebir, for the support; technical, financial and moral; and most importantly for being a mum to me throughout my stay in Germany. I extend my thanks to her family for making my stay in Berlin worthwhile.

I put on record my utmost thanks to my supervisor, Dr. Sebastian Groh, for the guidance in developing this thesis.

I also appreciate, Setu Pelz and Michael Goette, colleagues in the Micro Energy soldesign department. I am extremely thankful and indebted to them for sharing expertise, sincere and valuable guidance, and for reviewing my work.

I am thankful to my mum and my sister for the unceasing encouragement, support and attention.

To my colleagues, Vivian, Rolex, Yunus; I cannot thank you enough, I am forever grateful.

I also place on record, my sense of gratitude to one and all, who directly or indirectly, have lent their hands in this venture.

ABSTRACT

Close to 95% of the 1.2 billion global population without grid access live in Sub Saharan Africa, South and East Asia, and the remainder is spread just about equally across Middle East, Central Asia and Latin America. The situation is worse in Africa with the continent having some of the countries with the lowest electrification rates. For instance, in Liberia, Chad and Burundi, only 1 in 20 people have access to the grid. The main cause of this has been reported to be high costs involved in grid infrastructure extensions and community settlement arrangements where many communities are isolated. Off-grid energy systems have proven to be a silver-bullet to most of SSA energy access problems. Investments in the off-grid industry have grown by a 15-fold since 2012 to $276 million in 2015 with Pay-As-You-Go companies taking over 87% of the investments. It is estimated that 1 in 3 off-grid households globally will use off-grid solar by 2020, however, the off-grid system still suffers from problems, the main ones being operation and maintenance/user errors, capacity limitation and ensuring energy efficiency. Energy efficiency is a very critical part of energy systems because by boosting the efficiency of production, transmission and distribution processes, it frees up resources, thereby acting as a virtual power source. Therefore, in the move to ensure sustainable and equitable energy access, energy efficiency is an indispensable part that cannot be overlooked in developing economies. In this thesis therefore, a real-time SMS tool that informs off-grid households their electricity consumption through short text messages on their phones is developed. By informing users of their consumption, it is anticipated that energy awareness is enhanced thereby influencing users' behaviors and hence promoting energy efficiency. Besides awareness, majority of energy users often lack sufficient knowledge and skills to reduce their energy consumption, the tool aims to address this problem as well. The tool provides timely feedback about consumption through simple and understandable text messages. The algorithm collects data from the three main parts of the solar system i.e. power generation, storage and consumption. This is translated into simpler SMS which are sent to the user.

The thesis demonstrates that it is possible to avail consumption information timely to off-grid energy users and that this could be leveraged to improve energy efficiency in off-grid systems.

Key words: Energy Efficiency, Off-grid Energy, SMS, Feedback

RESUME

Près de 95% des 1.2 milliards de la population mondiale n'ayant pas accès direct à un réseau électrique vivent en Afrique Sub Saharienne, en Asie du Sud et de l'Est, et le reste est répandu juste à peu près également à travers le Moyen-Orient, l'Asie Centrale et l'Amérique Latine. La situation est pire en Afrique où certains pays ont les plus bas taux d'électrification. Par exemple au Liberia, au Tchad et au Burundi, seulement 1 sur 20 personnes ont accès à un réseau électrique. La principale cause est liée au coût élevé des infrastructures d'extension du réseau électrique et des dispositions de règlement d'implantation communautaire où plusieurs communautés sont éparpillées. Les systèmes énergétiques non connecté au réseau électrique ont prouvé, être une balle en argent (solution miracle) pour la plupart des problèmes d'accès à l'énergie en Afrique Sub Saharienne. Les investissements dans l'industrie du réseau électrique sont multipliés par 15 depuis 2012 à 276 million de dollars en 2015 avec les compagnies de Pay-As-You-Go qui prennent le dessus avec 87% des investissements. Il est estimé que 1 sur 3 ménages abonné au réseau électrique utilisera un système énergétique solaire d'ici 2020, cependant, le système souffre toujours de problèmes ; les principaux étant la limitation de capacité et l'assurance du rendement énergétique. Le rendement énergétique est une partie très critique du système énergétique car en stimulant l'efficacité de la production, la transmission et les processus de distribution, il libère des ressources, agissant ainsi comme une source de puissance virtuelle. Dans l'optique d'assurer un accès à l'énergie durable et équitable, l'efficacité énergétique est une partie indispensable qui ne peut être ignorée dans les économies en voie de développement. Dans cette thèse, un outil de SMS en temps réel qui informe les ménages non-abonnés au réseau électrique sur leur consommation d'électricité par un court message texte sur leur téléphone est développé. En informant les utilisateurs de leur consommation, c'est anticipé l'amélioration de la prise de conscience de l'utilisation de l'énergie ; ceci influencera les comportements des utilisateurs et par conséquent le rendement énergétique. En plus de la prise de conscience, la majorité des utilisateurs d'énergie manque souvent de connaissances suffisantes et de compétences pour réduire leur consommation d'énergie, l'outil a pour but d'aborder ce problème aussi. L'outil fournit un retour d'information opportune de la consommation par des SMS simples et compréhensibles. L'algorithme rassemble les données des trois parties principales du système solaire c'est à dire la génération d'énergie, le stockage et la consommation.

Ceci est traduit dans le SMS qui est envoyé à l'utilisateur plus simplement. Cette thèse démontre qu'il est possible d'envoyer des informations de consommation à temps réel aux utilisateurs non-abonnés au réseau d'énergie et ceci pourrait être utilisé pour améliorer le rendement énergétique dans les systèmes non connecté au réseau énergétique.

Mots clés: Rendement énergétique, Energie hors réseau, SMS, Retour d'information, Pay-As-You-Go.

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ACRONYMS

API	Application Program Interface
DC	Direct Current
EE	Energy Efficiency
EPP	Energy Poverty Penalty
GDP	Gross Domestic Product
GHG	Green House Gas
GSM	Global System for Mobile Communication
IEA	International Energy Agency
KiBaM	Kinetic Theory Battery Model
kWp	Kilo Watt Peak
MEMD	Ministry of Energy and Mineral Development
MPP	Maximum Point Track
MW	Mega Watt
MWp	Mega Watt Peak
NDP	National Development Program
OECD	Organization for Economic Co-operation and Development
PAYG	Pay As You Go
PV	Photo Voltaic
RE	Renewable Energy
REA	Rural Electrification Agency
RET	Renewable Energy Technology
SDGs	Sustainable Development Goals
SEforAll	Sustainable Energy for All
SHS	Solar Home System
SMS	Short Messenger Service
SOC	State of Charge
SSA	Sub Saharan Africa
TWh	Terra Watt Hour
USD	United States Dollar

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CHAPTER ONE: BACKGROUND

Outline

1.1 Introduction

Electricity access is critical in economic development and without it poverty eradication and hence achievement of SDG 8 is close to impossible. This among other reasons led to the formation of SEforAll initiative with a main aim to; (i) address global access to modern energy services, (ii) double the global rate of improvement in energy efficiency and (iii) twofold renewable energy share in global energy production [1]. The formation of SEforAll falls in line with the SDGs which is also an agenda that was set by the UN in 2015 to ensure global equitable sustainable development by 2030 [2]. In the background, it is the cognizance that energy is the engine for economic development and hence poverty alleviation. The framework of this is not only limited to extension of energy access but also doing it sustainably by recognizing other factors like environmental protection and GHG emissions.

It is however noteworthy that there has been an increase in concerns over climate change and global warming in the recent years which has seen the issue surfacing on top of almost every agenda concerning environmental conservation and effects mitigation [3, 4]. The role household energy use plays in this regard cannot be underrated [5]. Increased energy efficiency and reduction in the energy demand and use is a crucial step in curbing greenhouse gas emissions and climate change [6]. It also presents an opportunity for households to cut down the family budget and boost income through less spending on energy and hence improved standards of living.

Elsewhere in the world, different measures have been put in place to improve energy management and efficiency in the residential sector. Among the measures that have been employed include; metering systems that employ the use of feedback mechanisms, online monitoring systems, smart meters and many others [7]. Energy feedback mechanisms where users receive timely information about electricity consumption have been recorded to have the potential of lowering the energy use up to 20% [8]. In Africa however, particularly Sub Saharan Africa (SSA) where over 600 million people have no access to electricity [9] - whereas the traditional metering system where monthly paper bills are presented is the main means of monitoring in grid connected households, there is none in the biggest percentage of off-grid households. The situation is worse in off-grid households that use PAYG systems, users are charged a fee in bulk without provision of their actual energy consumption.

Close to 95% of the 1.2 billion global population without grid access live in SSA and South and East Asia, with the remainder spread just about equally across Middle East, Central Asia and Latin America (Figure 1.1) [10]. It has been reported that countries in Africa suffer from the lowest rates of electrification with countries like Burundi, Chad, Liberia having 5% grid access [10]. Majority of the countries in Africa have very low grid access and this has been one of the biggest motivation for the growth of the off-grid industry in the region. Among other factors is the falling prices of stand-alone RE systems. Products like solar mobile phone chargers, solar lamps and SHS can provide Tier 1-3 energy services (as per the global tracking framework tier based system) [11, 12] for between 4 – 20% of the required cost for grid extension [13]. Generally, the stand-alone electricity product market is expanding rapidly, and Navigant Research estimates the market for pico-solar products to develop from $550 million in 2014 to $2.4 billion in 2024 [14]. It is important to note that the success of off-grid technologies for providing energy solutions in recent years is largely attributable to the availability of energy efficient appliances [13].

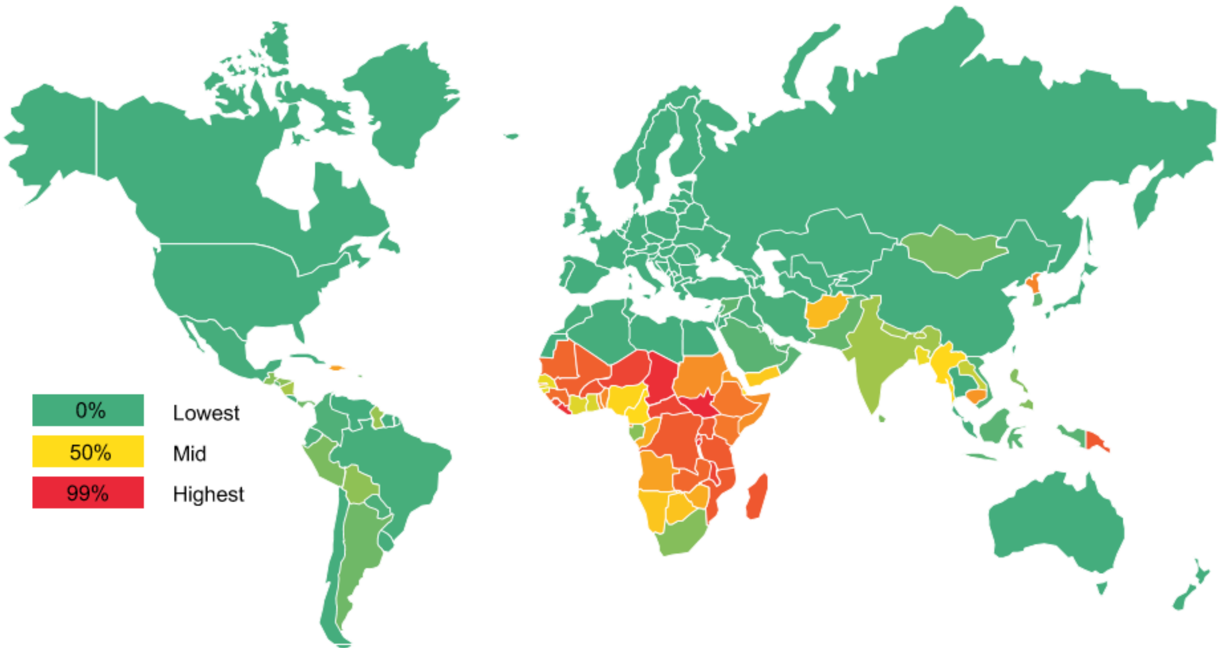


Figure 1.1: Share of population without grid access (percent of total) [10]

On the other hand however, off-grid systems still suffer from capacity limitation, high maintenance and servicing costs, sustainability issues [15, 16] among others. To improve and see more developments in the sector of energy access, energy efficiency is an indispensable part that cannot be ignored in emerging economies. Energy efficiency means doing more with less – so performance is maintained while saving both energy and money, by doing this; it saves, allows and extends energy to be utilized elsewhere, hence more energy services to more consumers. Whether access is grid connected or off-grid, EE provides a twin opportunity for refining energy delivery. By boosting the efficiency of production, transmission and distribution processes, EE frees up resources, thereby acting as a virtual power supply.

It is therefore imperative that as countries in SSA continue to grapple with low energy supply, more supportive measures that disclose information and encourage efficient use of the available energy be employed. One of the ways by which this can be promoted is through behavior based energy strategies where non-economic incentives are used to change how people perceive their energy use [17]. This can have an effect on electricity use behaviors and hence help achieve energy efficiency and savings. By providing household energy users with timely and detailed information, energy feedback a subset of behavior based energy strategies, discloses energy use information to consumers and discourages wasteful behavioral patterns than typical utility bills. It helps overcome barriers like the distrust people have in electricity utility companies and also gives them control over their energy use. Furthermore, it sheds more light on energy use and improves people's understanding of investing in energy efficient materials in homes.

1.2 Definition of Terms

1.2.1 Energy efficiency

The notion of energy efficiency is acknowledged as an indispensable energy policy strategy and has surfaced in many public and political discourses due to a number of issues ranging from environmental, social to economic. The efficient use of energy occasionally known as energy efficiency, is the objective to reduce the energy amounts required to avail services and products without affecting the quality and performance. For example, using, fluorescent lights, home insulation allowing a building to use less heating during cold times, using natural lighting to reduce the amount of illumination needed from electric bulbs, among others are some of the strategies used to ensure energy efficiency. The pressing need for sustainability is among the main drives for energy efficiency [18, 19]. There has been an improvement in energy efficiency on a global scale. In OECD countries, 15% reduction in energy use and 14% of carbon dioxide emissions was avoided in 2015 due to employment of energy efficient systems and processes [19]. It has been documented that Switzerland, Sweden, Germany and other countries in the IEA have saved close to USD 5.7 trillion as an outcome of energy efficiency investments and this has seen an avoidance of 256 EJ of total final energy consumption [19].

1.2.2 Relevance of energy efficiency

The relevance of energy efficiency is linked to social, economic, environmental and energy security benefits. Despite the continued interest in more production of energy to meet demand, comparatively, not so much attention has been drawn to energy efficiency [20]. A focused investment in energy efficiency can deliver innumerable benefits to many different stake holders. On the side of government and funding bodies, EE contributes to the reduction of government expenditure in setting up more infrastructure for energy systems. This means more funds available to finance other activities and diversify the economy. Utility companies benefit from the reduced costs for energy production, distribution and transmission as well as the improved system reliability. Energy efficiency contributes to the reduction in primary and final energy consumption thereby partly remediating the effects of GHG plus other emissions which are harmful to the environment. EE retrofitted houses were recorded to improve health by 75% for occupants particularly children, elderly as well those with pre-existing conditions. Reduced respiratory disease symptoms, allergies, rheumatism among others, were some of the diseases that were avoided [21]. For households, direct impacts include reduction of energy costs and increase in the household income. Figure 1.2 presents a summary of benefits of energy efficiency.

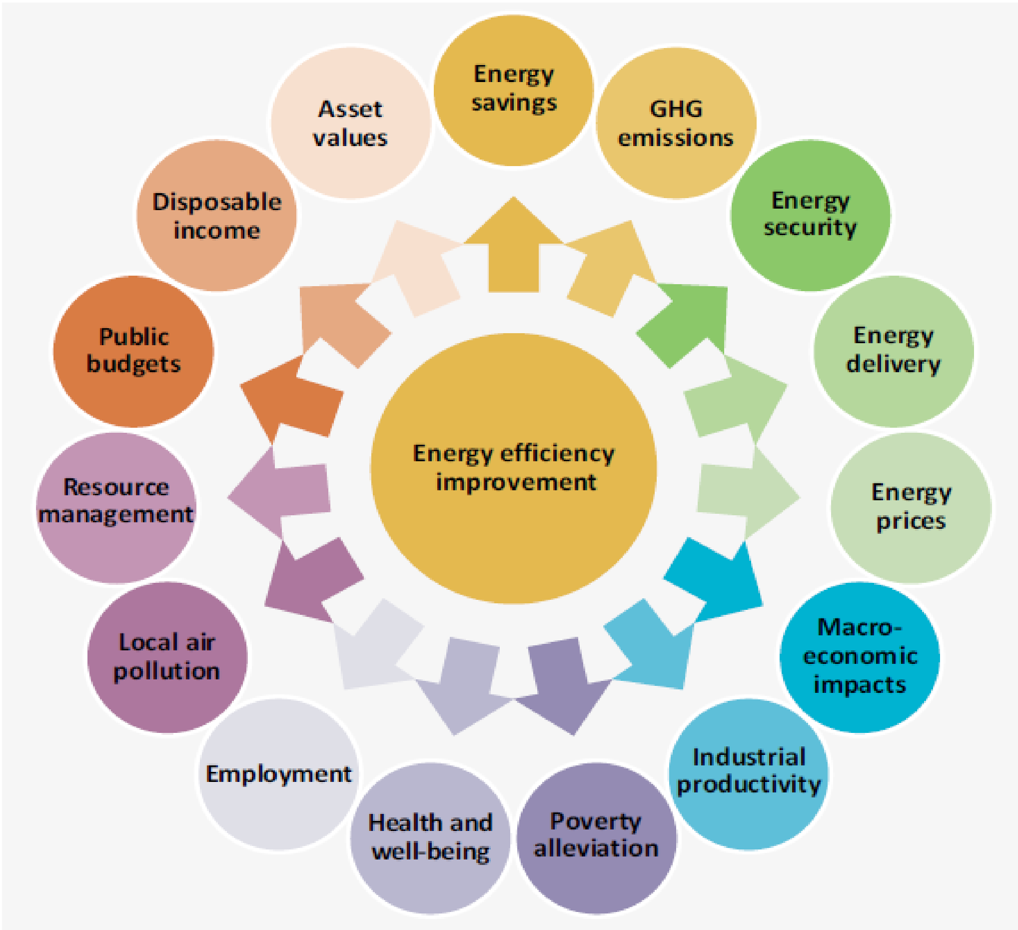


Figure 1.2: Multiple Benefits of Energy Efficiency [21]

1.2.3 Barriers to energy efficiency

These are obstacles that impede communities or individuals from practicing and implementing energy efficiency regardless of whether the implementation makes an economic sense. A number of barriers contribute to the low pick up of energy efficiency opportunities and these include; Information failures – gathering particular energy information/performance data from certain technologies and processes to effect energy efficient measures may be costly, this makes it difficult to monitor power consumption in relation to output. This sets a scenario where firms/individuals are not aware of the energy saving potential opportunities in the daily technology operations. Hence without relevant data on consumption and energy efficient measures that can be implemented, the savings potential remains in darkness and thus EE investments cannot be made. Capital constraints, uncertainty and risk as well as investor/user dilemma also affect the financing and hence implementation of EE measures [22]. Other factors include; high charges and import duties on EE appliances, financial constraints that lean towards products with lowest initial costs, lack of overlap between users and professionals involved in electricity access and energy efficiency.

1.2.4 Energy feedback

Often times, energy use is invisible to the user i.e. not many people have the ability to keep track of their energy usage because they just have a fuzzy idea of how much energy is consumed for the different purposes and what difference it could make by changing day to day habits. This is the premise under which feedback is based – it makes energy more visible and open to understand and thus control [23]. The process of energy feedback involves provision of specific and personalized information to consumers about their energy use. The primary focus of availing consumption information to consumers is to influence their habits as regards energy use. This feedback can be delivered in different ways i.e. through home displays, meters, phone applications etc.

1.2.5 Off grid System

Due to the growing need to tackle the energy access challenge, there has been a rise in off-grid renewable energy systems all over the world [24]. Sub-Saharan Africa has been recorded to have the highest off grid growing population in the World Bank state of electricity access report [13]. The simplicity and benefits of decentralized systems makes them more fit for deployment in many isolated and rural areas where extension of centralized grid would be rather costly. The least cost option for energy access varies with the distance from the grid and load size as shown in Figure 1.3. Other benefits of off-grid systems include; low land requirement than utility scale RE projects, less transmission losses, reliability and stability. Off grid systems is a broad term but for this study, it is used to mean stand-alone solar systems, both mini grids and single solar home systems.

