Smart Grid Solutions Enable the Accommodation of Wide-Scale Electric Cooking by Rural Electricity Infrastructure

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Dedication goes

To My Parents, Noureddine Keddar and Karen Therese Kehoe

For their endless love, support and encouragement

They were a source of motivation and strength, they always encouraged me to strive for excellence.

Even though my father was not with me throughout this journey, he has always been in my heart and mind. My love for him and his words that are engraved in my mind guided me to the end of the tunnel.

My mother is the fountain of tenderness, love and strength who did more than her best to support me in every moment. She said that I can do it, and ***YES****, here I am “****I DID IT****”*

“I love you both for eternity”

“If someone says that you can do it, just believe them as they see in you something that you cannot see. So, if you can dream, you can do it, do not leave any stone unturned to make it a reality”

DECLARATION

This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other awards.

Signed…………Shafiqa Keddar………………………. Date……18/12/2022…....

STATEMENT 1

This thesis is being submitted in partial fulfilment of the requirements for the degree of PhD

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STATEMENT 2

This thesis is the result of my own independent work/investigation, except where otherwise stated. Other sources are acknowledged by explicit references.

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ABSTRACT

Access to modern energy and clean cooking is being addressed widely in developing countries. By continuing to use traditional cooking methods such as three-stone stove, high level of household (HH) air pollution is created. Which has severe health implications, particularly on women and children. Cooking with electrical devices known as ‘eCook’ are becoming an attractive solution as it offers low carbon and is less harmful to health alternative to biomass. However, energy poverty remains a huge challenge in developing countries, electricity is unreliable in grid-connected areas leading to rolling blackouts and the infrastructure is weak and damaged. Therefore, the main research contributions of this thesis include the development of a novel impact assessment methodology to aid understanding of the technical and techno-economic implications of additional electric cooking demand (eCook) in rural mini-grids in developing countries. where the eCooks are directly connected to the power supply (direct eCook). To assess the design readiness, future design requirements and the potential solutions to increase their adoption without the need for a significant upgrade and reinforcement of the mini-grid network. The other main contribution centres on the modelling and simulation of an innovative control strategy through the introduction of battery-operated cooking devices. The smart eCook battery management system (‘smart’ EBMS) seeks to minimise installed generation capacity required to accommodate ‘new’ mini-grid eCook demand by maximising the utilisation of electricity from the daily PV generation and offsetting peak demand compared to direct eCook.

The analyses are carried out on a conventional ‘hub and spoke’ hybrid photovoltaic (PV)/diesel mini-grid topology model to quantify the main network problems. Two network studies are considered where the eCook appliances are directly connected to the power supply. The first investigates the limitations of the mini-grid in terms of the *generation capacity* available to supply the demand for different levels of eCook penetrations. While the second focuses on the *network constraints* for different eCook penetrations. The overall results of the second network study show that voltage drop and voltage imbalance issues can be reasonably and affordably addressed by using cables of a larger cross-sectional area. The main issue prohibiting higher penetrations of direct eCook is the limited generation capacity requirements to supply the additional demand. This entailed modelling an innovative ‘smart’ EBMS that maximises the utilisation of electricity from the daily PV generation and offsets peak demand by using a battery-

operated eCook. In addition, it actively monitors the state of the grid and decides on battery-operated eCook C-rate set-point required to address the network constraints. The results demonstrate that the 'smart' EBMS can alleviate the impact of conventional battery-operated eCook charging on the mini-grid network. It constantly monitors the state of the power grid; when the voltage drops below the allowed limit, the 'smart' EBMS detects the problem and adjusts the C-rate of the battery-operated eCooks. This allows the voltage to recover while maintaining the charging regime. Also, it increases the quality of the charging service (QoS), which relates to an increase in the number of battery-operated eCooks recharged daily compared to a network without the 'smart' EBMS.

An economic affordability assessment methodology is also developed to understand the upcoming cost trend of eCook adoption and to identify the key factors to bridge the affordability gap between the cooking energy cost of conventional fuel and battery-operated eCook. Three main factors need to be considered when estimating the cooking cost: the non-market cost of firewood; ensuring a low mini-grid tariff that is within a range of the national grid tariff and using an optimal battery-operated eCook size with the capability to meet the required demand. When taking these factors into account; for the 2022 analysis, cooking 100% using a battery-operated eCook is in a range of $29–30/month implying that there could be an opportunity for parity when the firewood cost reaches $29/month. The same applies to the cooking prediction costs for 2030, reducing further to $20–21/month. However, if the firewood is harvested sustainably, ensuring it is high quality and dry, it would be difficult for battery eCook to compete. It should be emphasised that this research has relevance to governments, practitioners, and researchers as it gives insights into the current issues and offers possible solutions to achieve clean and affordable energy for all.

The main conclusion drawn from this research study is that there is a need for a Head-Heart-and-Hands approach to move towards clean cooking for all from both the household (HH) level and mainly from Governments. However, to implement this strategy and for it to be successful all three parts must be implemented together. Unfortunately, this was not always evident during this research. Governments are mostly reluctant to implement or convey strategies or innovations to the consumer and there were insufficient policies to educate HH's on the short-term and long-term benefits of moving towards clean cooking for all.

ACKNOWLEDGEMENT

“بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ”

“*Yes, there are two paths you can go by, but in the long run there is still time to change the road you are on*”. “Stairway to Heaven, Led Zeppelin”. At the end of the day, this is still called the unknown and the final decisions lay in our hands leading us to the finish line. Our destiny is not written for us but by us; one word, one move or one action could turn the table around and make a big change in our lives.

This journey started with “**بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ**” and ends with “**الحمدلله**”, this part of my thesis joins my last jigsaw puzzle piece with the rest of the pieces to complete the final picture. Each of the invisible words on this piece will be printed on a script and placed in a bottle to be carried out by the wind and the tide to thank the people who directly or indirectly contributed to helping me to finish my PhD thesis. The message will also send a vibe to everyone out there who has dreams, although hesitating to chase them. So many dreams seem impossible at first, then seem improbable, then when we summon the will, they soon become a mosaic that pictures our future. When I look back to my thesis, I would like it to remind me of the ups, downs, hard times and the lessons learnt from this long journey which are engraved like flames of fire in my brain and in my heart that guided me towards what felt impossible, being my first invisible tattoo that led me to the end. Every morning I will listen to my heart with its rhythm controlling me and follow the beat of my drum and violin strings to compose a unique symphony.

First, I would like to thank God for the strength he gave me each day, the guidance, the knowledge, and the ability to undertake and complete my research study. Thanking him for all the blessings and all the people around me who made life meaningful and made it happen. Now, I am looking for more words, however, this will sum it all up “ الحمدلله”.

When we look around us, we mostly hear about successful people, forgetting to ask ourselves an important question “what did their journey look like?”. One quote which stands out is “never judge a book by its cover”, you need to dig deeper to discover the mystery inside the box. From my prospective, I see success as a jigsaw puzzle as each of the small pieces tells a story and the steps taken to reach the end. As we progress the pieces find themselves only when they are right for each other just like “love”. This also happens with the help of the people we meet, however, at the end of the day, we are the only ones who can achieve it, as, with each piece, we have decisions to make to move on to the next. However, seeing the full picture takes time, and experiencing different ups and downs in life. We all need to be patient.

To begin I would like to thank my academic supervisors Dr. Scott Strachan and Prof. Stuart Galloway, the completion of this thesis study could not have been possible without their expertise. The continuous support, motivation, and guidance I received from Dr. Scott Strachan pushed me to my limits. It seems funny to say this now but when I started my PhD I was determined not to publish any journal or conference papers as I believed this was an impossible task. However, his encouragement and his belief in me made the impossible possible. Who would have thought I would be the primary author for three journal papers, a conference paper and a co-author of others. It is a great achievement for a person, who wrote her first piece of work when starting her Master five years ago. It was an assignment for the “Safety and Probability” module, I remember it being one of my nightmares while experiencing a few white nights, nevertheless, I still achieved an “A” for it! (it seems so funny thinking about it now!). Even during my PhD I slept only four hours a day and at some point, I forgot the meaning of sleep, now I call this madness! Although, without doing so I would not have finished my research, which I feel is a great achievement. Never underestimate yourself or another person’s capability, the power and the strength are always present in your hands, just come out from your comfort zone “Just Believe in Yourself”. We maybe on different tracks but the beauty is that we all learn from our own hidden achievements, and from those of others with different life experiences and knowledge, so never look down or judge others.

My thanks also go to the EPSRC Centre of Doctoral Training in Future Power Network and Smart Grids for giving me the opportunity to pursue my PhD which has always been my goal.

The knowledge I gained from Modern Energy Cooking Service (MECS) consortium and from the Energy for Development Group (E4D) at the University of Strathclyde, throughout my PhD research was incredible as there was a lot to learn from their work in clean cooking, power networks and other research areas which helped me build pillars to frame my research study. Also, my thanks go to the research group within the University of Strathclyde as well as to Dr. Madalitso Chikumbanje, his knowledge of power systems in developing countries and his ongoing help are very much appreciated.

Before I move on to thank the people who were part of this journey, I would like to mention an important person that we all forget to acknowledge “Our Inner Selves”. I am taking this opportunity to thank my Inner Self “Shafiqa Keddar”, without her I would never have reached this point and the person I have become. She has kept me going until the final page, her power, her willingness and her confidence she inserted in me are magical and incredible, she gave me the hunger to continue which meant that my inner self kept glowing.

Throughout my life I met wonderful people and friends who have been a ray of sunshine, they filled my life with beauty and joy. Life moves on but they all have a special place in my heart, so thank you for the beautiful moments.

I usually prefer practising individual sports for many reasons, however, the warm welcome I received from the University of Strathclyde Handball team just made me feel part of the team from day one. They were so friendly, kind and humble. I shared wonderful moments with them which I will never forget. They taught me another aspect of what sport looks like. Thank you for everything.

My family! A lot to say although I need to narrow it down. I will commence with my siblings, my sisters Jamila and Farida, and my brother Ahmed. When life’s hills became too steep to climb, they were always there for me in their own ways. They have been my support, my entertainment, my audience and my critics. They were a rainbow that coloured my life. My gratitude goes to my younger sister Farida, I cannot deny that directly or indirectly, she had a great contribution in providing me with moral support. She was my little daisy that shone among all the spring flowers, sunshine that filled my life with happiness and put a big smile on my face. She did a great job! Thanking her will never be enough.

Also, a huge thanks goes to my sister Jamila’s husband Riad. Now I will move on to my little nephew Noureddine Daniel who is the cutest child “Mashallah”, he makes me feel loved and happy when I am around him. His cheekiness just adds a special ingredient to my life.