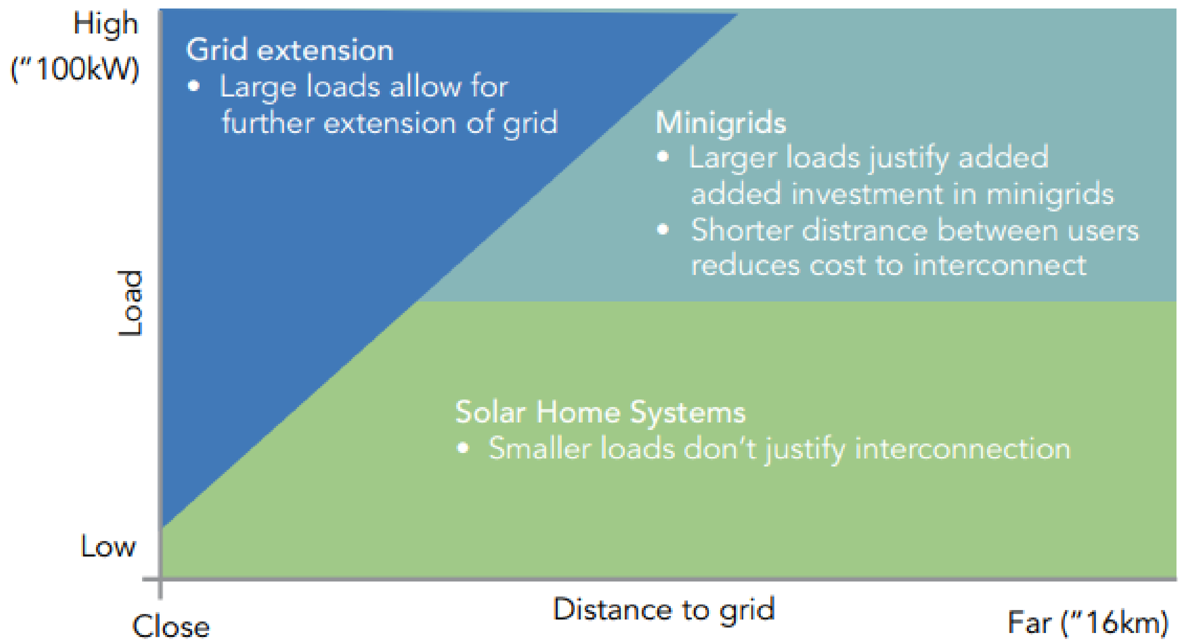


Figure 1.3: Variation of least cost option for energy access with load and distance [25]

1.3 Structure of the Thesis

Chapter 1	In this chapter, the introduction and back ground information to this thesis is presented. This includes the different global agendas to ensure energy access, the status of grid access on a global access and the role off-grid energy access is playing in this regard. The importance of promoting energy efficiency and the part information access can play in this direction is also highlighted. This is followed by a section of definitions of terms where different terms in this thesis are clarified.
Chapter 2	Information about Uganda which is the case study for this thesis is presented. Information about the geographical location, economic performance, energy access - both grid and off-grid, the different energy sources, consumption and demand as well as the upcoming plans in the energy industry plus the policy framework in support. This chapter also has a section for the problem statement, justification of the study highlighting the relevance and the feasibility of an SMS based energy feedback system in Uganda; as well as pointing out the recent growth in financing of off-grid sector, study objectives and the research questions.
Chapter 3	In this chapter, different literature about energy consumption information feedback is reviewed. The types of energy feedback, functions and effectiveness as well as message interpretation and application models are discussed. Behaviors as a promoter of energy efficiency plus the results about persistence is also discussed in detail.
Chapter 4	The materials and methods including the data collection is presented in in this chapter. The data collection device known as the Karana is highlighted. The theory behind the different formulations i.e. power prediction, production and storage is also presented.
Chapter 5	This chapter entails the developed algorithm flow, functionality and the events which invoke messages are elucidated. An explanation of the different message types, interpretation and sending criteria is also presented. A simple overview of the calculations and processes that run behind the algorithm segments is presented as well. Benefits and Limitations of the algorithm are highlighted.
Chapter 6	Conclusions, recommendations and way forward.

CHAPTER TWO: CASE STUDY – UGANDA

Outline

2.1 Geography

Uganda is a land locked country found in East Africa. The country is located on the East African Plateau and lies on coordinates 1.3733° N, 32.2903°E. Uganda shares border with South Sudan in the North, Tanzania in the South, Kenya in the East, Democratic Republic of Congo (DRC) in the West, and Rwanda in South west. The country is in the African great lakes region with a number of lakes, rivers and mountains. It experiences a tropical climate with mainly two dry seasons. The country covers a total surface area of 241,551 km^2 of which, 200,523 km^2 is covered by land and 41,028 km^2 by water. Uganda averages about 1,100 m above sea level sloping steadily to the Sudanese plain to the north. The western part of Uganda is partly crossed by the East African rift valley. The country's main activity is predominantly agriculture.

2.2 Economy

Uganda has natural resources including fertile soils, copper deposits, gold alongside other minerals, and oil. The most important sector of the economy is agriculture and employs over 80% of the work force, and contributes almost 25% of the total GDP [26], with coffee accounting for the bulk of the revenue. The country's total population was recorded to be 34 million in 2014, of which 81.6% is considered to be staying in rural areas [27]. The GDP per capita of Uganda is 5% to the world's average. The GDP per capita increased from 293.19 USD in 1997 to 637.57 USD in 2016, reflecting an average annual growth of 4.61% [28]. In the private sector, Uganda's ranking in the World Bank report doing business 2017 was stated to have improved compared to the previous years [29]. In a bid to accelerate growth, changes have been made to integrate industrial development as part of the government's overall development strategy in the NDP II period. The industrial sector development is at a nascent stage. During the fiscal year 2015/2016, the industrial sector accounted for approximately 18% of the total GDP [29].

2.3 Energy Situation in Uganda

The energy sector of Uganda is dominated by biomass. Indeed 90% of the total primary energy usage is generated from biomass. This can be grouped into different forms i.e. charcoal, firewood and crop residues accounting for 5.6%, 78.6% and 4.7% respectively. Electricity's contribution to the national energy balance is 1.4% while oil products which are predominantly used by the transport industry and thermal power plants accounts for 9.7% [27].

2.3.1 Grid electricity

Uganda has an installed capacity of 868.9 MW (862.5 MW on grid and 6.39 MW off-grid). Electricity access stood at 15% in 2013 at national level with 7% in rural areas. The country's energy consumption per capita is 215 kWh per capita per year which is among the lowest in the world, falling below SSA's average (513 kWh per capita) and the world's average (2975 kwh per capita). Figure 2.1 shows the contribution of different energy sources to grid electricity in Uganda.

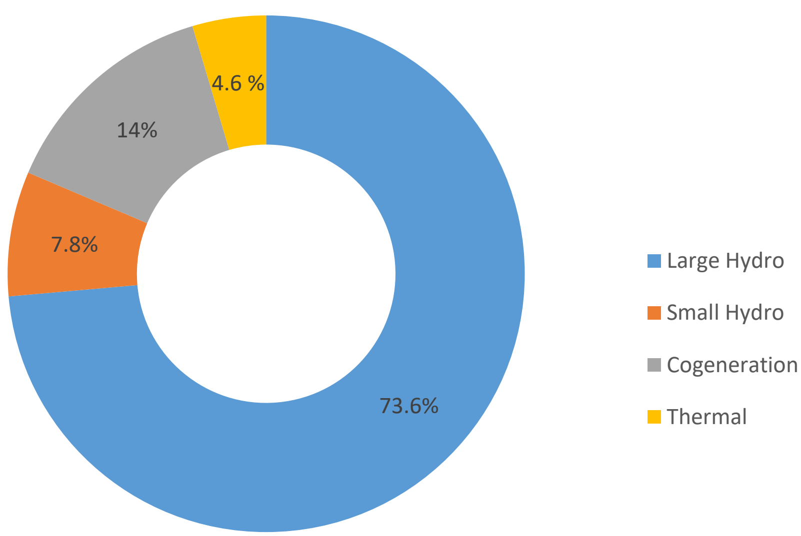


Figure 2.1: Contribution of different Energy Sources to Grid Electricity [30]

2.3.2 Off-grid electricity

Off-grid electricity systems play an important role in enabling energy access to the population. These systems continue to be very significant though relatively small in terms of quantity, and not included in the national statistics. Off-grid systems include stand-alone PV systems in isolated sites and backup systems that avail power when the grid is brown out or inaccessible. The market for solar electricity has been growing steadily for the past 15 years with growing numbers of private business and in Pico and solar home system (SHS) demand [31, 32]. Pico solar systems are widely available over the counters. An enormous number of households use solar lanterns. SHS provide a significant number of power more than Pico-solar (typically modules of 20-100 W). By 2012 solar PV systems had been installed in 5,600 households, 420 small commercial entities and 1,700 institutions through the rural electrification agency (REA) initiative. Furthermore, this can be contrasted with active over-the-counter sales, an estimated 12,000 solar home systems are sold per year. It is estimated that over 1.1 MW in off-grid systems was installed as of 2012 and, at the time the industry was growing at 20% per annum [33].

2.3.3 Current energy consumption and demand

By 2013, the total energy demand by end use sectors was 136 TWh. These sectors are household, commercial, Industrial and Transport as shown in Table 2.1 and Figure 2.2. The household sector takes the highest bulk of the primary energy supply. The majority of this primary energy is in the form of biomass. Electricity supply is dominantly taken by the industrial sector [33]. In 2013, energy demand per capita was 4,050 kWh/person/year, with the biggest portion from woody biomass as shown in Figure 2.2. There is a plan to increase per capita consumption of electricity to 588 kWh by 2020 and 3,688 kWh by 2040 [34].

Table 2.1: Energy Consumption and Demand by Sector [33]

Demand	Portion of Overall Energy Supply (%)	Portion of Electricity Supply (%)
Household	66.2	25.7
Commercial	14.3	14.9
Industrial	12.8	59.4
Transport	6.2	0.0

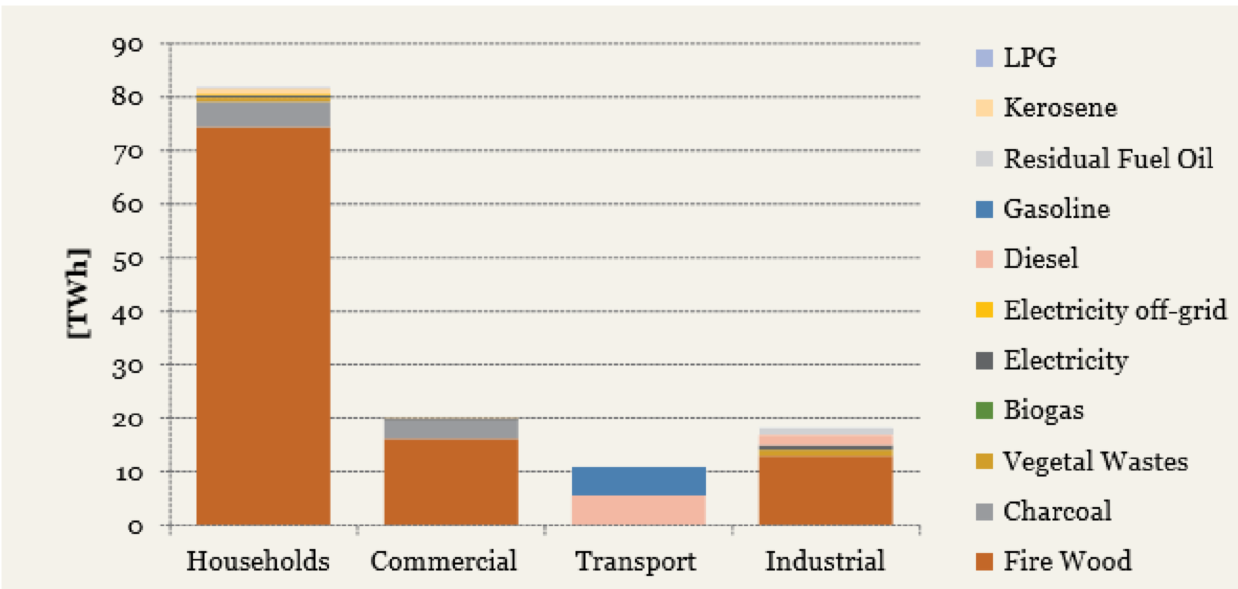


Figure 2.2: Annual Energy Demand (TWh) in 2010 and energy carriers to meet the demands [33]

2.4 Renewable Energy Potential

Uganda has a huge renewable energy resources potential ranging from biomass, solar, geothermal and hydropower, which is distributed in the different parts of the country. Figuratively, they are estimated to include; 2000 MW of large hydro, 200 MW of small Hydro, 450 MW of geothermal, 460 Million tons of standing biomass with a sustainable annual yield of 50 million tons , and an average daily solar irradiation of 5.1 kWh/m^2 [30]. Currently hydroelectric and biomass cogeneration plants contribute close to 90% of the country's electricity mix. A diversification of RETs has been suggested to ensure sustainable energy access for all. Table 2.2 shows the contribution of suggested RE power projects to Uganda's future electricity consumption which is estimated at 10,099 GWh in

2030. Solar PV will be the main contributor to electrify in off-grid areas, powering mini grids and providing energy access to schools and health centers as well as individual households.

Table 2.2: Contribution of Renewable Energy to Uganda Electricity Mix by 2030 [27]

Type of Connection		Additional installed capacity by 2030 (MW)	Estimated electricity generation (GWh/year)
On-grid	Large HEP	2410	9463 - 12050
On-grid	Small HEP	383	1330 – 1900
On-grid	PV grid connected	20	24 – 30
Off-grid	PV mini grid	26 - 32	40 - 70
Off-grid	PV microgrid	36 - 60	80
Off-grid	Solar street lights	5 - 10	10 - 14
Off-grid	9000 PV plants for water pumping and lighting	4 - 9	
Off-grid	PV Home systems	140	103
On-grid	Biomass cogeneration	16.5	100
	Total	**3,040 – 3,080**	**11,330 – 14,347**

2.5 Institutional Framework

The government of Uganda has put in place different policies over the years to support and reform the energy sector. These policies include; the electricity act which is aimed at liberalizing the electricity industry, the energy policy for Uganda which is aimed at steering power sector to meet the energy needs of the population for economic and social development in an environmentally sustainable manner, and the renewable energy policy whose overall goal is to increase the use of modern renewable energy technologies. The goal for energy reform was to increase energy access through production of clean and affordable energy to meet the demand and also promote economic growth, and eradicate poverty. The recent development has been the inclusion of the Energy efficiency and Conservation department as a fully-fledged department of the Ministry of Energy and Mineral Development as well as introduction of prepaid metering system.

2.5.1 Energy efficiency

An Energy Efficiency strategy for 2010 – 2020 has been put in place in Uganda. The main aim is to ensure efficient utilization of energy in all sectors of the economy through creation of a broader awareness, information and technology availability on energy saving opportunities in all sectors of the economy. The strategy addresses five main areas of intervention termed as "Pillars of Energy "[27]. These include;

- Awareness and information
- Training and Education
- Research and Development
- Financing and incentives
- Legislation and Framework

The strategy targets the different energy use sectors i.e. households and institutions, industry and commerce, transport as well as power transmission and distribution.

2.6 Problem Statement

In Uganda and in most of the African countries, the only feedback received by majority of the household electricity consumers is a monthly electricity bill [35]. This kind of system involves the electricity utility companies delivering paper bills entailing the electricity used in a stipulated period usually a month or more. This leaves a gap as consumers are challenged to monitor their consumption patterns which seems rather difficult and impossible without timely understandable information. This denies consumers an opportunity to keep track of their household electricity consumption and to save energy. The effects of this in poorer communities are adverse, ranging from underdevelopment to a vicious cycle of abject poverty among the masses as they are deprived of good energy service quality. The main cause is the higher energy expenses incurred in relation to the total income, which is not the case in communities where there is better energy service quality. People end up being subjected to the (EPP) energy poverty penalty [36]. This among other issues necessitates a stronger need to empower the off-grid electricity sector in Uganda and Africa at large to proactively engage in improving the energy service quality.

A feedback system that keeps consumers in the loop by timely informing them of their consumption can have a tremendous influence on the energy usage behaviors and hence the electricity bill spending [7]. Furthermore, in off-grid systems (mainly SHS), users are challenged by system failures, costly servicing and maintenance, as well as capacity limitation. This can be attributed to the general lack of consumption information coupled with improper servicing infrastructures. This contributes to general system under performance and to practices like system misuse, capacity mismatch, battery over discharge and overcharge among others. The result of this is a general loss of morale and trust in solar systems.

2.7 Justification

In Uganda and many African countries, the electrification system is characterized by central grids in urban areas and off grid in most of the rural and hard to reach areas. Households in both systems suffer from problems of lack of control over consumption, power blackouts (on grid) and capacity limitation (off grid) among others. One of the main causes of such issues is the inability of households to timely monitor and keep track of their consumption. Off grid systems have for long suffered from a problem of poor servicing infrastructures and this has been pointed out as the weakest link in off-grid systems development chain [16]. An SMS tool that helps consumers to track their consumption by providing real time consumption information on mobile phones through text messages, is anticipated to not only promote energy efficiency but also a better understanding of household electricity usage at large. This in the long run would have an impact on the consumer behavioral use patterns.

There has been an increase in investments in off-grid companies. This has greatly contributed to the success of the off-grid industry through development of more business efficient models like PAYG among others. In fact, the highest share of the 2015 capital investment in off-grid was taken by PAYG companies as shown in Figure 2.3. PAYG is the model where customers can pay for solar systems at affordable prices through small installments. In the event of non-payment by the user, the system functionality is locked. When the total payment of the solar system is completed overtime, the user owns the solar system perpetually. The model mimics the traditional users' behavior of having to buy kerosene every day for lighting in case it is needed. PAYG makes use of mobile telephone technology to channel with solar systems. The main focus of PAYG is mainly on the business side i.e. compelling and making payment plans easier for users [37] without a keen consideration of the users' knowledge, skills and behavior in relation to the solar systems. This gap created renders solar systems inefficient with many failures and hence low life spans. A sustainable model that not only compels users to pay but also ensures that users understand what they are paying for and how to get the best out of it, would be a better alternative.

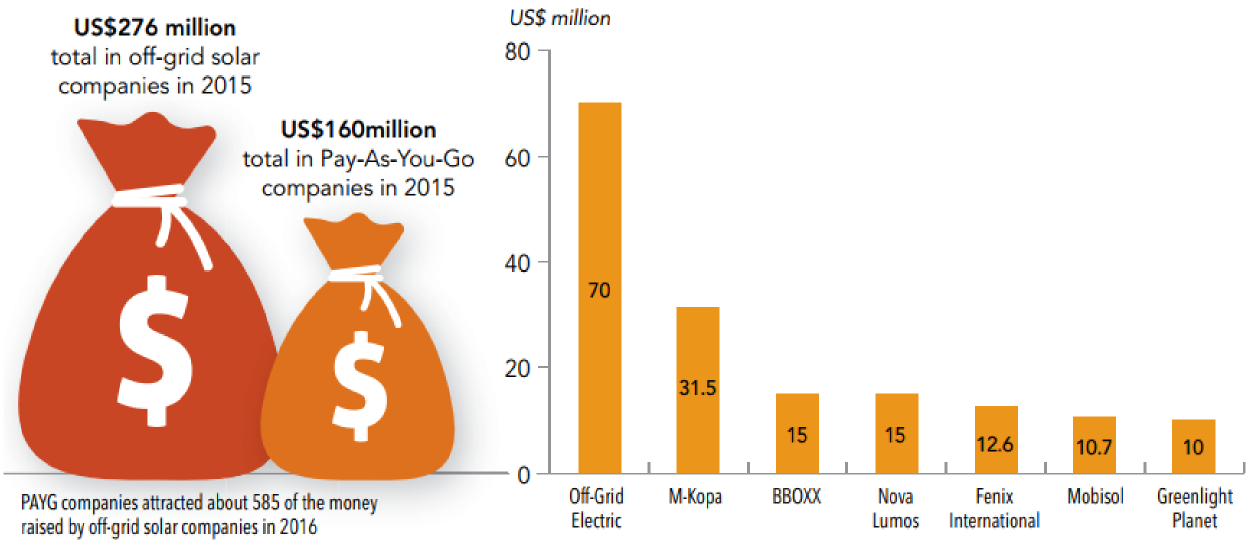


Figure 2.3: Increasing investments in off-grid and share of PAYG in 2015 [38]

2.7.1 Energy efficiency in off grid systems

There has been an increase in funding focused at initiatives involved in developing off grid energy services and products through advancement of standards and energy efficiency, with a specific focus on off grid appliances [39]. Saving a unit Watt from an off-grid appliance's load results in lower initial solar package costs, improved service or both [40]. Off grid solar systems are mainly affected by capacity limitation, it is no doubt promotion of energy efficiency in such systems would be of utmost importance. A thorough understanding of consumption of a particular appliance can be essential in determining the operational costs (where electricity is for a fee-for-service) and the system size (for stand-alone solar systems).

Many solar systems have been recorded to generate a surplus of energy during the day period when the sun is up. This energy in most cases goes untapped because users are not aware of such opportunities. This presents an antecedent where the battery gets overcharged – which leads to a decline in the lifespan and hence more running costs for replacement. Efficient usage of energy allows for proper dimensioning of solar systems, encourages general reduction of costs and also boosts business performance. In the research by [40] “the upfront cost of a typical off-grid energy system can be reduced by as much as 50 percent if super-efficient appliances and right-sized solar PV and batteries are used, while delivering equivalent or greater energy service.”

2.7.2 Feasibility of an SMS based feedback system for Uganda

The global usage of mobile phones has grown enormously in the past years with over 90% of the people having one in the developing countries as reported by [41]. In Africa alone, it has been reported that over 93% of the people have access to cell phones [42]. “Mobile phone, a device that was once considered a luxury of the affluent has now become a necessity” [43]. The number of mobile phones in some African countries like Kenya, has been reported to be greater than the number of adults in the whole country with 38 million mobile phones and a population of 45 million people [44]. Furthermore, the most common usage for phones was found to be “sending texting messages” in a study by [45]. The case is not any different in Uganda where currently the number of mobile phone users has grown and currently stands at approximately 22 million people as shown in Figure 2.3. The domestic letter traffic has seen a fall over the years with the number of users dropping from 1.42 to 0.5 million between 2010/2011 to 2015/2016 as shown in Figure 2.4 [46]. From these numbers, it is evident that an energy consumption information initiative that makes use of mobile phones SMS services would have a bigger outreach in terms of numbers than physical mails and emails.