Words seem too little to express my gratitude to my Nanny Patricia Veronica Mary and my Grandad John Michael for all the things you do for us. Thanking both of you is not enough to express how grateful we are for having you as grandparents. You have always been there for us whenever we needed you. Your generosity, kindness and support always made us speechless. We appreciate everything you do for us! Your names will be embroidered on my heart with gold thread.

My greatest thanks go to my mother who enabled me to get the best education, without her I would have given up on the first day. She was my strength and support in this PhD roller coaster ride, she believed in me until the end and saw something in me that no one else did. She has always been close to me keeping my sense of humour, her care, love and encouragement just made the impossible possible. As my mother always said to me "never say never, everything is possible, you never know what is around the corner". This always lightened the hope inside of me. I still have numerous thoughts coming back and forwards. There will never be enough words to finish sketching the full picture of her and the million stars in the sky.

My father! My deepest wish is if only he could see me now. There are not enough words to express how grateful I am to my dear father for all the years that he was close to me helping me in my studies. He will forever be my example in life. My life is influenced by him, and he made me what I am, always aiming to achieve the best. Without him, I would never have reached this level of education. He was and will always be my inspiration in life. “*A beautiful flower in my heart keeps blooming, which absorbs its nutrition from the unlimited care and love I provide it with, its roots are spreading in my veins whispering to me reminding me of my eternal love towards my father and that he is here with me standing by my side as he is one of the angels in my life*”. I do hope you are up there proud of me saying “that is my girl”.

My father and mother are my life pillars, thanking them will never be enough “Je leur tire mon chapeau”.

Behind the scenes, I experienced difficult moments although you just learn that life continues. I am blessed for always having my family with me, a phone call or a message from them lightens my day, it just reminds me that there is someone out there thinking of me, it really means a lot to me! I am also thankful for meeting all the wonderful people who put a positive impact on my life. This quote will summarise it all, *“Not everything is said or taught by words. Some actions lead us into a realm beyond words”.*

For the first time, I can say that I am so proud of what I have achieved, my mother always says to me, that what makes me special is my determination for no matter, how many times I fall, I get up stronger and wiser, I never never never give up!! Whatever happens, my smile is my strength.

It has been a long road and if I ever write a book about it, I will call it “**My Lonely Journey**”. It is beyond belief that I will be Dr. Shafiqa Keddar, I do have a very high respect for this title due to the hard work behind it, but please I prefer to be called only “Shafiqa” as it was not the title that got me to what I am now, it is my name that will always tell my story. I am a normal person just like you all, I will always be learning as with each day there is a new lesson to learn.

I will sum up now by asking myself a question “what stage am I at now?”. The answer is that I am just starting my journey, facing obstacles and still trying to discover myself, **WHILE AT THE SAME TIME I AM ENJOYING EVERY MOMENT OF MY LIFE AND VERY PROUD OF MYSELF**. What will I achieve? I do not know, life is a learning lesson which we need to go through before reaching our goals and in every shadow no matter how deep it is, sunshine will find a way to pass through. To conclude, life is more about rewriting than writing. If you do not like what is on the page, change it to find a way to join the pieces of the puzzle together. Although, an important thing to remember is that sometimes you can feel so close to reaching your goal as you are so far away. So, be patient, optimistic, strong and never give up whatever happens, because, life is full of challenges and surprises, everything happens for a reason, just to teach us who we are. I know that talking is much easier than applying, but this is what we will conclude after completing the full picture of our life’s jigsaw puzzle.

" .... إِنَّهُ مَن يَتَّقِ وَيَصْبِرْ فَإِنَّ اللَّهَ لَا يُضِيعُ أَجْرَ الْمُحْسِنِينَ (90) "سورة يوسف

I am now going to roll the dice, a lot of feelings in my mind, I could fall, or I could fly. It is time to close this chapter and for a new one to begin, I do not know what is waiting for me, the only thing that I do know is that God will be with me.

الحمد والشكر يا الله على كل شيء

أتوكل عليك

” لَا تَقْنَطُوا مِنْ رَحْمَةِ اللَّهِ“

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating current
AENS	Average Interruption Duration Index Energy Not Served
C_EBMS	Central ECook Battery Management System
CAPEX	Capital Expenditure
CB	Circuit Breaker
CC	Constant Current
COE	Cost of Energy
C-rate	Charging Rate
CSA	Cross-Section-Area
CV	Constant Voltage
D_EBMS	Distributed ECook Management System
DC	Direct current
DoD	Depth of Discharge
DSM	Demand Side Management
EBMS	ECook Battery Management System
eCook	Electrical Cooking Appliance
EPC	Electric Pressure Cooker
ESCOM	Electricity Supply Corporation
ESMAP	Energy Sector Management Assistance Program
EV	Electric Vehicle
GACC	Global Alliance for Clean Cookstove
GHG	Green House Gas
GTA	Global Temperature Adjustment
HH	Household

ICS	Improved Cookstove
LF	Load Following
LPG	Liquid Petroleum Gas
LV	Low Voltage
MECS	Modern Energy Cooking Services
MPPT	Maximum Power Point Tracker
MTF	Multi-Tier Framework
NPC	Net Present Cost
P	Real Power
PAYGO	Pay-As-You-Go
PV	Photovoltaic
QoS	Quality of Charging Service
RER	Renewable Energy Resources
SCL	Short Circuit Current Level
SDG	Sustainable Developing Goal
SHS	Solar Home System
SoC	State of Charge
THD	Total Harmonic Distortion
TV	Television
UN	United Nation
V	Voltage
V2G	Vehicle-to-Grid
VAVS	Variable Air Volume System
VSF	Voltage Sensitivity Factor
VSI	Voltage Stability Index
VUF	Voltage Unbalance Factor
WHO	World Health Organisation

LIST OF APPENDICES

1 INTRODUCTION

Access to modern energy and clean cooking is being addressed widely in developing countries. Globally 40% of the world population does not have access to clean cooking facilities equating to 2.6 billion people[1], [2]. Without accelerated action, an estimated 2.4 billion people will remain without clean cooking services in 2030. The situation is particularly dire in Sub-Saharan Africa and East Asia, where traditional fuels will still be used including wood, coal, straw, dung, and charcoal for cooking. By continuing to use simple/traditional stoves (without a chimney or grate) such as a three-stone stove, high levels of household (HH) air pollution cause severe negative health effects. Those most affected, are those most exposed to these fumes, i.e., women and children. The World Health Organisation (WHO) estimates that four million premature deaths occur annually worldwide [2], as a result of respiratory illnesses, heart disease and cancer which have been attributed to the inhalation of particulates caused by indoor cooking. Greenhouse gas (GHG) emissions from cooking with traditional fuels can reach a gigaton of CO_2 per year equivalent to about 2% of global emissions [3], [4], and as much as 25% of black carbon comes from burning solid fuel for HH energy needs [5]. Up to 34% [6] of wood is collected from unsustainable sources has a profound effect on climate change and local forest degradation by leaving bare areas improperly treated after being cropped, which is increasing at a much faster rate, particularly in the least developed countries.

Several interventions on access to clean cooking have been adopted to address this issue by designing improved cookstoves (ICSs) aiming to reduce GHG emissions [7]. However, their uptake has been limited and health problems often persist as they were not keeping pace with population growth [8]. In 2015, international agencies were openly stating it was a failing policy and there was a need to move the narrative away from 'business as usual' in energy for cooking [6]. Therefore, if the health impact is to be further reduced, an increased effort is required to enhance the efficiency of these ICS appliances, or another solution would be to move towards using other clean fuels such as electrical cooking appliances (or eCook as referenced in this thesis which is also a term used by the wider Modern Energy Cooking Services (MECS) community). The health and environmental benefits of replacing these traditional cooking fuels with eCook are stark, though implementing this transition represents significant technical, social, and economic challenges, these present the context and motivation for this PhD research.

Cooking with electricity is still in an embryonic phase; only a limited amount of studies have been conducted in this area, which were based on examining the cooking time, ease of use, cost of biomass cooking, and the dishes cooked using eCooks [9], without to date analysing the technical impact on the power network. In addition, energy poverty remains a huge challenge facing developing countries. In 2017 there remained around 840 million people without access to electricity due to the limited capacity and reliability of the grid. Although this is anticipated to decrease to 650 million people by 2030 [10]. The international community, at this time, is not on track to achieve the SDG 7 (Sustainable Development Goal) targets, despite the global rise in electricity access from 71% to 87% between 1990 and 2016 [2]. The impact of the coronavirus (COVID-19) on the energy sector and future electricity access rates in developing countries are still unknown. Also, a reprioritisation of international aid and funding could further slow progress towards achieving SDG 7. Another barrier is the affordability constraints of electricity which prevent poor and rural HHs to take measures to enable a switch to the use of eCooks. This derives from the lack of financial resources and appropriate policy, regulatory and institutional frameworks [1].

To accelerate electricity access in conjunction with eCook, off-grid solutions, particularly mini-grids are essential, as they offer advantages over connections to the main grid, such as enhancing the reliability of supply, improving quality of power, better environmental performance and accommodating consumer electricity needs in remote areas. Over the past decade, the number of solar/solar-hybrid mini-grids installed globally has increased from 60 to 2099 [11] and so this is not simply a niche area. Mini-grids can therefore open up the energy sector to independent power providers and expedite electricity access in rural regions with limited prospects of seeing the main grid extend to their location any time before the SDG target date of 2030.

1.1 Research Objectives, Novelty and Contributions

The research work presented in this thesis aims to examine the opportunities, benefits and techno-economic challenges when accommodating electric cooking, deployed at scale, across rural communities in Sub-Saharan Africa. Existing off-grid systems particularly mini-grids using non-dispatchable generation, and with limited generation and storage capacity, may find it difficult to accommodate the wide-scale demand associated with eCook appliances. This may increase their susceptibility to low-voltage events and system instability. Therefore, the key motivation for this work is to support rural energy system planning to aid the transition of rural HH towards eCook. by, supporting the integration of this transition into rural electrification strategies. This requires a framework to assess the readiness in terms of evaluating the main technical network constraints (voltage drop level, phase imbalance and system power losses) and upgrade requirements of existing off-grid systems and the design requirements of future systems. At present, these electrification strategies only focus on basic energy provision for lighting and mobile phone charging, where demand growth is defined as an increase in customer numbers with access to these basic energy provisions or possibly Tier-2 level appliances [12] such as TVs or refrigerators. These strategies do not currently consider electric cooking as a viable option for, or contributor to, rural demand growth. Changing this paradigm would require the development of innovative smart mini-grid control strategies and techniques to minimise the level of additional generation capacity required and ensure energy costs and prices remain affordable to stimulate the widespread adoption of eCook. The main research contributions and novelty of this thesis are outlined below:

1. A review of the state of the art on energy access in Sub-Saharan Africa, cooking practices and off-grid systems to present a holistic understanding of economic, social and technical forces that can both advance and obstruct an eCook transition.
2. Identification of the main technical network constraints currently limiting wide-scale eCook deployment in rural settings, through the design of a representative mini-grid case study and network model. The model allows power flow analysis to be carried out to assess the impact of eCook penetration on the network voltage drop, power losses, and voltage

unbalance factor (VUF). Understanding the features of these grids establishes their compatibility/incompatibility with eCook.