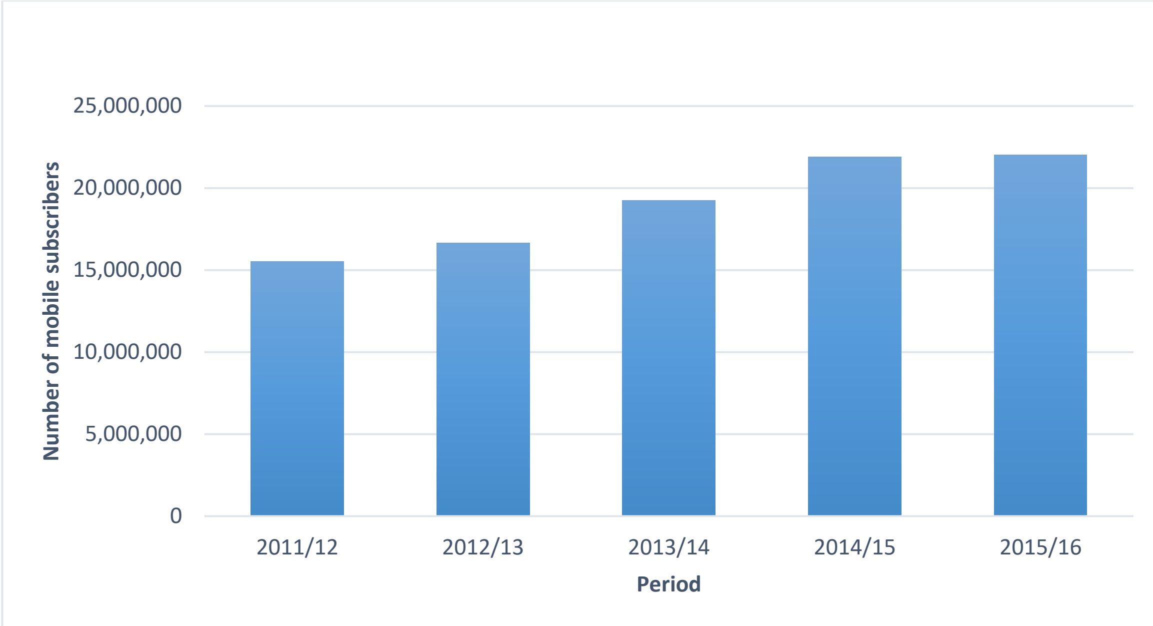


Figure 2.4: Growth of Mobile phone subscribers in Uganda [46]

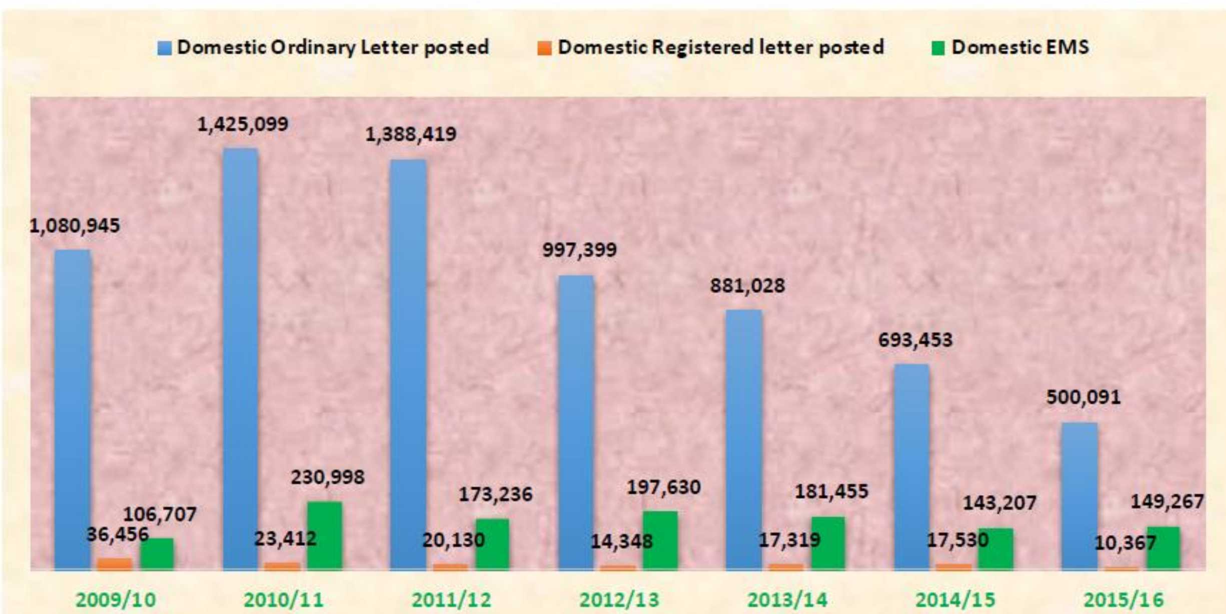


Figure 2.5: Decline in the domestic letter mailing traffic [46]

2.8 Main objective

The main objective of this study was to develop a real time SMS feedback tool that analyses and provides off-grid consumers an insight into their electricity consumption.

2.8.1 Specific objectives

The specific objectives of this study were;

- To develop an analysis mechanism to make energy consumption data understandable.
- To develop a text message sending scheme
- To translate electricity usage into simple SMSs

2.8.2 Scope

The scope of this study was limited to developing a message sending algorithm for off-grid household electricity users.

2.9 Research Question

How can electricity consumption information access be made transparent, understandable and accessible in off-grid household electricity users?

2.9.1 Other questions

- How can this be used to improve performance of solar systems in households?
- How can this be used to influence users' behaviors?

CHAPTER THREE: LITERATURE REVIEW

Outline

3.1 Energy Feedback System

Recently, a lot of effort and research has been invested in the field of energy feedback and its role in improving energy efficiency through demand side management. Research ranging from system effectiveness to comparisons between the designs of different feedback mechanisms and the way forward has been explored. In this section, a review of the different research in the field of energy feedback is presented. The chapter expounds on energy feedback systems, effectiveness, different behavior models and how this is connected to energy efficiency improvement.

3.1.1 Types of energy feedback systems

Different studies on energy consumption have revealed that there are substantial variations in the size of effects and impacts resulting from feedback systems. This has left more questions as regards which feedback type and design produces better results vis-à-vis encouraging energy peak demand, costs and energy conservation [47]. This vast range in variations could as well be explained by the different methodologies of evaluation [48]. Feedback can be classified into two types i.e. (i) direct (real time), and (ii) indirect [23]. The difference between the two classifications is in the time of delivery and access. The direct classification is characterized by prompt delivery either from a display device like monitor or a meter reading; the most recent technology being a “strip”. The indirect feedback type is characterized by a delivery of monthly electricity bills where interpreted and analyzed information is provided so as to provide recommendations and advice for reducing electricity usage [23, 49]. Both direct and indirect feedback classifications have been studied and the former has been recorded to be more effective [50]. Direct feedback has been recorded to have a higher impact compared to indirect feedback. Because consumption information is provided instantly, habitual behaviors e.g. unplugging appliances, switching off lights and other appliances can be fostered easily among household electricity uses [51].

The two main classifications of feedback (direct and indirect) have been broken down into more specific and elaborate feedback forms grounded on information availability [52].

Basically, there are four different forms of indirect feedback and two forms of direct feedback.

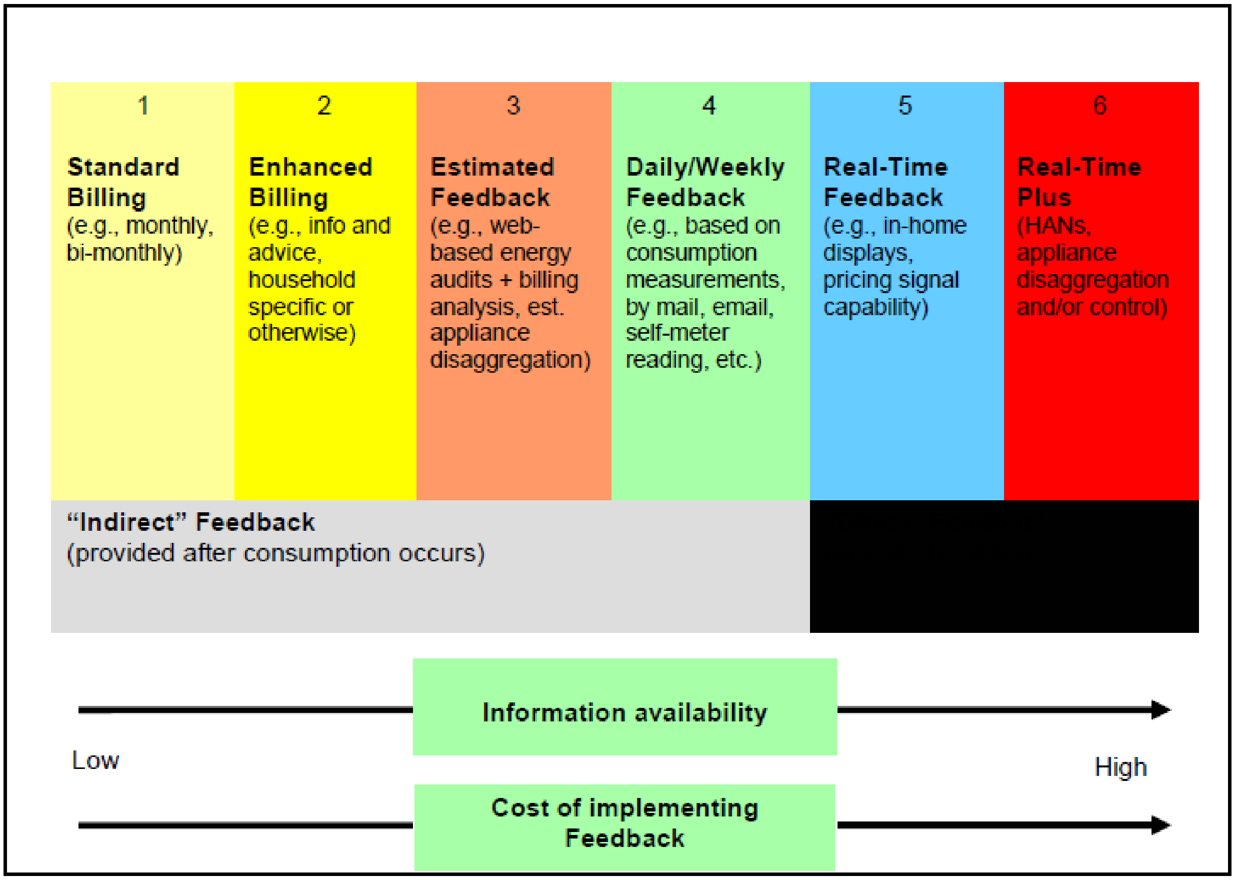


Figure 3.1: Classifications of Feedback

From the standards highlighted in the Figure 3.1, an interpretation of the feedback categories is as follows [52];

- Standard Billing – The electricity bill presents a display of the monthly kilowatt-hour (kWh) of electricity usage at a unit rate ($/kWh), the equivalent total cost, other billing charges plus the amount due. This feedback is short of comparative statistics or any detailed information about sequential characteristics of consumption.
- Enhanced Billing – avails more elaborate information concerning energy consumption patterns, and often includes comparative statistics i.e. comparing the current month energy consumption and expenditure with the past month's values and/or with that of other households.

- Estimated Feedback – Here statistical techniques are employed to assess and analyze the total energy consumption based on the user's household type, appliance information and billing data. As a result, an account of the main consumers of electricity in terms of appliances is provided. This kind of feedback is mostly web based.
- Daily/Weekly Feedback – This kind of feedback normally "uses averaged data and often includes consumer's self-studies (in which individuals read their meter and record energy usage themselves)". In other cases, daily or weekly electricity usage reports from the utility or research company are provided
- Real-time Feedback – This is normally in-home energy display devices that deliver real time or near real time energy consumption and cost information at the collective household level.
- Real time Plus – This is also in-home energy display device that delivers real time or close to real time energy consumption and cost information disaggregated by appliance.

3.1.2 Functions and benefits of feedback

Human beings carry out everyday activities without keen attention due to perceived norms and habits developed over time and this encompasses electricity usage as well [8]. Information disclosure has a role to play in building and creating rational consumers [47]. Information access affects the behavior of people to act rationally thereby maximizing and ensuring accountability for every dollar spent [53]. Feedback has the power to enhance demand response and demand side management programs, by affecting users' responsiveness to time of usage, pricing programs, pointing out energy saving opportunities and realizing the merits of load shifting [54]. Direct feedback can influence the users' buying choices of appliances; as they take note of the feedback that certain appliances are high energy consumers, consideration can be made to go for a less consuming appliance. This could as well affect behavioral usage in the long run. Change in usage habits or product selection is more relevant when electricity consumption information is made clearer and accessible to the consumer. Another benefit of direct feedback is that it can be more easily modified to target a specific consumer[51, 55]. With suitable data analysis and assessment, feedback could present usage patterns in formats more understandable and helpful to individual/specific households [55]. Literature about real time feedback suggests that, direct interventions can produce 5% to 15% reduction for the time of set up [54].

3.2 Effectiveness of energy feedback systems

In general, the effects of feedback interventions on energy use have been found to vary substantially in the effect size from one study to another. These variations can be partly attributed to the demographic set up, climate, regions and the type of housing. Studies have revealed that homes with higher incomes, education levels and electricity consumption show more positive results when feedback is employed [48, 56]. Furthermore, there has been correlation between income and household electricity consumption levels [57, 58]. Also, a positive correlation between income and reduction in consumption was found to exist in a study by [48, 58]. The response in low consumption households may be very low or nothing at all because it is assumed that all the potential avenues to reduce consumption have been exhausted [48]. Climate directly impacts the usage different house types and designs would have due to the different energy requirements. Households in more extreme climates would seem to have more potential for reducing electricity use, however it has been shown that houses in moderate climates produce more positive results when feedback is deployed [59].

Some studies have indicated a difference in responsiveness to feedback in the house types. However, it is still un clear how different the response would be if the frequency of information exchange is increased [52]. In their study about electricity monitors, Wallenborn *et al* [60] found out that feedback could only change perceptions of those willing to save energy. In another study action was taken to reduce consumption but, however, the electricity usage results were statistically insignificant. This was attributed to the self-selection of the participants in the study and the already invested interest to use electricity efficiently prior to the study [61].

In another study, the author applauds the importance of a feedback display device and how it reveals consumption through visualizations [62]. However, it was also noted that feedback hypothetically disregards some crucial practices in preference to others; a failure to address such issues would cause a disinterest over time [62].

It is argued by different researchers that the effectiveness of feedback is highly dependent on goal setting as this gives participants power to track their performance against a datum [47]. In a study by Becker [63], different results were obtained under different scenarios of goal settings when feedback was applied coupled with specific targets. (see Table 3.1)

Table 3.1: Percentage energy saving in relation to goal set [63]

Goal Set (%)	Energy savings (%)
0	4.5
2	5.7
20	15.1

The same strategy was used in a study by Schultz [64], it was found that households that had set personal conservation goals achieved savings as high as 8% which was higher compared to other households that did not. Furthermore, in an online study where over a 1000 electricity users participated, it was revealed that goal setting would boost energy usage [65]. The influence of target setting is not straightforward as it has been shown in some studies that feedback alone has worked well [8].

3.2.1 Comparisons

Feedback comparing electricity usage of different households was found to be more efficient due to the social pressure it creates thereby stimulating competition and ambition among users [66, 67]. Social proof was identified as a very important aspect in taking decisions [68]. In some studies consumers have resounded interest in getting to know the consumption patterns of their neighbors [69]. More than 70% of the participants in the study were found to have had conversations about their bills with other people including their neighbors [70]. Comparisons of consumption between neighbors have the potential to influence usage patterns as neighbors tend to share similar attitudes and habits. Indeed, peer effect has proven to be more effective than incentives in a number of instances [47]. However, in some studies the outcome is the contrary. Indeed, this is true because in a study by Fischer [66], comparative feedback was found to have no effect whatsoever on the savings benefit. The results were not any different from what Bittle *et al* [71] discovered. Moreover, the results were rather opposite in a sense that those who received comparative feedback consumed more than their counterparts who did not.

3.2.2 Credibility of the feedback source

In many instances electricity users have lost trust in the electricity utility companies. For that matter, it is really important that the feedback information is relayed from a credible and trusted source [47]. Priorities and decisions by government can be perceived not to be in line with energy efficiency due to the doubt people have in social institutions [72]. This was demonstrated in a study by Miller and Ford [73], where letters soliciting energy conservation programs were used as the case study. Those letters which had the utility company affiliation were flagged with poor responses compared to those that did not. Community based and not profit companies may be in better positions to take on the role of disseminating and examining conservation programs [72, 74].

3.2.3 Consumption metrics and mode of delivery

The information metrics is as important as the feedback system itself. Conversion into currency values has been well-thought-out as more desirable by some researchers [8, 23]. In a study by Fitzpatrick and Farhar [75] , cost based feedback was found to be preferred by the consumers. However, in another research, no positive results were yielded when cost based feedback was employed [75]. Environmental metrics have also been used in many cases [52]. Given the current climate change and global warming discourse, environmental metrics would play a leading role in stimulating personal norms and connections with respect to the environment [8, 48, 75]. A study by Brandon and Lewis revealed no significance in the results for electricity use efficiency when environment based feedback was used [76]. Gatersleben *et al* [57], postulated that the link between environmental concerns and electricity usage is not absolute even in households that seem to be aware of the environment. The common delivery system is the computerized system where users interface with applications on display screens and an extension normally added through emails [23, 66]. Email delivery has been cited to not only provide personal delivery but also can be integrated to websites that provide more interactive options than the email feedback alone. The use of timely feedback coupled with an SMS and email system was used in another study and an average yearly consumption reduction of 3% was noted. However, the authors argued that the kind of feedback would yield better results in another country setting [77]. Feedback that allows a user options to choose and interact i.e. internet, was cited to be effective by Fischer [66]. In some cases, paper based feedback has been considered environmentally unfriendly [78], while in others they are preferred over other feedback systems [79]. Whereas internet based feedback is easier and consequently more feasible for utilities, demographics and other location factors are as well important.

3.3 Persistence of Habits After Feedback

Different studies have provided different views on whether the intended energy saving behavior persists in the participants or not. In a study by Schleich *et al* [80], where over 1000 users participated, it was found out that the feedback influenced a habitual change that persisted among the participants. Furthermore it was noted that feedback effects increased over the entire period of the study [80]. On the contrary, Houde *et al* [81], argues that with time feedback effects fade away i.e. feedback only affects transitional behavior and after sometime people revert to their old consumption behavior.

3.3.1 Behaviors as promoter of energy efficiency

The effect of energy use behaviors cannot be underestimated as the potential for savings is valued to be as high as 20%, though in some studies values differ up to 100% depending on the experiences [82]. It is noteworthy that most of the research under energy behavior has been on residential sector and the focus has been largely on carrying out different testing techniques in the field to analyze behavioral effects towards energy use and how this can be implemented to ensure energy efficiency [82]. This shows how important different behavioral patterns are in ensuring energy efficiency in households. Different motivations can lead to change in people's behavior ranging from environmental protection, economic benefit to social norms. People make choices after weighing between the merits and demerits there by taking better informed decisions that maximize benefits. Preservation and conservation of the environment plus the moral obligation to be cognizant of environment sustainability is another motivation that can influence energy use behavior [83]. Other strategies that have been employed to promote more energy efficient behaviors include consequence strategies. The main goal of such strategies is to change the consequences following behavior on the theory that good energy use behavior will develop more when positive consequences are attached to it [84]. Such interventions include; commitment to achieve a certain objective, goal setting, information – this helps to improve awareness, modeling – giving examples of indorsed behaviors, feedback on energy consumption and rewards. While psychology and economics emphasis is more on individual behavior, sociology indicate that energy demand is also a social/societal paradigm and hence for effectiveness, the social aspect should as well be considered. This can be illustrated in arrangements like social learning, collective action and sociotechnical networks [85].

3.3.2 Message interpretation and application

Feedback messages require an understanding of the user's consumption in terms of appliances so that a specific message tailored to a specific user's needs is sent. Different users have different motivations but the end goal is to ensure a sustainable energy use behavior among users. According to a research by Helen *et al* [86], electricity users go through different stages of behavior from the first point a message is received. It is over time and through a series of reminders and messages that sustainable energy use behaviors become part and parcel of an individual’s everyday behavior. In different studies, it has been found out that messages tailored to specific individuals produce more positive results over time than a “one size fits all” type of messages which involve providing the same feedback to differently motivated individuals at different stages of readiness, willingness and ability to change. Different motivation techniques are used and these include [86];

Attitude Model: This works on the assumption that “pro-environmental behavior automatically follows from favorable attitudes towards the environment”

Rational Economic Model (REM): This type of model assumes that individuals will take a decision that is in support of the environment if it rationally makes economic sense i.e. they are primarily motivated by costs in terms of money.

Information Model: This model works on the assumption that when one knows what to do, they will do it. The model avails information to a problem, gives an insight of why it is a problem and steps to take in order to solve the problem.

Positive Reinforcement: This happens when “a response is followed by addition of a reinforcing stimulus which increases the likelihood that the response will be repeated in similar situations” e.g. no garbage collection payments if one’s garbage is sorted, this can be a positive reinforcement for future garbage sorting behavior.

Elaboration Likelihood Model: This model proposes a dual process theory of cognitive processing i.e. central route and peripheral route. Under central route, arguments are processed according to logic, rationale and quality of argument. The peripheral route bases more on emotional persuasion i.e. one is influenced not by the logical quality of the stimulus but rather emotional responses.

CHAPTER FOUR: METHODOLOGY

Outline

4.1 Overview

The study is based on the fact that there are events that take place in the energy system operational set up and these present hidden opportunities which can be leveraged to promote energy efficiency, improve system performance and extend the economic life of solar systems. This study therefore provides an insight on the design of a tool that would timely communicate these activities in a simplified way through an SMS platform directly to the electricity users' phones. This study therefore adopts the different models in the different system components (i.e. power production, storage and consumption) of a solar system set up as well as SMS sending algorithms to come up with a complete algorithm. This chapter entails data collection and a theoretical background as well as the mathematical modelling equations that were formulated to build an algorithm.

4.1.1 Principles

The algorithm was written in python. The choice for python was influenced by the prowess of the language in mathematical algebra and calculations. The language is powerful and fast, runs almost everywhere, plays everywhere and most importantly it is open source. Python can be learnt by beginners and used to build simple but effective programs. The robust math functions which gives it the ability to handle mathematical problems like linear algebra, data analysis, numerical solutions to differential equations, powers, primes and many others, makes it an indispensable language.

4.2 Data Collection

4.2.1 Primary data collection

The ability to gather primary data for testing was dependent on the Karana devices which were deployed in the field to monitor and avail data on the selected solar home systems. The level to which this source is appropriate relies on the research question and objectives. Therefore, the source device having real time monitoring capabilities, gives room to inspect any changes in system usage and performance.

The test data used was collected using a device known as the “Karana”. Karana is an open source hardware device that was developed at Micro energy international, within the ME sol-design laboratory. It was developed as an alternative to conventional monitoring devices and relies completely on open source software and hardware. The device has imbedded abilities to monitor and communicate with the back-end system at the server point where data in timeseries format is stored to the database (Influx DB). The data consists of the measurements, tag keys i.e. host and region, with the tag values, field key, field value and the timestamp. The device also provides a data visualization platform which can be observed via an open source graphing software (Grafana) for further inspection (Figure 4.2). The device has three ports i.e. for load connections, solar panel and battery. The data collected ranges from load current and voltage, PV current and voltage, plus battery current and voltage. This allows for efficient monitoring of power production, storage and consumption. The device is GSM enabled, which means it can be deployed anywhere and accessed from almost everywhere. Figure 4.1 shows the set-up of the monitoring system with the device.

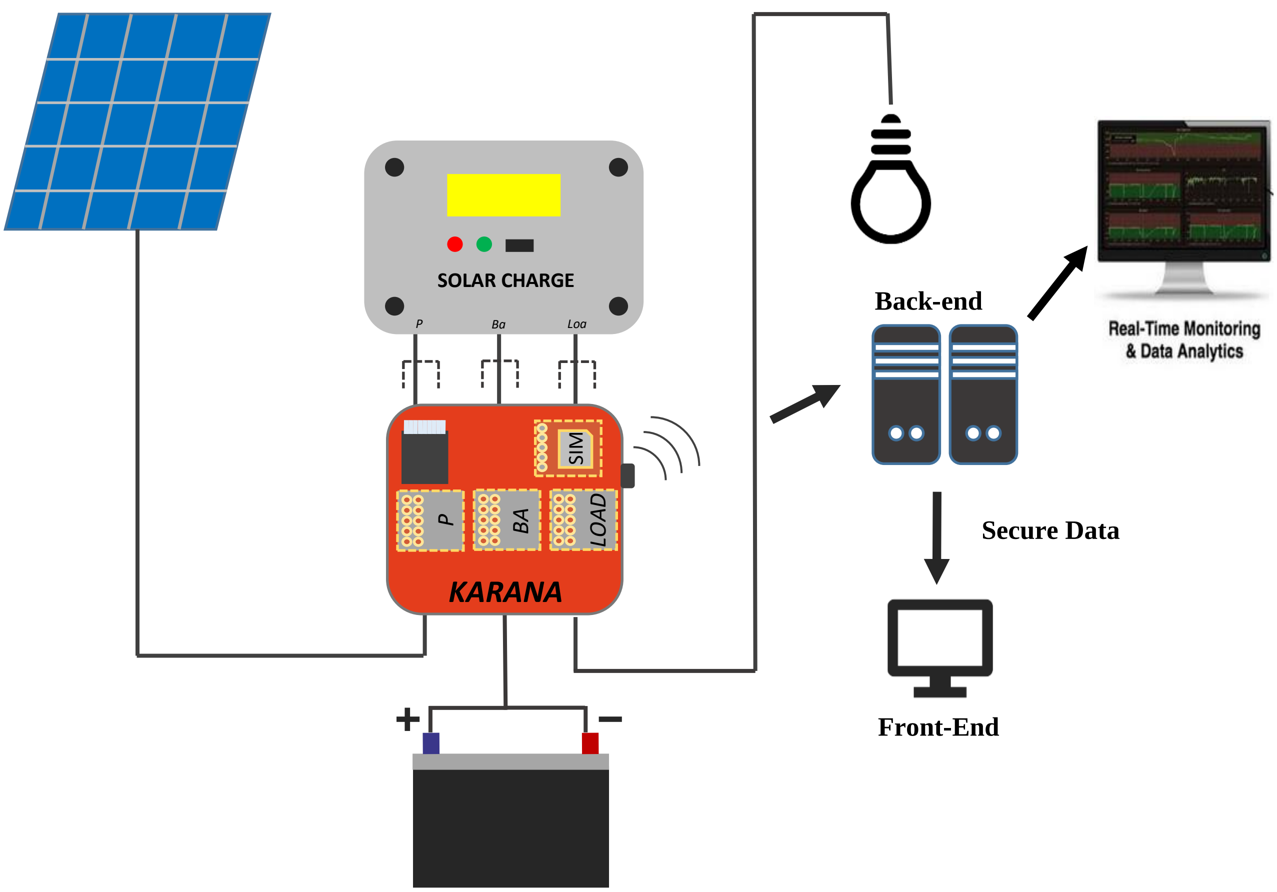


Figure 4.1: Monitoring System set up

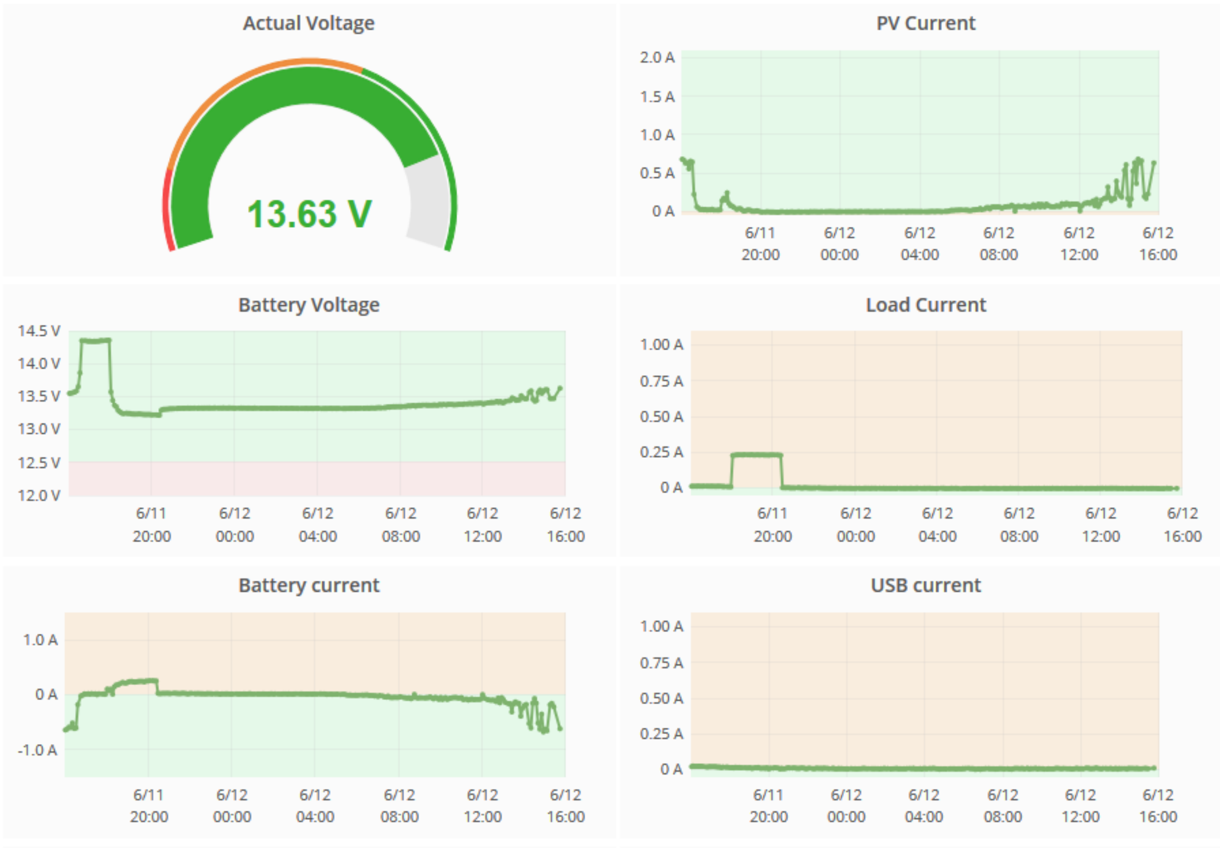


Figure 4.2: Sample web access to the current status of a solar home system installed at the office.

4.2.2 Secondary data collection

A number of literature sources were used as data sources in this study, the most outstanding ones being [87], [88], and [89]. The type of data from these sources included; formulas, real numbers and ideas.

4.2.3 Algorithm components design

The algorithm was broken down into different parts, i.e.;

I. Solar Irradiance prediction
II. Solar Power production
III. Battery storage

4.3 Solar Irradiance Forecast/Prediction

The forecast models and formulae as well as the system characteristics (from the manufacturer's datasheets) were used to determine the irradiance. The irradiance is one of the most crucial factors that affect the PV power output. The physical approach of PV forecasting where numerical weather prediction models (NWP) are employed, was used. It follows the process as shown in Figure 4.3.

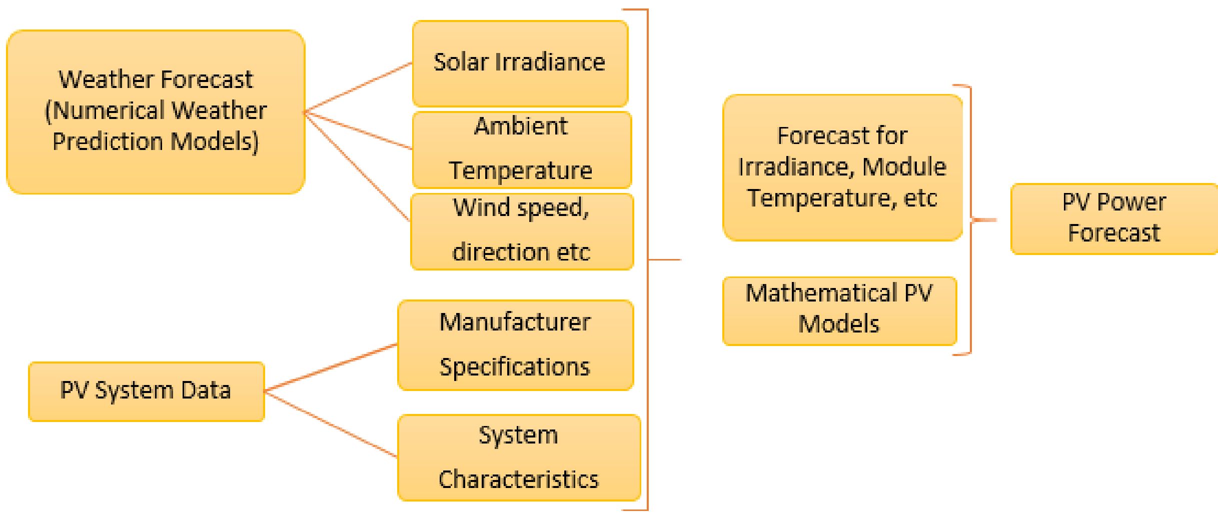


Figure 4.3: PV forecasting based on the physical approach [90]

4.3.1 Solar irradiance on the surface of the earth

Measured values on the earth's surface are normally lower than the solar constant due to the various atmospheric interference. For a horizontal plane, solar radiation is scattered and reflected when passing through the atmosphere i.e. due to atmospheric reflection, absorption and scattering [91]. Rays of extraterrestrial sunlight are virtually parallel while terrestrial sunlight consists of direct and diffuse components [92]. The total global irradiance on a horizontal surface ($E_{G,hor}$), is the sum of the direct irradiance ($E_{dir,hor}$), and diffuse irradiance, $E_{diff,hor}$.

$$\boldsymbol{E_{G,hor} = E_{dir,hor} + E_{diff,hor}} \qquad (1)$$

4.3.2 Calculation of the sun's position

The position of the sun was essential for many further calculations of the solar energy system. The solar altitude (γ_s) , and solar or sun azimuth (α_s), define the position of the sun as shown in Figure 4.4. However, the definitions for these angles and symbols used vary in literature. The solar altitude is the angle between the center of the sun and the horizon seen by an observer. The azimuth angle of the sun describes the angle between the geographical north and the vertical circle through the center of the sun. The solar altitude and the solar azimuth depend on the geographical location of the observer, the date, time and time zone. The position of the sun is strongly influenced by the declination angle δ, i.e. the angle between the equatorial plane of the earth and the rotational plane of the earth around the sun. The solar declination varies between ± $23^0 26.5'$ over a year. Any point on the earth's surface is determined by its latitude (φ) and longitude (ψ). Latitude is defined positive for points north of the equator, negative south of the equator. Noon solar time occurs once every 24h [88].

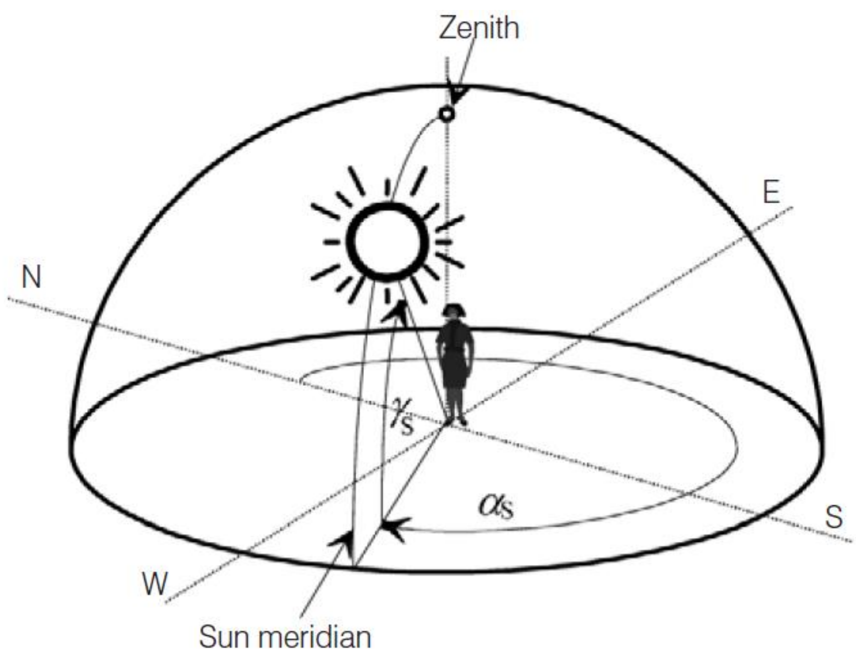


Figure 4.4: Definitions of the angles describing the position of the sun [88]

With the day angle;

$$\boldsymbol{y' = 360^0 \frac{day\ of\ the\ year}{number\ of\ days\ of\ the\ year}} \qquad (2)$$

The solar declination deduces to:

$$\boldsymbol{\delta(y') = 23.45 sin\left(360\ x\ \frac{284 + d}{365}\right)} \qquad (3)$$

And the equation of time was calculated from:

$$e\mathbf{qt}(\mathbf{y}') = [\mathbf{0.006 + 7.3525.\cos(y' + 85.9^0) + 9.9359.\cos(2.y' + 108.9^0)} \\ \mathbf{+ 0.3387.\cos(3.y' + 105.2^0)]\ min} \qquad (4)$$

With the local time, t_{local}, the time zone, t_{zone} and the longitude ψ, the Mean Local Time MLT was obtained from:

$$\boldsymbol{MLT = t_{local} - t_{zone} + 4.\psi.min/^0} \qquad (5)$$

A sum of the equation of time, eqt and the mean local time, MLT, provides the solar time, t_{solar}:

$$\boldsymbol{t_{solar} = MLT + eqt(y')} \qquad (6)$$

With the latitude φ, of the location, the solar hour angle ω defined as the angular displacement of the east or west of the local meridian due to rotation of the earth on its axis at 15^0 per hour, was calculated from;

$$\boldsymbol{\omega = (15^0 h^{-1})(t_{solar} - 12h)} \qquad (7)$$

4.3.3 Solar altitude

The solar altitude γ_s , can also be defined as the angle between the horizontal and the line to the sun, i.e. the complement of the zenith angle θ_z.

$$\boldsymbol{\theta_z = 90 - \gamma_s} \tag{8}$$

With the declination angle δ, latitude of location φ , and the solar hour angle ω, the solar altitude:

$$\boldsymbol{\gamma_s = \arcsin(cos\omega cos\varphi cos\delta + sin\varphi sin\delta)} \tag{9}$$

4.3.4 Solar azimuth

This is also known as the angular displacement from south of the projection of beam radiation on the horizontal plane [87]. Displacements east of south are negative and west of south are positive. Solar azimuth, α_s was obtained from:

$$\boldsymbol{\alpha_s = \begin{cases} 180 - arccos\dfrac{sin\gamma_s sin\varphi - sin\delta}{cos\gamma_s cos\varphi}, & t_{solar} \leq 12.00h \\ 180 - arccos\dfrac{sin\gamma_s sin\varphi - sin\delta}{cos\gamma_s cos\varphi}, & t_{solar} > 12.00h \end{cases}} \tag{10}$$

4.3.5 Irradiance on tilted surfaces

The global $E_{G,tilt}$ on a tilted surface is composed of the direct irradiance $E_{dir,tilt}$, the diffuse sky irradiance $E_{diff,tilt}$ and the ground reflection $E_{refl,tilt}$ and the ground reflection $E_{ref,tilt}$ (a factor that does not exist for horizontal surfaces):

$$\boldsymbol{E_{G,tilt} = E_{dir,tilt} + E_{diff,tilt} + E_{ref,tilt}} \tag{11}$$

4.3.6 Direct irradiance on tilted surfaces

The horizontal surface in Figure 4.5 with the area A_{hor} receives the same radiant power Φ as a small area A_S which is normal to the incoming light. With;

$$\boldsymbol{\Phi_{dir,hor} = E_{dir,hor}A_{hor} = \Phi_{dir,s} = E_{dir,s}A_s} \qquad (12)$$

and;

$$\boldsymbol{A_s = A_{hor}cos\theta_{hor} = A_{hor}sin\gamma_s} \qquad (13)$$

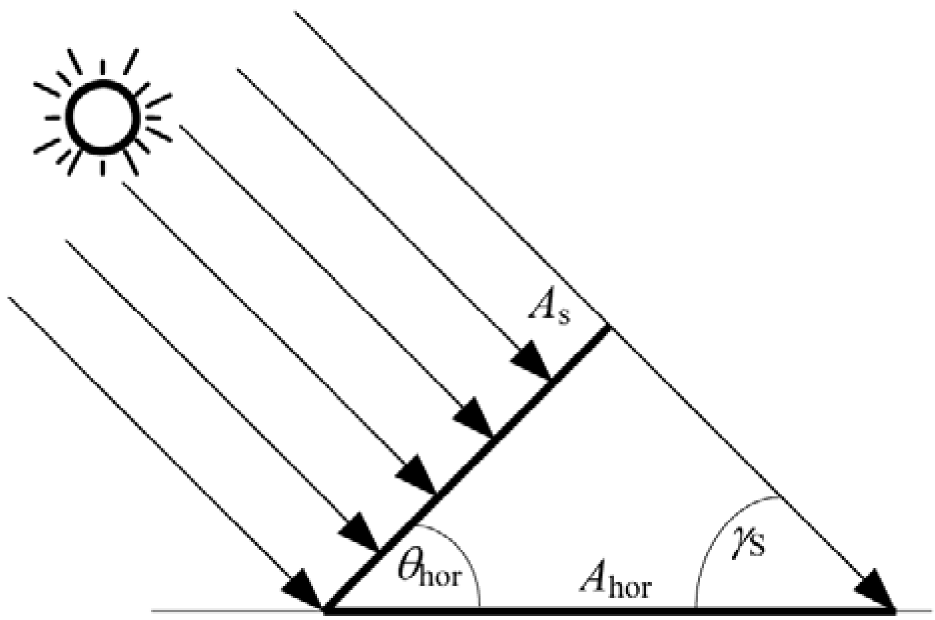


Figure 4.5: Beam on a horizontal area A_{hor} and an area A_s perpendicular to the sunlight [88]

4.3.7 Extraterrestrial radiation on horizontal surfaces

At any point in time, the amount of radiation normal to a surface outside the atmosphere i.e. the extraterrestrial direct normal radiation is given as;

$$\boldsymbol{G_O = G_{sc}\left(1 + 0.033cos\left(\frac{360n}{365}\right)\right)} \qquad (14)$$

for a day n of the year. Therefore, the radiation falling on a horizontal surface outside the atmosphere is given as;

$$G_O = G_{sc}\left(1 + 0.033cos\left(\frac{360n}{365}\right)\right)cos\theta_z \qquad (15)$$

The relation can be integrated from sunrise to sunset to give the amount of solar energy H_0, in J/m^2, received on a horizontal plane for the whole day *n*, as:

$$H_O = \frac{24\ x\ 3600\ x\ G_{sc}}{\pi}\left(1 + 0.033cos\left(\frac{360n}{365}\right)\right)\ x\ \left(cos\varphi cos\delta sin\omega_s + \frac{\pi\omega_s}{180}sin\varphi sin\delta\right)$$

(16)

Where;

H_O is the monthly mean daily extraterrestrial radiation

4.3.8 Estimation of monthly average solar radiation

In a study by Mubiru *et al*, [93] a performance assessment of the global solar radiation empirical formulations in Kampala-Uganda, were ranked and the model by Ogelman *et al* was ranked best. This model was adapted for this thesis to predict the monthly radiation basing on the sunshine hours. The model is expressed as a ratio of global radiation to extraterrestrial radiation by a second order polynomial function of the ratio of sunshine duration [94] as shown in equation 17.

$$\frac{\overline{H}}{\overline{H_0}} = a + b\left(\frac{\overline{S}}{S_0}\right) + c\left(\frac{\overline{S}}{S_0}\right)^2 \qquad (17)$$

Where;

$\overline{H}$ is the (unknown) monthly average total daily solar radiation on horizontal surface

$\overline{H_0}$ is the extraterrestrial monthly average total daily solar radiation on horizontal surface

$\bar{S}$ is the monthly average daily number of hours of sunshine (recorded)