3. Determination of the future mini-grid sizes required to accommodate the new eCook demand and the cost of reinforcement. Finding the optimal sizes for mini-grid components is an important factor in design, to avoid under/oversizing the system, which may lead to undesirable technical or economic impacts, and loss of confidence in eCook and mini-grid technology. Therefore, given the momentum towards eCook use in developing countries, combined with global impetus towards rural electrification via mini-grids, it is necessary to consider how ‘fit for purpose’ existing mini-grids are to effectively smooth the path to accommodate increasing eCook demand.
4. An inclusive literature review on existing research and work on demand-side management (DSM), that is most utilised in both developed and developing countries.
5. Development of a modelling framework for exploration of concept/s for ‘smart’ eCook charging, DSM and network management to accommodate eCook deployment. ‘Smart’ solutions including DSM approaches (active and passive), may be employed to time-shift eCook (or other lower priority) demand, to accommodate it, without the need for any significant network reinforcement.
6. Development of a methodology to assess the economic affordability and to identify the least cost, best-fit, inclusive cooking scenarios for eCook, as well as the role of fuel-stacking in this. In developing countries, wealthy and urban HHs have greater opportunities to adopt eCook, due to their higher HH incomes, relative to rural HHs. In this thesis, fuel stacking is investigated through modelling, as an eCook transitions strategy.
7. Evidence-based recommendations are provided for rural eCook to move towards cooking with electricity which will contribute to improving people’s lifestyles, empowering women and introducing public health and environmental benefits.

1.2 Outline of the Thesis

The thesis is organised into six chapters, the remaining five chapters following this introduction are as follows:

Chapter Two: Outlines the background of energy access and cooking practices in developing countries. An overview is given regarding cookstove types (improved cookstoves and energy-saving stoves), off-the-shelf eCooks, existing research on eCook practices and device trials, and comparing and evaluating eCook to other types of loads. In addition, a literature review is carried out on the main technical challenges that may limit the wide-scale deployment of eCook in rural and urban areas. Then, it moves on to present a thorough literature review of the state of the art of DSM in both developed and developing countries before determining the most appropriate approach and technology for ‘smart’ eCook deployment on rural hybrid PV/diesel mini-grids.

Chapter Three: Presents the development of a methodological and analytical framework that could be used by mini-grid developers to assess the design readiness and future design requirements to accommodate increasing eCook demand. It also lays out the strategy used to model the mini-grid case study, the generic system model is designed using OpenDSS/MATLAB as a simulation platform, while the techno-economic analysis was conducted in HOMER-Pro software. The mini-grid model in OpenDSS is a hybrid system consisting of a PV panel, battery bank and a diesel generator. The model allows initial studies on the impact of eCook penetration on the network voltage profile and thermal constraints, etc. Understanding the features of these grids will establish their compatibility/incompatibility with eCook. The application of the methodology developed in this chapter is applied to Use Cases to investigate the mini-grids limitation analytically.

Chapter Four: The techno-economic analysis conducted in HOMER-Pro assessed future mini-grid sizes required to accommodate eCook demand and meet socio-economic and environmental targets. The main barriers limiting the eCook deployment are discussed followed by suggestions for future work that addresses new design specifications for the next generation of eCook mini-grids.

Chapter Five: With a further continuation of the research work in chapter 4 and the literature review in chapter 2.6 on DSM, this chapter introduces the proposed ‘smart’ eCook battery charge management system approach and the simulation results. Conclusively, the last two sections of this chapter evaluate the quality of charging service provided to HHs with battery-operated eCook to assess the number of battery-operated eCooks recharged daily compared to a network without the ‘smart’ eCook battery charge management system and provide the conclusion of the chapter.

Chapter Six: Chapter 5 focused on the technical viability of the eCook-operated battery while this chapter moves on to assess its economic affordability, in which a methodology is proposed to analyse the cooking energy cost of contextualised cooking scenarios with either conventional fuels (e.g. charcoal, firewood) or with eCook appliances (e.g. electric pressure cookers (EPC) or hotplates), connected to and supplied from an integrated or portable battery. The cooking costs for the scenarios are assessed with and without fuel stacking using a degree of eCook with conventional fuels. Realistic concepts of the best-fit scenarios are presented together with factors to close the affordability gap between the energy cost of conventional fuel and eCooking (with batteries).

Chapter Seven: Outlines the conclusion of the thesis; summarising the main findings of the research work, the limitations and several suggestions for future works that can follow the work presented in this thesis.

1.3 List of Publications

1.3.1 Journal papers

First Author

- S. Keddar, S. Strachan, B. Soltowski, and S. Galloway, “An overview of the technical challenges facing the deployment of electric cooking on hybrid pv/diesel mini-grid in rural Tanzania—a case study simulation,” *Energies*, vol. 14, no. 13, p. 3761, 2021.
- S. Keddar, S. Strachan, and S. Galloway, “A Smart eCook Battery-Charging System to Maximize Electric Cooking Capacity on a Hybrid PV / Diesel Mini-Grid,” *Sustainability*, vol. 14, no. 13, p. 1454, 2022.
- S. Keddar, S. Strachan, and S. Galloway, “Bridging the Affordability between Battery-Supported Electric Cooking and Conventional Cooking Fuel,” *Energies*, vol. 15, no. 24, p. 9549, Dec. 2022.