S_0 is the monthly average day length (calculated for the average day of the month)

a and *b* and c are constants depending on the location

4.4 Power Production

Solar panel data sheets provide the data necessary to calculate the I-V curve ($I_{sc}, V_{oc}, V_{MPP}, I_{MPP}$), at a given reference radiation normally $1000W/m^2$. Hence, the model would use these parameters as input data to calculate the power produced by the solar panel. The performance of a solar panel is mainly affected by the radiation intensity and temperature as shown in Figure 4.6. The short circuit current I_{sc}, is approximately equal to the photo current I_{ph}. Since the photocurrent is proportional to the irradiance E, the short circuit current also depends on the irradiance:

$$\boldsymbol{I_{sc} \approx I_{Ph} = c_0 E} \qquad (18)$$

The short circuit current rises with increase in temperature. In order to get a power output dependent on the sun radiation and temperature, these input values from the solar data sheets were adapted to the real operating conditions by the following equations:

$$\boldsymbol{V_{oc} = V_{oc,0} \cdot \frac{\ln(E)}{\ln E_{1000}} . \left(1 + \alpha_v(\theta - \theta_{25})\right)} \qquad (19)$$

$$\boldsymbol{V_{MPP} = V_{MPP,0} \cdot \frac{\ln(E)}{\ln E_{1000}} . \left(1 + \alpha_v(\theta - \theta_{25})\right)} \qquad (20)$$

$$\boldsymbol{I_{MPP} = I_{MPP,0} \cdot \frac{E}{E_{1000}} . \left(1 + \alpha_I(\theta - \theta_{25})\right)} \qquad (21)$$

$$\boldsymbol{I_{sc} = I_{sc,0} \cdot \frac{E}{E_{1000}} . \left(1 + \alpha_I(\theta - \theta_{25})\right)} \qquad (22)$$

Where:

θ_{25} is the temperature at standard testing conditions usually 25 ℃

α_v is the voltage temperature coefficient

α_I is the current temperature coefficient

E_{1000} is the irradiance at standard testing conditions usually $1000W/m^2$

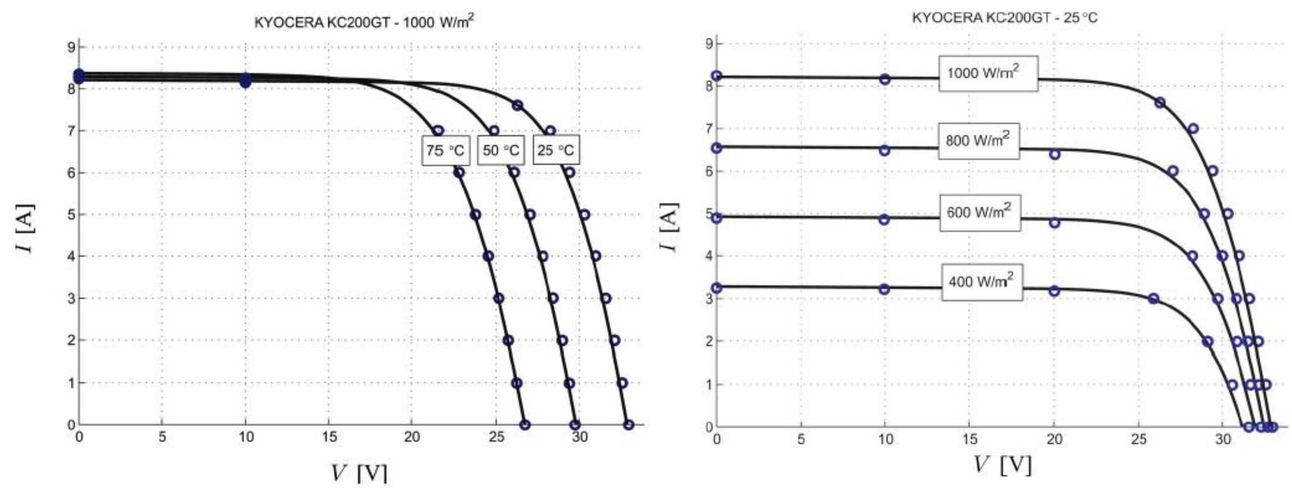
The equations allow for a fast-approximate module performance parameter estimation for different temperatures θ and irradiances E. With the parameters

$$C_1 = I_{sc}.\exp(-C_2.V_{oc}) \quad (23)$$

$$C_2 = \frac{\ln(1 - \frac{I_{MPP}}{I_{sc}})}{(V_{MPP} - V_{oc})} \quad (24)$$

The relation between the module current I and module voltage V can be found approximately as:

$$I = I_{sc} - C_1.\exp(C_2 V) \quad (25)$$



(a) (b)

Figure 4.6: I-V model curves and experimental data of the KC200GT solar array at (a) different temperatures (1000 W/m2), (b) different irradiations (25⁰C) [95].

4.4.1 Maximum power point

This is the operating point on the I-V curve in which the solar cell has its highest efficiency. The I-V curve and therefore the location of MPP depend on the sun radiation and the cells temperature. By directly connecting the solar panel to the battery, the battery voltage defines the module operating voltage. Therefore, maximum power point trackers (MPPT) are used to track the maximum power point of the module I-V curve, by DC to DC conversion electronics. However, the operating voltage decreases with higher temperature as shown in Figure 4.6 (a).

4.5 Power Storage

Batteries in solar systems handle various charge and discharge processes throughout the day. This is especially important since a battery's capacity and lifespan is dependent on the number of cycles i.e. on the discharge/charge speed and the charge events that occurred in the near past. When a battery was charged and discharged immediately, the discharge rate will be faster than after a longer rest period. In order to put such effects into account, the Kinetic Battery Model (KiBaM) by Maxwell and McGowan was chosen to model the batteries' performance [89]. The model is based on the assumption that a battery has two types of charge, that is; available and bound charge. These two different types of load are represented through two tanks, as shown in Figure 4.8. The left tank represents the bound charge and is through a tube connected with the available charge in the right tank. When the battery gets discharged with a high current, only a part of the bound charge is available, which is modelled by the thin balance tube. If the battery rests for a while the charge is balanced again. The aspects the KiBaM accounts for and its restrictions are indicated in Table 4.1. The battery is viewed as a storage source in series with a resistance as shown in Figure 4.7. Therefore, the terminal voltage is calculated with the constant resistance and the variable internal voltage E

$$\boldsymbol{V = E - IR_0} \qquad (\mathbf{26})$$

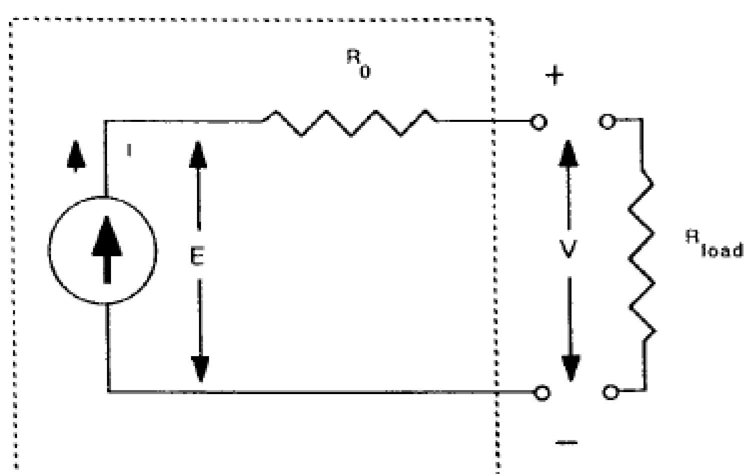


Figure 4.7: Overall battery electrical schematic [89]

Table 4.1: Aspects and restrictions of the Kinetic Battery Model

Considered	Restrictions
Decrease in capacity with increasing charge or discharge rates	Sharp increase in voltage near at the end of charging
Recovery in charge	Sharp drop in voltage when the battery is nearly empty
Increase of voltage with charging current and state of charge	Temperature effects
Decrease in voltage with discharging current and state of charge	

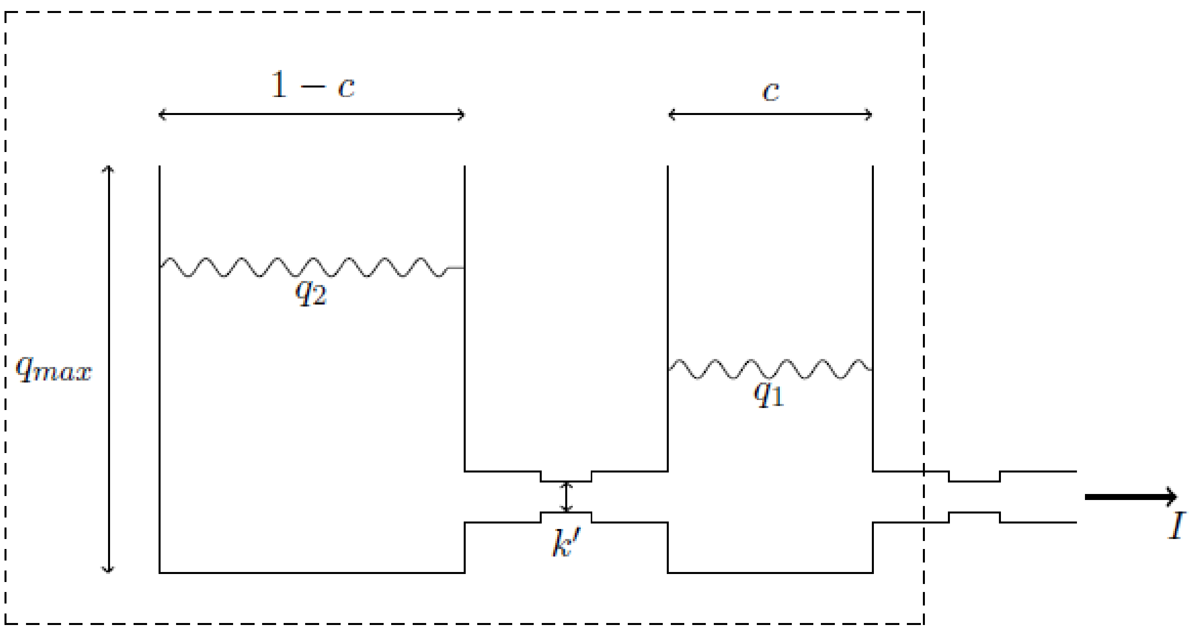


Figure 4.8: Illustration of the Kinetic battery model [89]

Figure 4.8 illustrates the kinetic battery model. Each tank has unit depth, but different widths, corresponding to different volumes. The width of tank 1 (“available”) is c and that of tank 2 (“bound”) is $1 - c$. The combined widths of the two tanks is thus equal to 1, and gives a combined tank area of unity. The combined volume of the tanks represents maximum battery capacity q_{max}. Because the area is unity, when both tanks are full, the head, h_{max} is also equal to q_{max}. The value between the tanks has a fixed conductance, k'. The current regulator operates such that the current I is constant, over onetime step. The model is described by the equations:

$$\frac{dq_1}{dt} = -I - k'(h_1 - h_2) \qquad (27)$$

$$\frac{dq_2}{dt} = -k'(h_1 - h_2) \qquad (28)$$

Where q_1 is the available charge, q_2 is the bound charge and h_1, h_2 are the heads respectively. The heights and the rate constant *k* can be described as:

$$h_1 = \frac{q_1}{c} \qquad (29)$$

$$h_2 = \frac{q_2}{1 - c} \qquad (30)$$

$$k = \frac{k'}{c(1 - c)} \qquad (31)$$

By inserting these new definitions and performing a Laplace Transformation on equations (26) and (27), the following equations for q_1 and q_2 are yielded.

$$q_1 = q_{1.0}e^{-kt} + \frac{(q_0kc - 1)(1 - e^{-kt})}{k} - \frac{Ic\left(kt - 1 + e^{-kt}\right)}{k} \qquad (32)$$

$$q_2 = q_{2.0}e^{-kt} + q_0(1 - c)\left(1 - e^{-kt}\right) - \frac{I(1 - c)\left(kt - 1 + e^{-kt}\right)}{k} \qquad (33)$$

Where $q_{1,0}$ and $q_{2,0}$ are the amount of available and bound charge, respectively, at the beginning of the calculation.

In order to get the parameters *c* and *k*, characteristics of a general battery data sheet can be taken. The batteries capacity to discharge time is given. The model uses the ratio:

$$\boldsymbol{F_{t1,t2} = \frac{q_{t1}}{q_{t2}}} \qquad (34)$$

to determine the batteries characteristics. Where $F_{t1,t2}$ is the relative amount of charge that can be extracted at faster rate t_1 compared to the standard rate t_2. When multiple values of Ft_1t_2 are known, least squares fit can be used to find the best values of c and k by solving the equation.

$$\boldsymbol{c = \frac{F_t(1-e^{-kt_1})t_2 - (1-e^{-kt_2})t_1}{F_t(1-e^{-kt_1})t_2 - (1-e^{-kt_2})t_1 - kF_tt_1t_2 + kt_1t_2}} \qquad (35)$$

After determining *c* and *k*, all parameters are available to calculate the capacity and currents of the battery, depending on the energy demand or supply.

4.5.1 Calculation of battery Input and Output

The battery is not able to handle infinite high input or output currents. It is limited by the maximum charge and discharge current $I_{c,max}$ and $I_{d,max}$ which depend on the current state of charge and the charging events that occurred in the previous time steps. The previous charging events are represented through the different loads q_1 ("available") and q_2 ("bound"). The calculation of the maximum charge current requires the maximum capacity q_{max}, too, which given by:

$$\boldsymbol{q_{max} = \frac{q_t[(1-e^{-kt})(1-c) + kct]}{kct}} \qquad (36)$$

Where q_t is discharge load according to discharge time t. It is recommended to take a slow discharge rate, in order to calculate with the highest possible maximum charge. With q_{max}, all parameters are identified to calculate the maximum possible currents in one time step.

4.5.2 Discharging

At each time interval, the amount of power required can be found, P_{need}. Using a nominal system voltage, V, the desired discharge current I_d, can be obtained:

$$\boldsymbol{I_d = \frac{P_{need}}{V}} \tag{37}$$

The maximum discharge current, I_{dmax}, can be obtained from:

$$\boldsymbol{I_{d,max} = \frac{kq_{1,0}e^{-kt} + q_0kc(1 - e^{-kt})}{1 - e^{-kt} + c(kt - 1 + e^{-kt})}} \tag{38}$$

Where t is the length of the system model time step, q_0 and $q_{1,0}$ are the total charge and the available charge respectively, at the beginning of the time step.

The maximum discharge that can be obtained is got from:

$$\boldsymbol{Maximum\ discharge = I_{d,max}t} \tag{39}$$

4.5.3 Charging

The desired charging current, I_c, is obtained in the same way as in the discharging case. However, in this case the I_c will be a negative number.

$$\boldsymbol{I_c = \frac{P_{need}}{V}} \tag{40}$$

The maximum allowable charge current $I_{c,max}$ can be obtained from:

$$\boldsymbol{I_{c,max} = \frac{-kcq_{max} + kq_{1,0}e^{-kt} + q_0kc(1 - e^{-kt})}{1 - e^{-kt} + c(kt - 1 + e^{-kt})}} \tag{41}$$

4.6 Message Sending Integration

The algorithm was written using python as the coding language. Python is a widely used high level programming language for general purpose programming. The hug API, was used in integrating the SMS sending algorithm with the Karana back end system. The hug Application Programming Interface (API) lays a platform which enables the different system components i.e. the influx database, Karana device and Grafana to communicate. The Karana back end system is the set of code procedures that run in the back ground of the Karana device described in Section 4.2.1. This set of code forms the entire back end API. The Twilio text message sending platform was leveraged in SMS sending.

CHAPTER FIVE: RESULTS AND DISCUSSION

Outline

5.1 Overview

This chapter entails the preliminary calculations, algorithm flow, functionality and operation as well as a description of the different categories of text messages that are sent to the household user.

5.2 Preliminary Calculations

I. Power prediction and production

This section aims at demonstrating part of what happens behind the code segments.

Day of the year was considered to be January 1st, day of the year d = 1. The location coordinates of the place (Kampala) are 0.3476^0 N, 30.0781^0 E. $Solar\ Constant, G_{sc} = 1367\, W/m^2\, , \pi = 3.14$

From equation (3)

$$declination\ angle, \delta = 23.45 sin\left(360\ x\ \frac{284+1}{365}\right)$$

$$= -23.0116^0$$

From equation (7), the hour angle, $\omega_s = cos^{-1}(-tan\varphi tan\sigma)$

$$= cos^{-1}(-\tan(-23.0116)\tan(0.3476))$$

$$= 89.9^0$$

From equation (16),

$$H_O = \frac{24\ x\ 1367}{\pi}\left(1 + 0.033 cos\left(\frac{360\ x\ 1}{365}\right)\right)\ x\ \left(cos 0.3476\, cos(-23.0116)\, sin 89.9 + \frac{\pi\ x\ 89.9}{180} sin 0.3476 sin(-23.0116)\right)$$

$$= 29361.21\, Wh/m^2 day$$

For equation (17), Coefficients $a = 0.288, b = 0.154, c = 0.448$ as reported by [93].

From Climwat, Monthly average number daily sunshine hours, $\bar{S} = 5.6$

$$S_0 = \frac{2}{15}\ x\ \omega_s$$

$$= \frac{2}{15}\ x\ 89.9$$

$$= 11.987$$

From equation (17), monthly average solar radiation can be obtained;

$$\overline{H} = \left(0.288 + 0.154\ x\left(\frac{5.6}{11.987}\right) + 0.448\ x\left(\frac{5.6}{11..987}\right)^2\right) x\ 29361.21$$

$$= 11996.03\, Wh/m^2\, /day$$

$$Estimated\ Power\ production\ on\ solar\ panel\ per\ unit\ area\ per\ day$$
$$=\ 11.996\ kWh/day$$

This procedure is carried out every month to determine the expected radiation.

II. Power Storage – Application of the KiBaM to obtain the SOC

From the battery data set. (Appendix A5)

Obtaining constants c and k

Table 5.1: Performance Specifications (Appendix A5)

Nominal Capacity		
Hours		**Ah**
20	125 mA to 10.50 volts	2.5
10	220 mA to 10.50 volts	2.2
5	400 mA to 10.20 volts	2
1	1.5 A to 9.00 volts	1.5
0.25	4.5 A to 9.00 volts	1.13

At t=20 hr, Nominal capacity = 2.5 Ah., At t =10 hr, Nominal Capacity = 2.2 Ah

From equation 34,

$$F_{10,20} = {}^{2.2}/_{2.5}$$

$$= 0.88$$

From equation 35,

$$c = \frac{0.88\ x\ \left(1 - e^{-10k}\right)\ x\ 20 - \left(1 - e^{-20k}\right)\ x\ 10}{0.88\ x\ (1 - e^{-10k})\ x\ 20 - (1 - e^{-20k})\ x\ 10 - k\ x\ 0.88\ x\ 10\ x\ 20 + k\ x\ 10\ x\ 20}$$

At t = 5 hr, Nominal capacity = 2.0 Ah

$$F_{10,20} = {}^{2.0}/_{2.5}$$

$$= 0.8$$

$$c = \frac{0.8\ x\ \left(1 - e^{-5k}\right)\ x\ 20 - \left(1 - e^{-20k}\right)\ x\ 10}{0.8\ x\ (1 - e^{-5k})\ x\ 20 - (1 - e^{-20k})\ x\ 5 - k\ x\ 0.8\ x\ 5\ x\ 20 + k\ x\ 5\ x\ 20}$$

For each battery performance specification in the data set, $F_{t1,t2}$ is determined and the corresponding substitutions in equation 35 are made. For each set of two equations, values of c and k are obtained by solving simultaneously. This is done for all the equations under different specifications until a given value of k gives the same value of c at two discharge rates.

After obtaining c and k, equations 32 and 33 are solved to find the values of q_1 and q_2. The state of charge is obtained from,

$$SOC = q_1 + q_2$$

5.3 General Process Set up

The set up involves three main sections i.e. input, processing and output as shown in Figure 5.1.

5.3.1 Input Section

The input section involves acquisition of the different data types ranging from weather data, static data and dynamic data also known as timeseries data. Weather data consists of the solar radiation data, Static data; solar system data which entails the battery capacity and solar system peak, and timeseries data consists of the real-time data from the solar system which is accessed from the influx database.

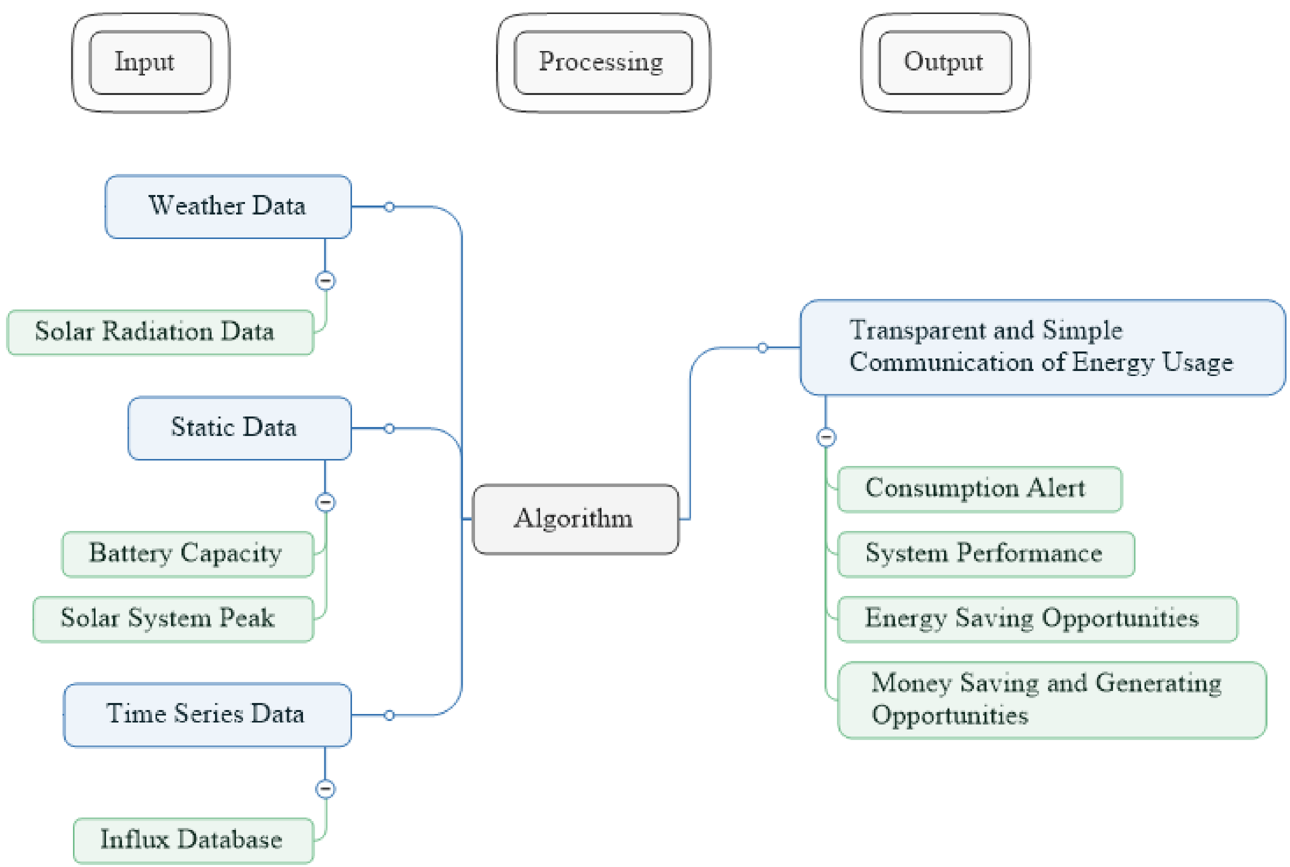


Figure 5.1: General Process set up

5.3.2 Processing section

This section involves action and functioning of the algorithm which follows a systematic flow as shown in Figure 5.2. ***P_1M, P_2M, P_3M*** and ***P_4M*** are the different types of message sending schemes which are triggered by the events as described in the flow chart.