Co-Author (Contribution: Software)

- M. Leach *et al.*, “Modelling the Costs and Benefits of Modern Energy Cooking Services-Methods and Case Studies,” *Energies,* vol. 14, no. 12, p. 3371, 2021.

1.3.2 Conference papers

First Author

- S. Keddar, S. Strachan, A. Eales, and S. Galloway, “Assessing the Techno-economic Feasibility of eCook Deployment on a Hybrid Solar-Diesel Mini-grid in Rural Malawi,” 2020 IEEE PES/IAS PowerAfrica, PowerAfrica 2020, 2020.

Co-Author (Contribution: Technical power network study and Editor)

- C. Dorward, S. Strachan, S. Keddar and S. Galloway, “Design of a Low Cost Smart Meter for Capturing Usage Data for Battery-Operated Cooking Devices, ” In 2022 IEEE PES/IAS PowerAfrica, PowerAfrica 2022, 2022.
- A. Eales, D. Frame, S. Keddar, A. Richer, D. Kloser and S. Galloway, “Opportunities and Challenges for ECooking on Mini-grids in Malawi: Case Study Insight, ” In 2022 IEEE PES/IAS PowerAfrica, PowerAfrica 2022, 2022.

1.3.3 Working papers

Co-Author (Contribution: Software)

- M. Leach *et al.*, “Modelling the costs and benefits of moving to Modern Energy Cooking Services – methods & application to three case studies,” MECS: Hong Kong, China, 2021.

2 LITERATURE REVIEW

To address the research problem, a comprehensive literature review was undertaken in this chapter, by investigating energy access and cooking practice in developing countries that act as drivers for moving towards clean cooking, particularly electric cooking. The primary focus considers off-the-shelf electric cooking devices, highlighting their benefits as well as previous publications on cooking practices, energy consumption patterns and prototype testing, as well as clarifying how eCook deployment challenges differ from other types of network electric loads and the main technical network constraints limiting eCook transition in rural and urban settings. It should be noted that this research has synergies with, and learn lessons from, similar challenges in developed countries arising from electric vehicle (EV) charging. This chapter also outlines a literature review that was conducted to investigate the state of the art on DSM in both developed and developing countries, which paved the way to determine the most appropriate approach and technology for the “smart” eCook concept which was developed in chapter 5.

International efforts in clean cooking have been championed by the WHO, United Nations (UN) and the World Bank (WB) and directed by multinational partnerships such as The Global Alliance for Clean Cookstoves (GACC) to support and enable access to affordable, reliable, and modern energy. A significant amount of work has been deployed to improve traditional cookstoves characterised as ICS based-biomass [7], [13]. New designs were manufactured, using a range of materials and techniques, improving performance and thermal efficiency, as well as providing the consumer with a choice of style and size. Except, these efforts failed to demonstrate a reduction in air pollution or health effects sufficiently as they are designed with standards of low-quality performance and due to ongoing demand growth that outpaces improvement efforts[8]. As mentioned before, in 2015, international agencies were openly stating it was a failing policy and there is a need to move the narrative away from ‘business as usual’ in energy for cooking [6]. This explains one of the reasons for the slow adoption rate of clean cooking between 2010 and 2017 [7]. As a result, more work has shifted towards the use of renewable and low-carbon fuels such as liquid petroleum gas (LPG), liquid fuel, biogas fuel and electricity [14], [15]. Although clean cooking presents numerous advantages in increasing stove efficiency and reducing air pollution, it still holds challenges including affordability, together with low community awareness and willingness to switch to clean cooking alternatives [7].

2.1 Cookstove Types

The traditional three-stone stove is the primary cooking method used among HHs in Sub-Saharan countries. It is an open fire constructed from three stones arranged on the ground in the form of a triangle, allowing a pot to be placed upon it [16], [17]. This results in high firewood consumption where most of the heat produced from burning does not reach full combustion, causing high energy losses in the conversion process, with an efficiency accounting for 2-10%. As mentioned previously, to reduce the usage of traditional stoves, it is necessary to move towards clean cooking with the adoption of energy-efficient stoves. These can be classified into two major types: ICSs and energy-saving devices.

2.1.1 Improved Cookstoves

ICSs are commonly used around the world as they continue to use solid fuel, yet, in lesser amounts. They are more efficient, safer than traditional cook stoves, minimises loss of heat and emits less emissions as it insures better combustion of the fuel. As an example, this can be achieved by providing an insulated combustion chamber which enhances the temperature of the fire and maximises the transfer of heat of combustion from the flame and the hot gases to the cooking pot [13], [16]. ICSs can take many shapes and can include the following features [18]:

- A chimney to remove smoke from the kitchen
- An enclosed fire to retain the heat
- Dampers to control and optimise the airflow
- A ceramic insert to minimise the rate of heat loss
- A grate to allow a variety of fuel to be used and ash to be removed
- A metal casing gives strength and durability
- Multi-pot systems maximise heat use and allow several pots to be heated simultaneously

2.1.2 Energy Saving Stoves

Sophisticated energy-saving equipment [16] helps to further reduce solid fuel consumption; however, local cooking habits and social conditions must be considered. These include eCook appliances, thermo-flask and other cooking appliances which rely on clean fuel and also hot bags, which will permit the cooking process to continue for a limited time and allow the food to be kept warm.