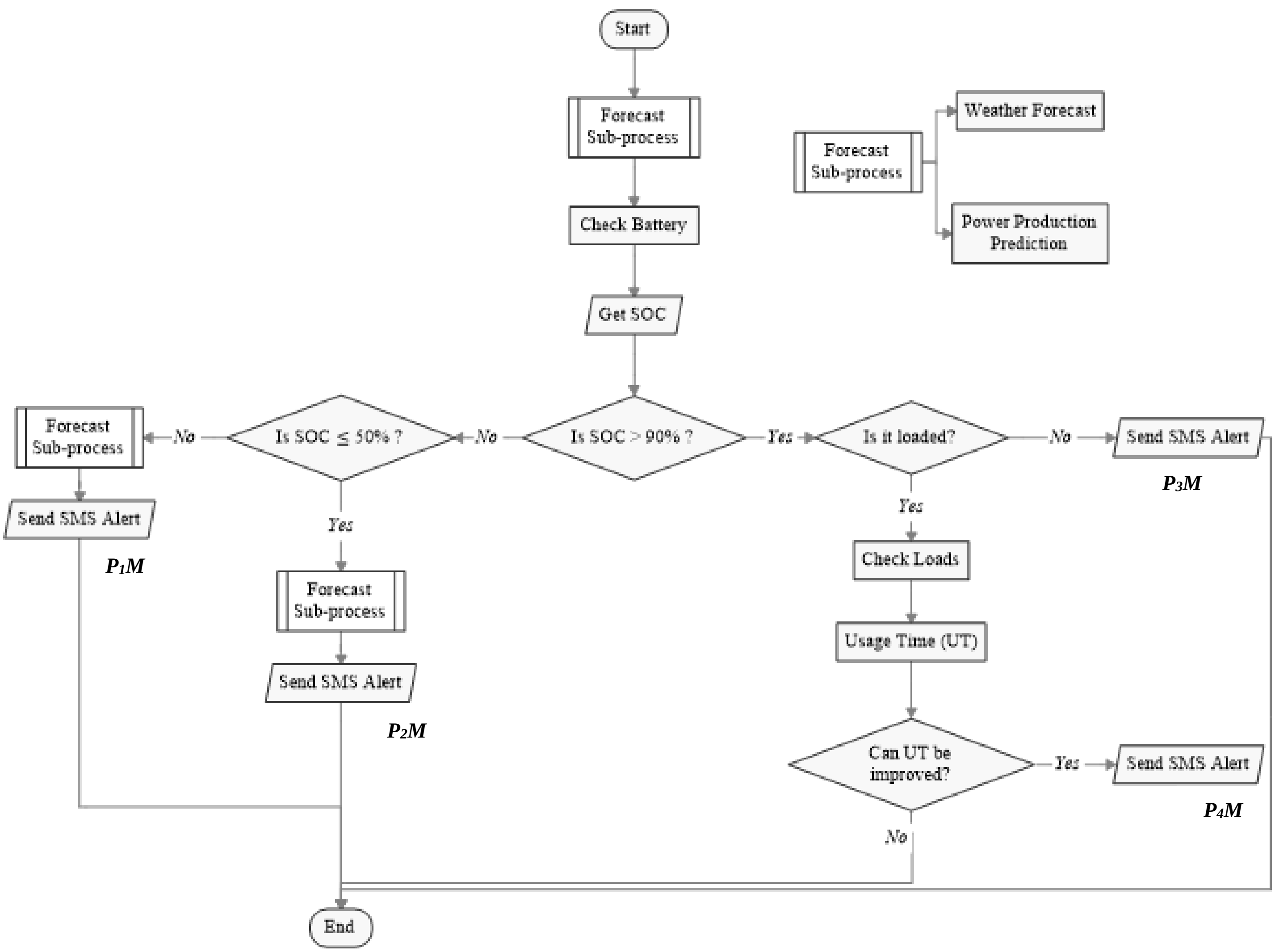


Figure 5.2: A process flow chart of the algorithm with the different message categories

5.3.3 Algorithm functionality

The start point initiates the processing section. The algorithm proceeds to the forecast sub-process. The forecast sub-process involves two steps; weather forecast followed by determination of solar power production and prediction. At this stage, the expected solar radiation is attained, and this is used to calculate the expected power in a day and hence the estimated time it would take the battery to charge. The next step is to check the battery in order to ascertain the level of charge. This is done by acquiring the state of charge which is analyzed further in order to take a decision for the next operation. If the state of charge (SOC) is above the high threshold mark e.g. 90%, the algorithm proceeds to check whether there are loads or appliances in use.

If there are no loads, a text messages sending function is invoked (P_3M). At this point the text message to be sent is to inform the user of the surplus and/or energy availability and how this could be utilized for productivity. The message is also supposed to offer some protection to the battery against overcharging through demand side management.

On the other hand, if there are loads/ appliances in use, the algorithm proceeds to check the type of loads, rating and consumption. This is followed by how much the battery power would last at the current consumption rate; or for how long the appliances would be supported by the battery until the SOC reaches the low threshold point i.e. 50%. If the appliance usage time can be improved or increased, a message sending function is invoked and an SMS sent to a user suggesting how best usage time can be improved (P_4M). This message entails information suggesting ways of how the usage time can be increased i.e. by turning off lights that are not in use, replacing appliance with more energy efficient ones etc.

If the state of charge is not above 90%, the algorithm proceeds to check whether it is below the low threshold point i.e. 50%. If SOC is below 50%, the forecast sub-process is revisited to determine how long it may take the battery to charge to an adequate SOC. A text message is sent to the user informing them how long it would take for the battery to charge (P_2M) and hence the recommended time at which appliances can be connected. On the other hand, if the SOC is not below 50%, the algorithm proceeds to the forecast sub-process, determines how long it would take the battery to charge, system general performance and then sends a text message informing the user of these revelations (P_1M) and the recommended time for appliance connection.

5.3.4 Output section: Message Categories, Details and Sending Criteria

This section encompasses the SMS interpretation and sending part of the algorithm. Messages to be sent to the users were categorized into priorities. There are mainly four message categories labeled according to the priority number given (P_1M, P_2M, P_3M, P_4M). Priorities were given depending on the frequency a particular message type is sent i.e. SMSs that ought to be sent everyday were categorized priority 1 (P_1M). The categorization of messages was done to avoid sending many unnecessary messages that could turn out redundant. It also helps to lessen the costs involved in message sending. On the users side, it helps to avoid the superfluous notifications in form of inbox messages on their phones which has been reported to be a contributing factor to disinterest and general lack of response to feedback systems [47].

I. Priority 1 Message (P_1M)

This category of SMS aims at informing and advising users the most appropriate time for connecting appliances. This message is also aimed at promoting and ensuring load shifting among users by alerting them of the times when excess energy/ peak times are expected. And in the periods when the weather forecast shows a period of low irradiance from the sun, adjustments that would ensure prolonged usage and maximum utilization without harming the solar system would be communicated. This message category is sent at least once every day in the morning depending on the state of the solar system and usage. Message samples would look like this (Figure 5.3);

"To have more lighting time, at night, consider connecting your appliances at 2:00 pm"

"To have enough TV time with your mates, consider doing your laundry at 1:30 pm"

"To have more lighting time for your children's homework, consider charging your phones at 1400 hrs."

"It's examinations time, to ensure more reading hours at night for your children, consider connecting appliances at 2:00pm"

"There will be rain in the next two days, consider turning off highly consuming appliances to have more lighting time"

"Today, weather is cloudy, turn off appliances that are not in use to have more conversational time with your friends at night"

"Abaana bo okusobola okola homuwaaka, kyajjinga essimu zo ku sawa munana ez'omutuntu"- (in the local language). *Loosely translated as "Charge your phones at 2 pm to avail more lighting time for children's homework"*

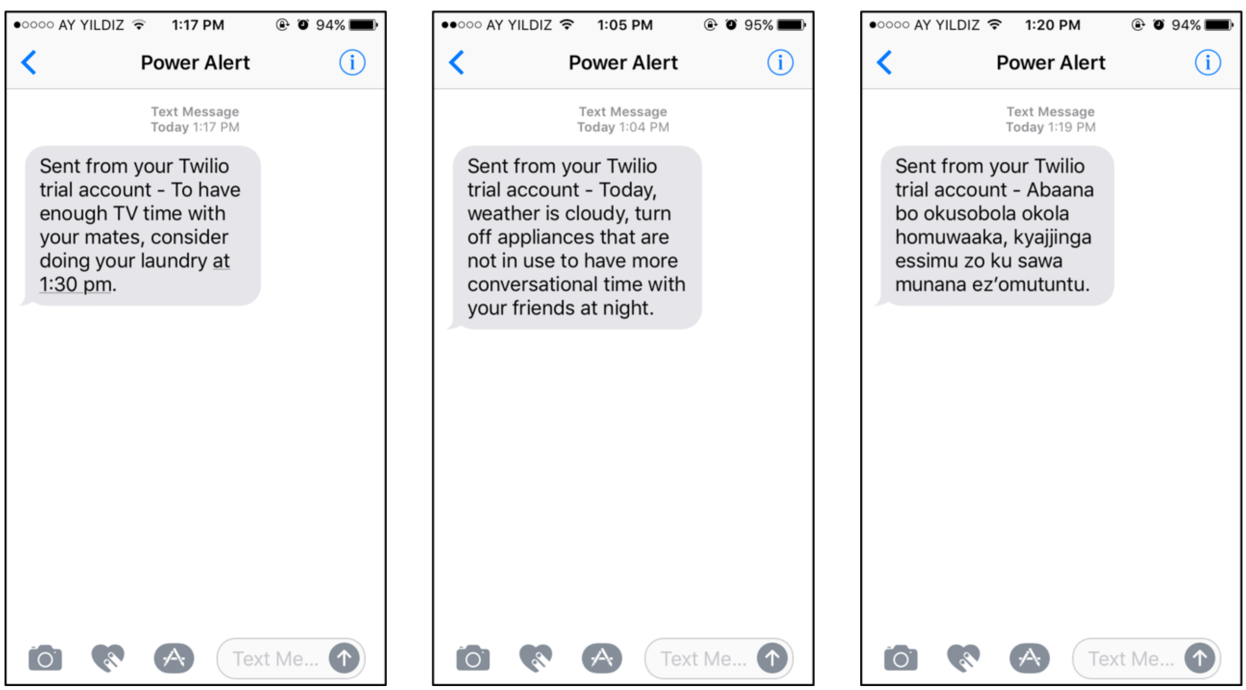


Figure 5.3: Screenshots of sample P_1M messages generated by the algorithm

II. Priority 2 Message (P_2M)

This message category is invoked when the battery SOC is below or equal to the low threshold point. This message type is aimed at protecting the battery as well as informing the user of the appropriate time for connecting his/her desired appliances. This message would be sent regardless of whether priority 1 message was sent or not. However, a second message of the same category cannot be sent on the same day. Message sample would look like this (Figure 5.4);

"To enjoy your system tomorrow and the days to come, consider disconnecting appliances and connecting later at 3:00 pm"

"Okusobola okwewala okugula battery empya mu banga etonno, gyako ebikozesebwa byonna ogya kubizaako ku sawa kumi ez'olwegulo" – (in the local language). Loosely translated as "To avoid buying a new battery soon, turn off appliances, you will turn them on at 4 pm"

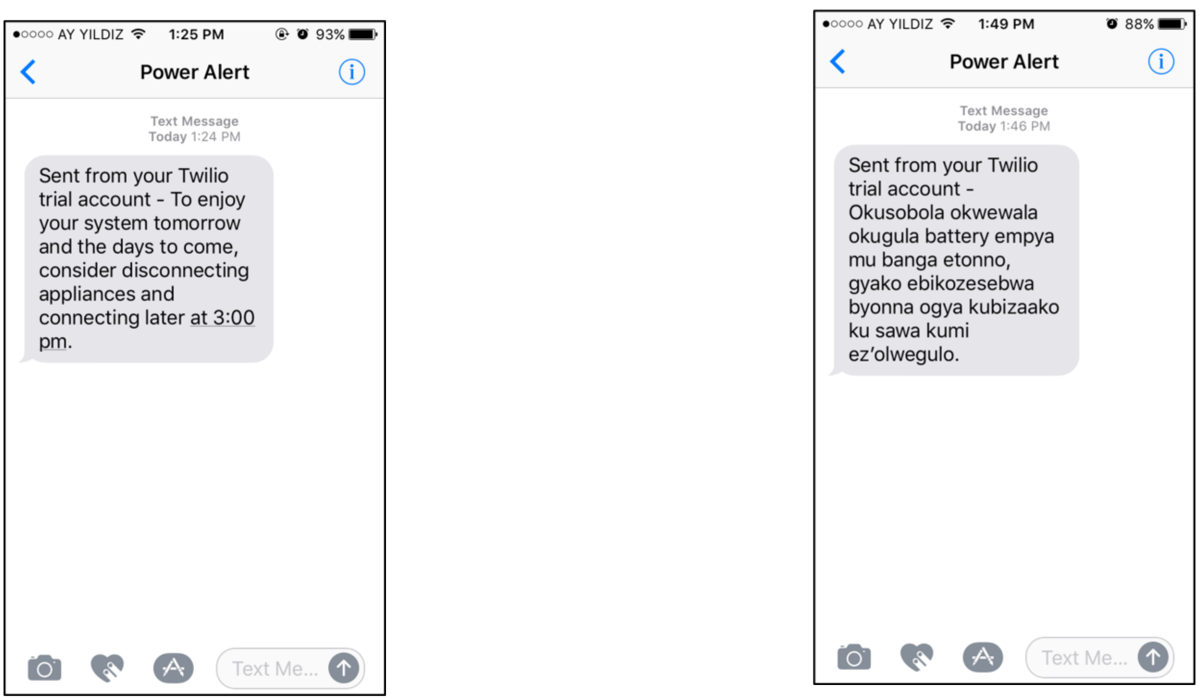


Figure 5.4: Screenshots of sample P_2M messages generated by the algorithm

III. Priority 3 Message (P_3M)

This message category aims at making the users realize the wasted and missed energy usage opportunities and how this can be avoided the next time [96]. By informing the user of their past consumption and how this could be improved in different ways, the message points the user to the energy awareness benefits and how the system can be utilized maximally. This message type also includes short texts that provide encouragement for the small energy actions to encourage larger energy efficient actions in the future. This is expected to influence the user behavior rather than solely focusing on the appliance efficiency. The message also aims at alerting the user incase the battery SOC goes beyond the maximum threshold value. Messages of this category would be weekly and dependent on the last time a previous message of the same category was sent. Message sample would look like this (Figure 5.5);

"Last week you missed 10 hours of lighting time because of high consuming appliances, replace 10 W bulbs with 3 W bulbs for more reading time for your children"

"Thanks for changing your lights, you were able to achieve 2 hours more lighting time for your children's homework"

"Okusobozesa abaana bo okufuna obudde obusoma obulungi, gyako amataala mu bisenge ebitakozesebwa" – (in the local language). Loosely translated as turn off lights in rooms that are not in use to avail more reading time for your children.

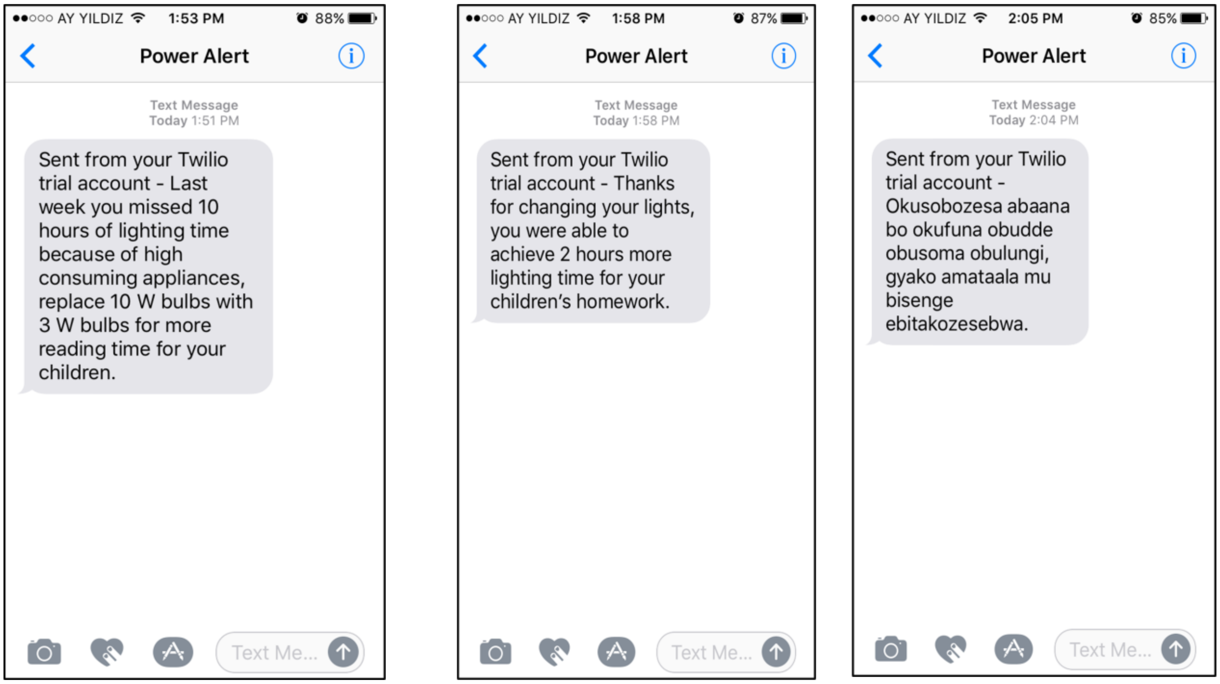


Figure 5.5: Screenshots of sample P_3M messages generated by the algorithm

IV. Priority 4 Message (P_4M)

This message category focuses on informing users of the appliance usage times and how this can be increased by replacing with more energy efficient appliances plus other recommendations. These messages aim at educating the user how well the system would perform if more energy efficient appliances were used. This is communicated through tangible ways like citing lighting time, amount of laundry that can be done, and number of phones that can be charged. Also, this message category addresses the general system routine preventive maintenance. There could be a fall in the system performance caused by dust on the panels, loose connections, corroded battery terminals or any other breakages in the system [96, 97] due to poor maintenance. Since such incidences are not so common every day in the system, messages of this category are sent after 2 – 3 weeks from the last time a message of this kind was sent. Message sample would look like this (Figure 5.6);

"To have more un-interrupted TV time, consider cleaning your solar panels"

"To ensure more lighting time consider replacing your 4 Watt bulbs with 2 Watt bulbs"

"okunyumirwa Tivi yo nga totagataganyizidwa, siimula ku sola pano yo okugyako enfufu" - *(in the local language). Loosely translated as "clean dust off your solar panel to have more uninterrupted TV time"*

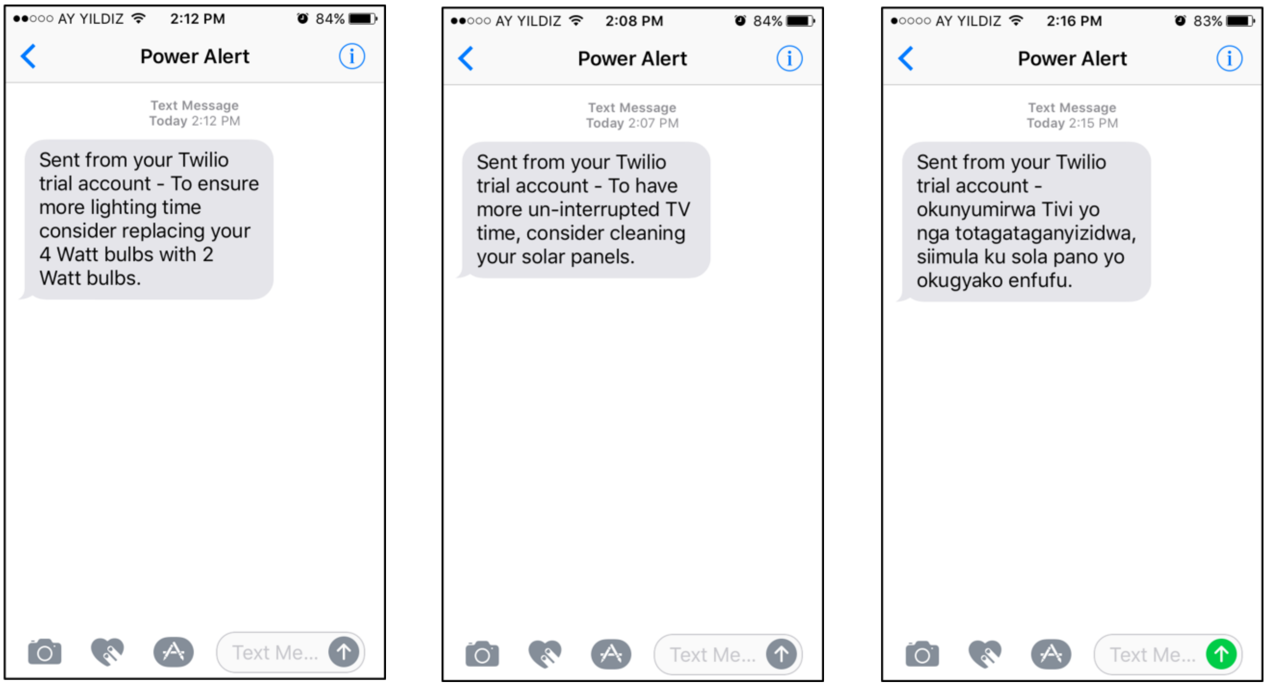


Figure 5.6: Screenshots of sample P_4M messages generated by the algorithm

5.4 Analysis and Discussion

5.4.1 Effective communication strategy

The decision of what to send and how well this can be communicated is mainly dependent on the user's perspective and understanding. The user perspective is among the most important aspects in feedback systems because the actions that proceed after receiving the information are dependent on whether the information is understood or not. From individual experiences, assumption and research, message samples were developed in both the commonly spoken languages in Uganda i.e. Luganda and English. For effectiveness of communication, it would be important to involve users in the development process by engaging and sensitizing them on the importance of such a system and how to interpret the messages received. This in some way would help to draw a line on what matters to the users and how well this can be incorporated into the messaging system. In some studies, feedback systems have been coupled with incentives to make them more efficient [23]. Incentivizing the whole process would cause an impact in the results achieved as reported in some studies.