This research intends to fully capture the opportunities of adopting eCooks, which are becoming an attractive solution to address the challenges of conventional cooking in developing countries providing health and environmental benefits. The UK Aid program MECS [6], with which this research project engaged closely, explores this solution as one of the alternatives to meet SDG 7 ensuring access to affordable, reliable and modern energy for all [7].

The SDG are 17 global goals with 169 targets that were adopted by the 193 UN Member States in 2015 with a vision to reach zero poverty, protect the planet and ensure people’s well-being around the world by 2030. The 17 goals are all interconnected, and each action will indirectly affect the other [19]. Consequently, cooking with electricity will not only contribute to SDG 7, but it will also deliver gains across 9 other SDGs targets: SDG-1 “No Poverty”, SDG-2 “Zero Hunger”, SDG-3 “Good Health and Well-Being”, SDG-4 “Quality Education”, SDG-5 “Gender Equality”, SDG-8 “Decent Work and Economic Growth”, SDG-11 “Sustainable Cities and Communities”, SDG-13 “Climate Action” and SDG-15 “Life on Land” [19].

Developing a world market for eCook as a form of clean cooking will ensure an improvement in people’s lifestyles as it will help reduce the spread of disease and illnesses by limiting GHGs released mainly from charcoal and biomass stoves. Hours can be spent collecting and transporting the cooking fuel (1.5-5 hours per day), as well as preparing food (2-4 hours per day) [20]. Hence, there is a lack of opportunity for women to become involved in economic participation, decision-making, and productive activities, most importantly there is little prospect for children to receive an education. ECooks will create a general movement towards the opening of many opportunities by saving time, drudgery reduction and opening doors for gender equality as it will provide opportunities for women to become involved in economic practices. In addition to this, these devices are characterised by their simplicity to use and possibly encourage men to participate in cooking. The excess battery energy in the case of battery-supported eCooks can be used to power existing electrical HH devices such as TV (television), lighting, radio and mobile telephone charging encouraging HHs to switch to using eCooks. Cooking with electricity also aims to strengthen global trends in protecting ecosystems and biodiversity by addressing forest degradation, deforestation, and climate change [21].

2.2 Introducing eCook Devices

ECook appliances are electrically powered to cook and reheat food such as induction hobs, hotplates, and multicookers (rice cookers and EPCs) that feature electric timers and temperature controllers. They are more efficient, user-friendly, and more durable and environmentally sustainable than traditional facilities. The cooking time is reduced, as the heat tends to spread evenly across the base of the pan or the pot. The devices are also easier to clean and reduce indoor emissions [6], [22]. They can be classified into two categories, AC or DC devices either battery-supported (battery-operated eCook) or directly connected to the power supply (direct eCook). Battery-operated eCook are further classified into photovoltaic eCook (PV-eCook) and grid-eCook (could be supplied from the main power grid or off-grid system) (see Figure 2-1) [23], where both types are connected to a battery and a charger. The battery storage provides backup in the case of a power deficit from either the PV panels or the grid and assures power availability during outages and system instability. PV-eCook uses a DC battery charged from a PV panel as a source of power in rural areas, while grid-eCook uses an AC charger for AC/DC conversion to charge the battery. This type is generally used in urban areas to meet cooking needs when grid-connected [23], [24].

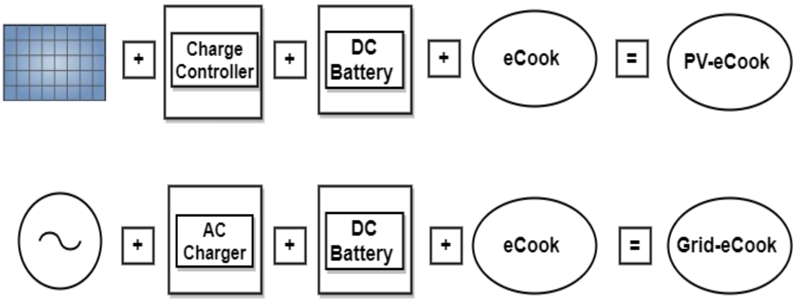

Figure 2-1. Battery-operated eCook categories depending on their energy source [23].

2.3 Existing Research on Cooking Practices and Device Trials

Previous research has been associated with investigating eCook deployment in Sub-Saharan countries and East Asia linked to the MECS program, and publications of the case studies can be found in [9]. Several trials were carried out in Kenya, Tanzania, Zambia and Myanmar, where the research group actively pursued various methods to gather data [23]–[26]: (1) measuring the energy consumption of meals when cooking with electricity and other fuels, (2) some eCook prototype tests, and (3) surveys and cooking diaries.