5.4.2 Frequency and time of notification

The frequency of notification is dependent on the message priorities that were set i.e. the algorithm sends a minimum of 1 message every day (P_1M) depending on the system performance and general usage. The messages were prioritized depending on the period of delivery and on how frequent specific information would be required to be passed on to the user so as to keep the positive usage behaviors repetitive.

However, the user has a pivotal role to play in deciding how frequent he/she should be notified and deliberating on the appropriate time to do this. This is so because the messages are dependent on how well the system is being used and maintained.

5.4.3 Potential benefits

A system such as this would not only benefit the users by ensuring better system performances, reduction in system failures and hence economic boost; but also, it would ensure energy awareness among off-grid energy users. The importance this could have on standards of living among users cannot be underestimated. The different messages sent are meant to capture the scope of the entire solar system in use hence ensuring an understanding of what users are paying for when it comes to metering and other platforms like PAYG. Also, communicating consumption to users would be key in reducing maintenance costs involved and rampant system breakages. These messages sent can play a role in stimulating users to think of other business avenues like trading electricity among other community members because of availability of surplus energy. The messages given are part of the solution in solving the problem of intermittency in off-grid solar systems.

Some studies have mentioned failure of many donor funded off-grid projects due to a complete detachment of the communities from the projects. Feedback systems as the one developed in this thesis would be key in stimulating community participation and ownership in such projects.

5.4.4 Limitations and improvements

Though the intention was to build a fully-fledged functional algorithm that could be tested in the field, this was not done due to resources and time constraints as well as hardware limitations at the time. Having a view of the field testing would provide a user perspective and hence a change in the preconceived notions among off-grid rural household electricity users.

Parts of the algorithm were developed basing on models like the kinetic theory of battery model. The model works on the assumption that the system is quasi steady, however, in real life situations, conditions can be different.

The solar radiation estimation model used in the algorithm predicts the radiation without consideration of other climate factors. Due to lack of cloud cover, temperature and other weather data, the radiation used was assumed to be on a horizontal surface.

Sample messages were crafted and translated basing mainly on assumptions, research and individual experience. A view from different people from field studies would have probably influenced the way messages are written.

The frequency of message sending is also dependent on assumptions and research, this could have been solved if field visits were conducted. Also, it would be important if a user could have the powers to invoke an SMS about their consumption details anytime without waiting for the algorithm to do this. Arrangements like these would put users in control and allow them to check their system performance and usage history anytime anywhere.

While a lot of research work has been done about energy efficiency in households using different kinds of feedback mechanisms, the main focus has been on on-grid households, commercial centers and computer complexes, and none has been carried out in an African setting. At the time of writing of this thesis no research work was found focusing on off-grid rural households in Africa.

5.4.5 Business case

The business case for the SMS system could be viewed in two different schemes i.e. in solar systems under the PAYG scheme and those that are obtained through the loan scheme. Under the PAYG scheme, a small percentage of the payments made by users can be billed into funding the SMS service. Under the loan scheme, microfinance system of financing has emerged to be one of most successful platforms through which rural households access loan services for solar systems and other related products [98-100]. In this case, if a household acquires a solar system through a loan scheme, part of the loan repayment goes towards the SMS service. Once the household repays the loan or finishes paying the system through the PAYG, then the user can choose whether they continue receiving the service at a small monthly subscription or not.

CHAPTER SIX: CONCLUSION

Outline

6.1 Contributions and Summary

This thesis attempts to answer the question of how consumption information can be made accessible and communicated in a transparent, simple and an understandable way in off grid rural households. Furthermore, it elaborates on how this information can be leveraged to improve the performance of solar systems by influencing user behaviors. The thesis argues that in order to achieve this, already existing platforms like mobile phones could be a vantage in this regard (Chapter 2) because they are common in rural households as they are used to maintain links among families and friends on the other side.

The algorithm developed in the thesis uses weather data, static data like battery capacity and solar system peak size, plus real-time data series from the influx database. In the weather data, solar irradiation data is targeted thereby predicting the expected power production from the solar system. The battery capacity data and solar system data are used to set threshold parameters for monitoring the entire system. The battery, solar PV and loads/appliances are the basis over which the SMS sending scheme depends.

Using SMSs to communicate energy consumption information is a very feasible solution, the thesis argues. However, the matter in which the information is relayed is very important. Technical terms have to be broken down and translated into information that users can relate to. It is true users require feedback to keep them informed about consumption and performance of their systems but this to have an effect, the manner in which information is communicated matters more; the thesis attempts to give general translation of messages basing on individual experiences, assumptions and studies encompassing the needs of rural households.

In the face of slow growth of grid electricity among isolated and dispersed communities, off-grid electricity has taken a steep growth. However, the literature as far as measures to address EE in off-grid systems is concerned, is still limited. In this regard therefore, this thesis work tackles the problem of invisibility of consumption information in off-grid households which is a stronghold to influencing user behaviors and hence promoting EE. This document could therefore be used by solar supplier companies to develop sustainable models which not only persuade users to pay but also encourage understanding and performance of solar systems. This thesis work lays a ground work for policy makers to structure policy instruments that create environments where suppliers have to ensure that users obtain quality solar products. On the side of innovation, this work plays a key role in brainstorming and thinking of new low cost innovative ideas that could encourage energy efficiency among off grid households by bridging the gap between users and professional communities involved in electricity access and energy efficiency.

6.2 Recommendations and Further Work

In the thesis, it is proposed that for better communication and tailoring of consumption messages that resonate with the users' needs, it is important that community sensitization about the importance and need of such a system is held. This would allow room to have the community perspective as well.

Further work should focus more on development and field testing of such algorithms to establish relationships between users and consumption information access in off-grid areas. More development can be focused on mobile apps that could be able to show the visual aspect of the entire system, however such applications may not be suitable for the rural households considering the type of phones that are common in those areas. Nevertheless, for a different demographic setting, the results would be worth a try.

Also, an assessment of how feedback systems do influence the uptake of solar home systems and what economic impact this has.

A lifecycle assessment of the solar system performance before and after the deployment of such a feedback system would be part of further work that could be done. It could give an insight of the extent to which the feedback system can affect the general system performance, user perspectives and the system lifespan.

An analysis of the business models that could be developed around such a system is another area that would need further research.

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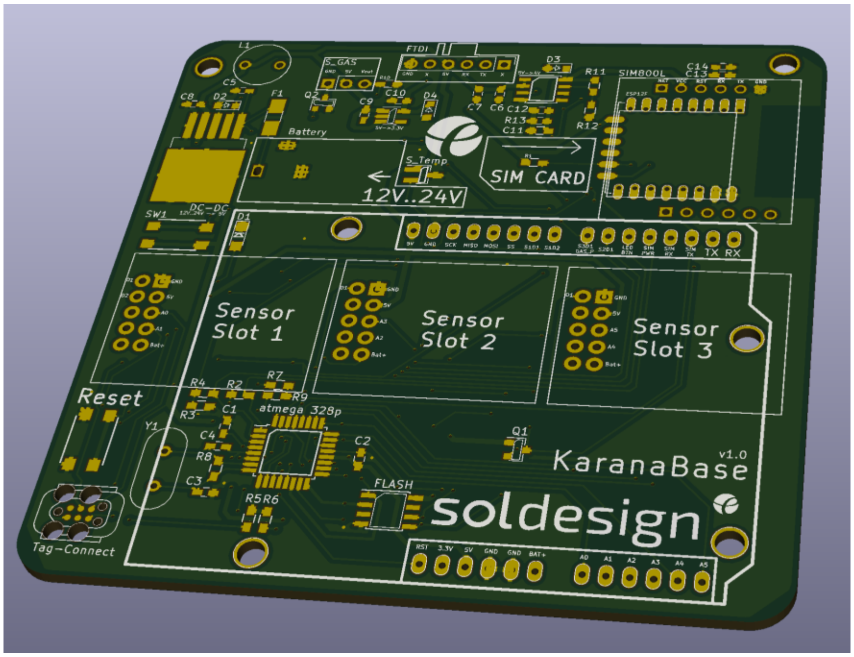
APPENDIX

A1: The Karana device pictorial display and technical features



- Onboard GSM-Module (SIMCOM SIM800L)
- Quad Band: 850 MHz, 900 MHz, 1800 MHz, 1900Mhz
- WiFi chip footprint
- SPI, I²C, UART
- Tag-Connect
- Powered by 7V-30V
- Three inbuilt SHS current- and voltage sensors, max current: 15 amp
- Max voltage: 24 V
- Wire screws (no-solder installation)
- Onboard temperature sensor, measures from -10°C to 125°C, (+- 2°C)
- Arduino footprint (plug-and-play)

A2: Messaging sending: incorporation with the Karana Back end API

```
from twilio.rest import Client
import logging
import json
from configparser import ConfigParser

MESSAGE = """ This is a test alert"""

NOT_CONFIGURED_MESSAGE = """Cannot initialize Twilio. Required environment variables
                        TWILIO_ACCOUNT_SID, TWILIO_AUTH_TOKEN or TWILIO_NUMBER missing"""

class Messaging(object):
    def __get_parser__(self):
        """This returns the parser of the config.ini file"""
        parser = ConfigParser()
        #self.log.debug('Load config.ini')
        parser.read('config.ini')
        return parser
    def send_sms(self, msg, to):
        parser = self.__get_parser__()
        twilio_account_sid = parser.get('twilio', 'TWILIO_ACCOUNT_SID')
        twilio_auth_token = parser.get('twilio', 'TWILIO_AUTH_TOKEN')
        twilio_number = parser.get('twilio', 'TWILIO_NUMBER')
        sms_client = Client (twilio_account_sid, twilio_auth_token)
        message = sms_client.messages.create(body=msg,from_=twilio_number,to=to)
```

A3: Main source code: Communication with Influxdb, Karana and message sending

```
#!/usr/bin/env python3
docstring = """This is the main api which will be started by running run.sh"""
import hug
import falcon
from logger import log
import logging
from db import KaranaDBWrapper
from jwtoken import JWTWrapper
import json
from influx import InfluxDBWrapper
from Sms import Messaging

module_log = logging.getLogger(__name__)
log.info(docstring)
module_log.info('test for logger name __name__')

db = KaranaDBWrapper()
smsclient = Messaging()
jwtoken = JWTWrapper(db)
token_key_authentication = hug.authentication.token(jwtoken.token_verify)
origin = 'http://tonnyssandbox.karana-desktop-1.mei'
@hug.request_middleware()
def process_cors(request, response):
    log.info('This is how the request looks like:' + request.method)
    response.set_header('Access-Control-Allow-Origin', origin)
    response.set_header('Access-Control-Allow-Methods', 'POST, PUT, GET, PATCH, DELETE')
    response.set_header('Access-Control-Allow-Headers', 'content-type, authorization')

@hug.get('/{resources}/{resource_id}/', version=1, requires=token_key_authentication)
def get_resource(resources: hug.types.text, resource_id: hug.types.text, response):
    """This method returns either the resource with given ID or all resources"""
    if resources == 'v1': # This is necessary when resource_id is empty
```

```
        resources = resource_id
        resource_id = ''
    try:
        log.debug('Trying get Resource for resource: ' + resources + ' with id: ' + resource_id)
        if resource_id == '':
            all_res = db.get_res(resources)
            results = {'results': [all_res]}
            if results['results'][0] or results['results'][0] == {}:
                return json.dumps(results)
        else:
            results = {'results': [{resource_id: db.get_res_by_id(resources, resource_id)}]}
            if results['results'][0][resource_id]:
                return json.dumps(results)
        log.error('Results: ' + str(results))
        raise
    except Exception as e:
        log.error('Couldnt get Resource for resource: ' + resources + ' with id: ' + resource_id)
        raise falcon.HTTPBadRequest('Get Resource Error', 'Failed to get requested resources Resource')


@hug.post('/{resources}/new/', version=1,requires=token_key_authentication)
def create_resource(resources: hug.types.text, data, response):
    """This method creates a resource"""
    log.debug("Incoming data is_ " + str(data))
    if resources == 'v1':  # This is necessary when resource_id is empty
        return False
    try:
        results = {'results': [{'uuid': db.add_new_res(resources, str(data))}]}
        if results['results'][0]['uuid']:
            return json.dumps(results)
        raise
    except Exception as e:
        log.error('Could not Create Resource: ' + resources + ' with data: ' + str(data))
        raise falcon.HTTPBadRequest('Create Resource Error', 'Failed to create new Resource')
```

```
@hug.post('/{resources}/login/', version=1)
def login_resource(resources: hug.types.text, user, password, response):
    """This method creates a resource"""
    log.debug("Incoming data is_ " + str(user))
    if resources == 'v1':  # This is necessary when resource_id is empty
        return False
    try:
        results = {'results': [{'token': jwtoken.token_generate(user, password, resources)}]}
        if results['results'][0]['token']:
            return json.dumps(results)
        raise
    except Exception as e:
        log.error('Could not login Resource: ' + resources + ' with username: ' + str(user),e)
        raise falcon.HTTPBadRequest('Create Resource Error', 'Could not login Resource')

@hug.put('/{resources}/{resource_id}/', version=1,requires=token_key_authentication)
def updated_resource(resources: hug.types.text, resource_id: hug.types.text, data, response):
    """This method updates a resource completely"""
    if resources == 'v1':  # This is necessary when resource_id is empty
        return False
    try:
        results = {'results': [{resource_id: db.update_res(resources, resource_id, str(data))}]}
        log.debug('Results ' + str(results))

        if results['results'][0][resource_id]:
            return json.dumps(results)
        raise
    except Exception as e:
        log.error('Could not update Resource: ' + resources + ' with data: ' + str(data),e)
        raise falcon.HTTPBadRequest('Update Resource Error', 'Failed to update Resource')

@hug.patch('/{resources}/{resource_id}/', version=1,requires=token_key_authentication)
def modify_resource(resources: hug.types.text, resource_id: hug.types.text, data, response):
    """"This method modifies a resource in this case only one field allowed"""
```

```
    if resources == 'v1':  # This is necessary when resource_id is empty
        return False
    try:
        results = {'results': [{resource_id: db.modify_res(resources, resource_id, str(data))}]}
        log.debug('Results ' + str(results))
        if results['results'][0][resource_id]:
            return json.dumps(results)
        raise
    except Exception as e:
        log.error('Could not modify Resource: ' + resources + ' with data: ' + str(data))
        raise falcon.HTTPBadRequest('Modify Resource Error', 'Failed to modify Resource')

@hug.delete('/{resources}/{resource_id}/', version=1,requires=token_key_authentication)
def delete_resource(resources: hug.types.text, resource_id: hug.types.text, response):
    """This method deletes a resource"""
    if resources == 'v1':  # This is necessary when resource_id is empty
        return False
    try:
        resp = db.get_res_by_id(resources, resource_id)
        if resp:
            all_res = db.rm_res(resources, resource_id)
            results = {'results': [all_res]}
            if results['results'][0] or results['results'][0] == {}:
                return json.dumps(results)
        log.error('Results: ' + str(results))
        raise
    except Exception as e:
        log.error('Could not delete Resource: ' + resources + ' with uuid ' + resource_id)
        raise falcon.HTTPBadRequest('Delete Resource Error', 'Failed to delete Resource')

@hug.post('/sync/db/all', version=1,requires=token_key_authentication)
def sync_db_all_states(response):
    try:
        if not db.__sync_state_action__() or db.__update_uniqueness_index__():
```

```
            raise
    except Exception as e:
        log.error('Failed Synching Database')
        raise falcon.HTTPBadRequest('Sync DB error', 'Failed to sync db')
@hug.get('/my/first/end/point', version=1)
def energy_alert():
        """Alerts about energy consumption"""
        wrapper = InfluxDBWrapper()
        wrapper.create_db('testing')
        wrapper.insert_timepoint('testing', 'test', 'hello', str(1))
        smsclient.send_sms('To have more un-interrupted TV time, consider cleaning your solar panels','+491635985474')

        return "alert"
```

A4: Power Forecast and Production

Main Function

The calculation of the actual Sun irradiance dependent on the Module orientation and angle, after "Quaschning - Regenerative Energiesysteme"

Constraints:

- Total Sun irradiance is supposed to be direct irradiance E_dir. There is no split in

  diffuse irradiance, because there is no weather information about the cloudiness of the region.

- Reflection is neglected

Input:

- E_hor = Measured local irradiance

- irradiation_angle = in func Irradiation_Angle.py calculated angle sun to normal vector PV-Module

- elevation_angle = in func Irradiation_Angle.py calculated angle sun to horizontal earth

Output:

- E_sun = Actual Irradiance on the PV-Panel [W]

```
'''
import math
from logger import log


def irradiance_dhi(E_dir_h, E_dif_h, irradiation_angle, altitude_angle, panel_grade):
if altitude_angle > 0 and E_dir_h > 0:  # devision by very small sin(gamma_s) lead to high E_dir_gen


    theta_gen = math.radians(irradiation_angle)
    gamma_s = math.radians(altitude_angle)
    gamma_e = panel_grade   #already in degree, since defined in Excel


    # Radiance direct \Quaschning p.68
    E_dir = float(E_dir_h) * math.cos(theta_gen) / math.sin(gamma_s)


    # Radiance diffuse \Quaschning p.68
    F = 1 - (E_dif_h/(E_dir_h + E_dif_h))**2
```

```
        E_dif = E_dif_h * 0.5*(1+math.cos(gamma_e)) * (1+F*math.sin(gamma_e/2)**3) *
(1+F*math.cos(theta_gen)**2 * math.cos(gamma_s)**3

        # Radiance reflection (not considered so far!!!)

        E_refl = 0


        E = E_dir + E_dif + E_refl


    else:

        E = 0



    return E



def irradiance_ghi(E_g_h, irradiation_angle, altitude_angle, panel_grade):
    if altitude_angle > 0 and E_g_h > 0:  # devision by very small sin(gamma_s) lead to high E_dir_gen


        theta_gen = math.radians(irradiation_angle)

        gamma_s = math.radians(altitude_angle)

        gamma_e = panel_grade  # already in degree, since defined in Excel

        k_t = E_g_h / (1360.8 * math.sin(gamma_s))

        if k_t <= 0.3:

            E_dif_h = E_g_h * (1.02 - 0.254 * k_t + 0.0123 * math.sin(gamma_s))

        elif 0.3 < k_t < 0.78:

            E_dif_h = E_g_h * (1.4 - 1.749 * k_t + 0.177 * math.sin(gamma_s))

        else:

            E_dif_h = E_g_h * (0.486 * k_t - 0.182 * math.sin(gamma_s))


        # Radiance direct \Quaschning p.68

        E_dir_h = E_g_h - E_dif_h

        E_dir = float(E_dir_h) * math.cos(theta_gen) / math.sin(gamma_s)


        # Radiance diffuse \Quaschning p.68

        F = 1 - (E_dif_h / E_g_h) ** 2
```

```
        E_dif = E_dif_h * 0.5 * (1 + math.cos(gamma_e)) * (1 + F * math.sin(gamma_e / 2) ** 3) * (
        1 + F * math.cos(theta_gen) ** 2 * math.cos(gamma_s) ** 3)

        # Radiance reflection (not considered so far!!!)
        E_refl = E_g_h * 0.2 * 0.5 * (1 - math.cos(gamma_e))

        E = E_dir + E_dif + E_refl

    else:
        E = 0

    return E

Main Functions
--------------
Calculates the angle between sun irradiation and the normal vector of the PV-Module surface

Input:
- current_day = current day in range 0 -> 365
- number_days = numer of days in current year
- local_time = current time at the PV-Module position 0 - 24 [h]
- time_zone = time zone at PV-Module position (e.g. GMT -> time_zone = 0) [h]
- longitude/latitude = coordinates of PV-Module position in degree (e.g. 10[degree] 30[min] -> longitude = 10.5)

- module angle = angle Module to horizontal surface
- module orientation = deviation angle of south orientation of PV Module (>0 -> West, <0 -> East)

Output:
- alpha_s = Azimuth angle of sun
- gamma_s = elevation angle of sun

- theta_s = absolute angle sun to PV-Module
'''
```

```
import math
import numpy as np
from logger import log


def sun_angle(current_day, number_days, local_time, time_zone, longitude, latitude):
    lam = longitude
    phi = math.radians(latitude)
    J = 360 * current_day / 365  # TODO check this

    sun_decl = 0.3948 - 23.2559 * math.cos(math.radians(J + 9.1)) - 0.3915 * math.cos(
        math.radians(2 * J + 5.4)) - 0.1764 * math.cos(math.radians(3 * J + 26))  # Sun Declination [degree]
    time_func = 0.0066 + 7.3525 * math.cos(math.radians(J + 85.9)) + 9.9359 * math.cos(
        math.radians(2 * J + 108.9)) + 0.3387 * math.cos(math.radians(3 * J + 105.2))  # [min]
    time_func = time_func / 60  # convert to hours

    LMT = local_time - time_zone + 4 * lam / 60  # Local Mean Time

    TST = LMT + time_func  # True Solar Time

    omega = (12 - TST) * 15  # hour angle
    # print 'hour angle:', omega
    omega = math.radians(omega)  # conversion to radian coordinates for math.cos function
    sun_decl = math.radians(sun_decl)  # conversion to radian coordinates for math.cos function

    gamma_s = math.degrees(
        math.asin(math.cos(omega) * math.cos(phi) * math.cos(sun_decl) + math.sin(phi) * math.sin(sun_decl)))

    gamma_s = math.radians(gamma_s)
    alpha_s = 0
    if TST <= 12:
        alpha_s = 180 - math.degrees(
            math.acos((math.sin(gamma_s) * math.sin(phi) - math.sin(sun_decl)) / (math.cos(gamma_s) *
math.cos(phi))))
    elif TST > 12:
```

```
        alpha_s = 180 + math.degrees(
            math.acos((math.sin(gamma_s) * math.sin(phi) - math.sin(sun_decl)) / (math.cos(gamma_s) * math.cos(phi))))
    else:
        log.error('error alpha_s')

    #log.info('Time Step: ' + )
    gamma_s = math.degrees(gamma_s) if gamma_s > 0.035 else 0

    return alpha_s, gamma_s



def incidence_angle(module_angle, module_orientation, sun_azimuth, sun_elevation):
    if sun_elevation >= 0:  # check if it is past sunrise
        # conversion for math.cos function
        alpha_e = math.radians(
            module_orientation)  # deviation angle of south orientation of PV Module (>0 -> West, <0 -> East)
        gamma_e = math.radians(module_angle)  # angle PV-Module to horizontal surface
        alpha_s = math.radians(sun_azimuth)  # azimuth angle
        gamma_s = math.radians(sun_elevation)  # angle sun altitude

        vec_sun = (np.cos(alpha_s) * np.cos(gamma_s), -np.sin(alpha_s) * np.cos(gamma_s), np.sin(gamma_s))
        vec_normal = (-np.cos(alpha_e) * np.sin(gamma_e), np.sin(alpha_e) * np.sin(gamma_e), np.cos(gamma_e))

        theta_gen = np.degrees(np.arccos(np.dot(vec_sun, vec_normal)))  # absolute irradiation angle sun to PV-Module

    else:
        theta_gen = 0

    return theta_gen

Output:
- Solar_Energy = Production of Energy [Wh]
'''
```

```
from classes.production.Production import production
import math
from functions import Irradiance
from logger import log


class solar(production):
    def __init__(self, tech_data, radiation_glo_hor, radiation_angle, sun_elevation, temperature_ambient, watt_peak):


        self.E_g_h = radiation_glo_hor    #[kWh/m^2]
        self.rad_angle = radiation_angle    #[Degree]
        self.sun_elevation = sun_elevation  #[Degree]
        self.panel_grade = tech_data[8]     #[Degree]


        self.temp_amb = temperature_ambient #[DegreeC]


        self.U_oc_0  = tech_data[0]   #[V]
        self.U_n_0 = tech_data[1]     #[V]
        self.I_sc_0 = tech_data[2]    #[A]
        self.I_n_0 = tech_data[3]     #[A]
        self.E_0 = tech_data[4]       #[W/m^2]
        self.alpha_U = tech_data[5]   #[1/K]
        self.alpha_I = tech_data[6]   #[1/K]
        self.eff = watt_peak
    def getpower(self, timestep)
        E_dir = Irradiance.irradiance_ghi(self.E_g_h[timestep], self.rad_angle[timestep], self.sun_elevation[timestep], self.panel_grade)
        #ambient data
        T_a = self.temp_amb[timestep]
        c = 32  #[DegreeC], Constant for Module Temperature Calculation for a single Panel on the roof
        T_m = T_a + c * E_dir/self.E_0   #Approximation of Module Temperature \Quaschning, p.193
        T_25 = 25


        if E_dir > 0:   #\Quaschning, p.196
```

```
            a_U = math.log(E_dir)/math.log(self.E_0)*(1+self.alpha_U*(T_m-T_25))
            a_I = E_dir/self.E_0*(1+self.alpha_I*(T_m-T_25))
            #calculation parameters according to Temperature and radiation
            U_oc = self.U_oc_0 * a_U
            U_n = self.U_n_0 * a_U
            I_sc = self.I_sc_0 * a_I
            I_n = self.I_n_0 * a_I

            c2 = math.log(1-I_n/I_sc)/(U_n-U_oc)
            c1 = I_sc * math.exp(-c2*U_oc)

            I = I_sc - c1*math.exp(c2*U_n)      #assumed module operates always in MPP

Solar_Energy = I * U_n    #assumption operates in MPP
        else:
            Solar_Energy = 0
        return self.eff * Solar_Energy
Output:
- Solar_Energy = Production of Energy [Wh]
'''
from classes.production.Production import production
import math
from functions import Irradiance
from logger import log


class solar(production):
    def __init__(self, tech_data, radiation_dir_hor, radiation_diff_hor, radiation_angle, sun_elevation,
temperature_ambient, watt_peak):


        self.E_dir_h = radiation_dir_hor    #[kWh/m^2]
        self.E_dif_h = radiation_diff_hor   #[kWh/m^2]
        self.rad_angle = radiation_angle    #[Degree]
        self.sun_elevation = sun_elevation  #[Degree]
        self.panel_grade = tech_data[8]     #[Degree]
```

```
        self.temp_amb = temperature_ambient #[DegreeC]
        self.U_oc_0  = tech_data[0]   #[V]
        self.U_n_0 = tech_data[1]     #[V]
        self.I_sc_0 = tech_data[2]    #[A]
        self.I_n_0 = tech_data[3]     #[A]
        self.E_0 = tech_data[4]       #[W/m^2]
        self.alpha_U = tech_data[5]   #[1/K]
        self.alpha_I = tech_data[6]   #[1/K]
        self.eff = watt_peak
    def getpower(self, timestep):
        E_dir = Irradiance.irradiance_dhi(self.E_dir_h[timestep], self.E_dif_h[timestep], self.rad_angle[timestep],
self.sun_elevation[timestep], self.panel_grade)
        #ambient data
        T_a = self.temp_amb[timestep]
        c = 32  #[DegreeC], Constant for Module Temperature Calculation for a single Panel on the roof
        T_m = T_a + c * E_dir/self.E_0   #Approximation of Module Temperature \Quaschning, p.193
        T_25 = 25
        if E_dir > 0:   #\Quaschning, p.196
          a_U = math.log(E_dir)/math.log(self.E_0)*(1+self.alpha_U*(T_m-T_25))
          a_I = E_dir/self.E_0*(1+self.alpha_I*(T_m-T_25))
          #calculation parameters according to Temperature and radiation
          U_oc = self.U_oc_0 * a_U
          U_n = self.U_n_0 * a_U
          I_sc = self.I_sc_0 * a_I
          I_n = self.I_n_0 * a_I
          c2 = math.log(1-I_n/I_sc)/(U_n-U_oc)
          c1 = I_sc * math.exp(-c2*U_oc)
          I = I_sc - c1*math.exp(c2*U_n)      #assumed module operates always in MPP
          #print 'Time step: ',timestep,'U_n: ',U_n, 'I_n: ', I,'I_mpp: ',I_n
          Solar_Energy = I * U_n    #assumption operates in MPP
        else:
          Solar_Energy = 0
        return self.eff * Solar_Energy
```

A5: Battery storage

```
Main Functions
--------------
- Calculate the Battery Capacity, according to Kinetic Battery Model by Manwell & McGowan


Input:
I = Current to charge/discharge battery [A]
c, k = Battery parameters calculated in functions.ck_claculation.py
delta_t = duration of time step [h]
q_0_0 = total charge before current time step [Ah]
q_1_0 = available charge before current time step [Ah]
q_2_0 = bound charge before current time step [Ah]


Output:
q_0 = total charge after current time step [Ah]
q_1 = available charge after current time step [Ah]
q_2 = bound charge after current time step [Ah]
'''
import numpy as np
def get_available_charge(c, k, I, q_0_0, q_1_0, delta_t):
    q_1 = q_1_0 * np.exp(-k * delta_t) + ((q_0_0 * k * c - I) * (1 - np.exp(-k * delta_t))) / k - (I * c * (
        k * delta_t - 1 + np.exp(-k * delta_t))) / k
    return q_1
def get_bound_charge(c, k, I, q_0_0, q_2_0, delta_t):
    q_2 = q_2_0 * np.exp(-k * delta_t) + q_0_0 * (1 - c) * (1 - np.exp(-k * delta_t)) - I * (
        (1 - c) * (k * delta_t - 1 + np.exp(-k * delta_t))) / k
    return q_2
def get_total_charge(q_1, q_2):
    q_0 = q_1 + q_2
    return q_0



def get_max_charge(c, k, t, I):
```

```
    q_max = (t * I * ((1 - np.exp(-k * t)) * (1 - c) + k * c * t)) / (k * c * t)
    return q_max
```

Main Functions

- Calculate the Battery Charge Current, according to Kinetic Battery Model by Manwell & McGowan

To Function get_max_I_charge:

Before calculating I_max it is necessary to get the maximum available load q_max. Therefore t_slow and charge_slow are factors from the

battery specifications, but it also depends on current I. Hence, q_max has to be calculated separate from q_0 (the state of charge).

Input:

c, k = Battery parameters calculated in functions.ck_calculation.py

delta_t = duration of time step [h]

q_0_0 = total charge before current time step [Ah]

q_1_0 = available charge before current time step [Ah]

q_max = maximum capacity battery can provide in current time step [Ah]

t_slow = time to charge battery slow

charge_slow = battery capacity when charging in time t_slow

Output:

I = Current to charge/discharge battery [A]

'''

```
import numpy as np
from functions.battery_cap_calculation import get_max_charge


def get_max_I_discharge(c, k, q_1_0, q_0_0, delta_t):
    I_max = (k * q_1_0 * np.exp(-k * delta_t) + q_0_0 * k * c * (1 - np.exp(-k * delta_t))) / (
        1 - np.exp(-k * delta_t) + c * (k * delta_t - 1 + np.exp(-k * delta_t)))
    return I_max
def get_max_I_charge(c, k, q_1_0, q_0_0, delta_t, q_max):
    I_max = (-k * c * q_max + k * q_1_0 * np.exp(-k * delta_t) + q_0_0 * k * c * (1 - np.exp(-k * delta_t))) / \
            (1 - np.exp(-k * delta_t) + c * (k * delta_t - 1 + np.exp(-k * delta_t)))
    return I_max
```

Main Functions

```
--------------
- Calculate the parameters c and k, according to Kinetic Battery Model by Manwell & McGowan

With two input parameters t_1 and t_2, c and k are calculated by using the function fsolve() in Initialization.py
There they become individual parameters for the battery of each client

Input:
- z = guess for initial values
- t_slow = time to charge battery slow
- t_medium = time to charge battery normal
- t_fast = time to charge battery fast
- c_slow = battery capacity when charging in time t_0
- c_medium = battery capacity when charging in time t_1
- c_fast = battery capacity when charging in time t_2
Output:
c, k = Battery parameters
'''
import math

def get_c_k(z, t_slow, t_medium, t_fast, c_slow, c_medium, c_fast):
    c = z[0]
    k = z[1]
    t_1 = [t_fast,t_slow]
    t_2 = [t_medium,t_slow]
    S = [0.0, 0.0]
    F = [round(c_fast/c_slow, 2), round(c_medium/c_slow, 2)]

    S[0] = F[0]*(1-math.exp(-k*t_1[0]))*t_1[1]-(1-math.exp(-k*t_1[1]))*t_1[0] -c*(F[0]*(1-math.exp(-k*t_1[0]))*t_1[1]- (1-math.exp(-k*t_1[1]))*t_1[0]-k*F[0]*t_1[0]*t_1[1] + k*t_1[0]*t_1[1])
    S[1] = F[1]*(1-math.exp(-k*t_2[0]))*t_2[1]-(1-math.exp(-k*t_2[1]))*t_2[0] -c*(F[1]*(1-math.exp(-k*t_2[0]))*t_2[1]- (1-math.exp(-k*t_2[1]))*t_2[0]-k*F[1]*t_2[0]*t_2[1] + k*t_2[0]*t_2[1])
    c = S[0]
    k = S[1]
    return c, k
```

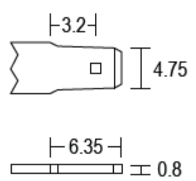
A6: Battery Sample Data Set

Features

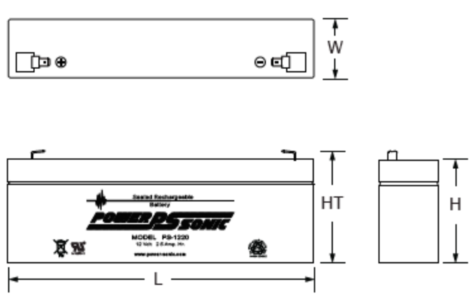
- Absorbent Glass Mat (AGM) technology for superior performance
- Valve regulated, spill proof construction allows safe operation in any position
- Power/volume ratio yielding unrivaled energy density
- Rugged impact resistant ABS case and cover (UL94-HB)
- Approved for transport by air. D.O.T., I.A.T.A., F.A.A. and C.A.B. certified
- U.L. recognized under file number MH 20845

Terminals (mm)

- F1 - Quick disconnect tabs, 0.187" x 0.032"- Mate with AMP. INC. FASTON "187" series



Physical Dimensions: in (mm)



L: 7.00 (178) W: 1.38 (35) H: 2.36 (60) HT: 2.56 (65)

Tolerances are +/- 0.04 in. (+/- 1mm) and +/- 0.08 in. (+/- 2mm) for height dimensions. All data subject to change without notice.

Performance Specifications

Nominal Voltage .... 12 volts (6 cells)

Nominal Capacity

20-hr. (125mA to 10.50 volts) .... 2.50 AH

10-hr. (220mA to 10.50 volts) .... 2.20 AH

5-hr. (400mA to 10.20 volts) .... 2.00 AH

1-hr. (1.5A to 9.00 volts) .... 1.50 AH

15-min. (4.5A to 9.00 volts) .... 1.13 AH

Approximate Weight .... 2.10 lbs. (0.95 kg)

Energy Density (20-hr. rate) .... 1.32 W-h/in3 (80.30 W-h/l)

Specific Energy (20-hr. rate) .... 14.29 W-h/lb (31.49 W-h/kg)

Internal Resistance (approx.) .... 60 milliohms

Max Discharge Current (7 Min.) .... 7.5 amperes

Max Short-Duration Discharge Current (10 Sec.) .... 25.0 amperes

Shelf Life (% of nominal capacity at 68°F (20°C))

1 Month 97%

3 Months 91%

6 Months 83%

Operating Temperature Range

Charge .... -4°F (-20°C) to 122°F (50°C)

Discharge .... -40°F (-40°C) to 140°F (60°C)

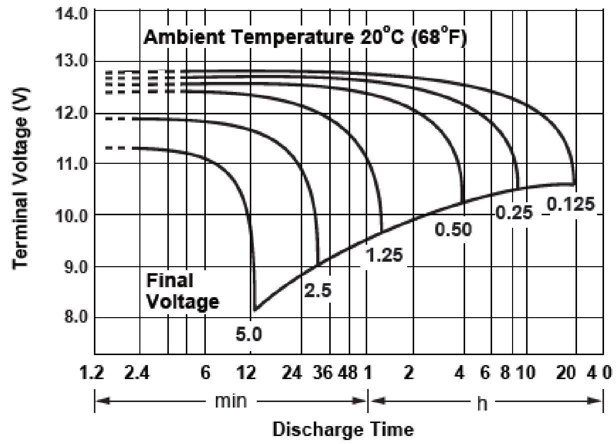
Case .... ABS Plastic

Power-Sonic Chargers PSC-12500A

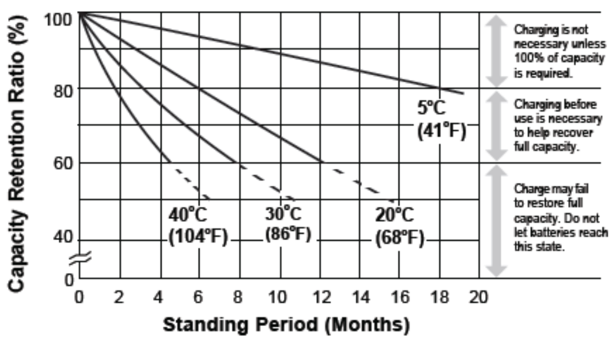
To ensure safe and efficient operation always refer to the latest edition of our Technical Manual, as published on our website.
All data subject to change without notice.

www.power-sonic.com

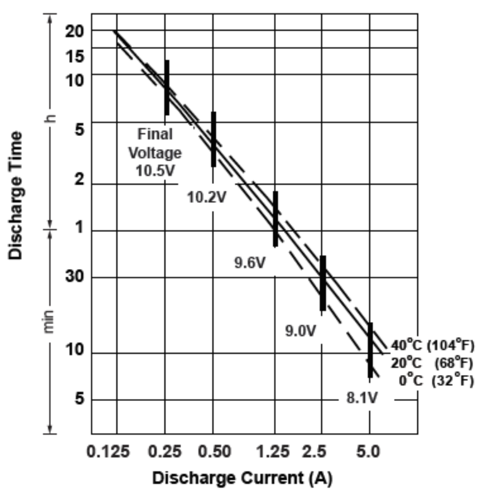
Discharge Characteristics



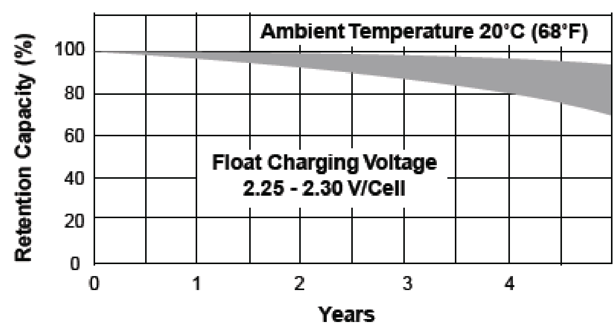
Shelf Life & Storage



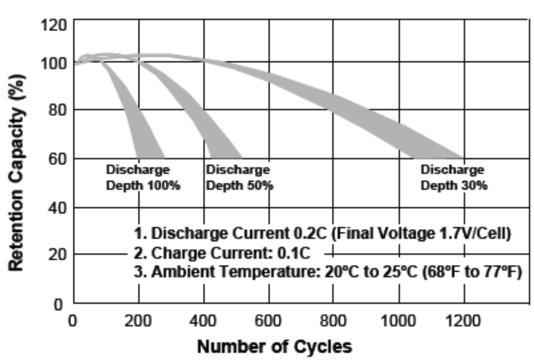
Discharge Time vs. Discharge Current



Life Characteristics in Stand-By Use



Life Characteristics in Cyclic Use



Charging

Cycle Applications: Limit initial current to 750mA. Charge until battery voltage (under charge) reaches 14.4 to 14.7 volts at 68°F (20°C). Hold at 14.4 to 14.7 volts until current drops to under 25mA. Battery is fully charged under these conditions, and charger should be disconnected or switched to "float" voltage.

"Float" or "Stand-By" Service: Hold battery across constant voltage source of 13.5 to 13.8 volts continuously. When held at this voltage, the battery will seek its own current level and maintain itself in a fully charged condition.

Note: Due to the self-discharge characteristics of this type of battery, it is imperative that they be charged within 6 months of storage, otherwise permanent loss of capacity might occur as a result of sulfation.

Chargers

Power-Sonic offers a wide range of chargers suitable for batteries up to 100AH. Please refer to the Charger Selection Guide in our specification sheets for "C-Series Switch Mode Chargers" and "Transformer Type A and F Series". Please contact our Technical department for advice if you have difficulty in locating suitable models.

A7: Sample from the Influx database

timeseries

time	ASU	ID	current_load	current_pv	current_usb	geohash	voltage
2017-05-10T16:01:10.283702658Z	27	"0000"	-231	-140	17	"u33d8h8zd2ms "	13274
2017-05-10T16:02:08.881896226Z	28	"0000"	-231	-156	14	"u33d8h8zd2ms "	13275
2017-05-10T16:02:28.202080198Z	29	"0000"	-233	9	16	"u33d8h8zd2ms "	13254
2017-05-10T16:02:43.021987892Z	29	"0000"	-232	-113	14	"u33d8h8zd2ms "	13270
2017-05-10T16:02:56.482441743Z	29	"0000"	-232	-125	12	"u33d8h8zd2ms "	13270
2017-05-10T16:04:58.243443586Z	18	"0000"	-229	-171	15	"u33d8h8zd2ms "	13275
2017-05-10T16:05:11.661535694Z	18	"0000"	-231	-174	13	"u33d8h8zd2ms "	13275
2017-05-10T16:05:24.982259507Z	19	"0000"	-229	-173	15	"u33d8h8zd2ms "	13275
2017-05-10T16:05:40.041543643Z	19	"0000"	-230	-174	14	"u33d8h8zd2ms "	13273
2017-05-10T16:05:53.402454976Z	17	"0000"	-229	-160	12	"u33d8h8zd2ms "	13276
2017-05-10T16:06:15.52187382Z	19	"0000"	-230	-146	12	"u33d8h8zd2ms "	13273
2017-05-10T16:06:30.082320494Z	20	"0000"	-232	-144	15	"u33d8h8zd2ms "	13273
2017-05-10T16:06:49.642608324Z	18	"0000"	-231	-144	17	"u33d8h8zd2ms "	13273