The findings show that there is a high potential for using electrical cooking appliances in these countries since they are consistent with their type of cooking. The EPC is recommended for Kenya, Tanzania, and Zambia cuisine, while, in Myanmar, a variety of appliances could be used e.g., rice cooker, electric frying pan, thermo-pot and EPC. In [23], [26]it was mentioned that the grid in some urban regions of Kenya, Tanzania and Zambia is strong enough to promote the uptake of electric cooking devices. However, this statement is provided with no clear technical evidence [23]–[26], as little attention has been given to systems studies and analysis of network constraints when cooking with eCooks [27]. Most of the research into eCook has focused on collecting and analysing demand and user-side data on the cooking times, ease of use, cost of cooking with different fuels, and the dishes cooked using eCooks. Most grids in developing countries are notoriously weak and overloaded [28] which prevents consumers from using electricity for daily activities, specifically high-power devices such as those needed for cooking. To date, there are very few studies mentioned in literature [8], [27], [29] that consider the possibility of eCooking at the network level due to the difficulties in modelling the power network infrastructure – the scarcity of reliable input parameters as well as the absence of standardisation. Both [8] and [29] assess the feasibility of eCooking on an isolated micro-hydro grid in Nepal, the quantitative and qualitative data from the electrical meters and cooking diaries were collected. The electrical data showed that as eCooking becomes widely used, control issues, voltage stability and limited micro-hydro plant capacity provide obstacles. The same conclusion was drawn in [27] through carrying out technical analysis in to identifies the main technical challenges that exist when accommodating eCook loads in solar home systems, micro-grids and low voltage (LV) distribution networks in developing countries. However, more work and depth analysis are still needed to have a clearer understanding of the technical network impact when additional electricity is used to cook. As mentioned before, one of the main barriers preventing this is that power system modelling is a crucial part of the operation, management and planning of electricity network which directly correlates with high quality and accuracy of the data and input used. Unfortunately, power network information (feeder data, generation and meter data) is not widely available to researchers. It is always the case that during modelling a network, pieces of information are gathered and stitched together to form a 'fair' representation of the real network to conduct power flow analysis. This consumes more time and efforts. Other challenges are the limited data on base-load and cooking load profiles, the cost of electricity and socio-cultural barriers. Connecting a low penetration of eCooks to the grid may not cause any issues, however, increasing the number could lead to an instability of the system or even blackouts. Therefore, especially in the long-term prospect, it is critical to evaluate the level of eCook penetration the system can sustain without posing any negative impacts, to ensure the distribution system remains stable at the grid and off-grid system levels. Moreover, no practical methods are available to support the assessment of power network readiness to adopt the additional cooking demand, future design requirements and the potential solutions to increase the uptake without the need for a significant upgrade and reinforcement of the mini-grid network. To address this gap in knowledge, this PhD research proposes to supply answers to these questions through developing a network assessment methodology and modelling a representative power network case study to conduct power flow analysis and to examine the impact of eCook penetrations on the network voltage profile and thermal constraints. As well as to understand feature of the grid which may make them compatible/incompatible with eCook and evaluate smart solutions enabling cooking in the context of mini-grids.

SUNSPOT [30] is another group active in this area, with the main objective of building an affordable off-grid solar electric cooking prototype for rural areas. The model designed comprises of two PV modules of 330 kWp, a lead-acid battery rated at 24V/120 Ah, an inverter/charge controller and a 2 kW induction cooktop with an 80% efficiency, and 4 port USB integrated into the system to provide more services including LED lights and mobile telephone charging. Comparing the SUNSPOT model design, with a BBOXX solar home system (SHS) capacity, installed in rural Rwanda comprising of a 50 kWp PV and 12 V, 17 Ah sealed lead-acid battery for basic lighting and telephone charging [31], it is apparent that there is a need for larger capacity PV systems to supply the high-powered cooking devices. Furthermore, the significant increase in capital costs to accommodate eCook is only made 'affordable' by SUNSPOT due to the business model with the facility of a long payback period, which has been prohibitive to widespread private sector investment – and so illustrating the technical solution itself as being comparatively expensive in the context of typical SHSs deployed in rural areas of Sub-Saharan Africa.

Other work conducted is by GACC [32], in conjunction with a global network of partners and organisations from the private sector, NGO, philanthropic, donor, humanitarian, multilateral, and academic fields. They seek to build solutions to fill the gaps in clean cooking technologies and fuels and to familiarise women in Kenya with the benefits of using clean cookstoves including eCook appliances. A cookery programme is televised to educate families on the preparation of nutritious meals using these devices. This programme also collects feedback on the efficiency of the cooking appliances and highlights any future improvements deemed necessary, to make them more efficient, safer, cleaner, and more affordable.

Much focus has been placed on capturing the various type of data, market assessments and eCook prototyping to give a clear vision of how people cook and the requirements to ensure the use of this technology in the future. However, to the knowledge of the author, there appear to be no detailed publications on the work, which provide analysis of the technical impact of these devices for on-grid and off-grid systems. Furthermore, attention is mostly directed to deploying eCook appliances in urban areas, while the focus should arguably be towards rural communities since most of the developing countries' populations live in remote areas and are the most affected by the problems encountered by traditional stoves. This again emphasises the importance of this PhD research.

2.4 Comparing eCook to Other Types of Loads

The universal resurgent of new electric loads caused a strong challenge to the electricity grid to maintain the balance between generation and demand. However, it is only with recent advancements in network management and control that more flexibility is seen in some of the loads, making it possible to reduce the peak load in the case of flexible loads [33]. Flexible loads, include EV, irrigation pumps, heat pumps, washing machines, dryers and dishwashers. Large-scale penetration of these electric devices in the system has gained significant attention in developed countries due to their high electricity demand which leads to unwanted peaks and negative effects on the power network parameters.

Although, due to their flexibility the load profile can be modified to reduce the daily peak without significant loss of efficiency and conversion simply by shifting their starting time to non-peak hours. For EVs, research academics and distribution network communities [34]–[37] mainly focused on the different possible solutions to enable their uptake, as well as keeping the system balanced by incorporating cost incentive strategy and/or smart charging. Some of the studies include; probabilistically interrupting cars charging during expected peak times and on/off scheduling schemes [34], EVs are also a valuable source towards Vehicle-to-Grid (V2G) technology [36]. Proper load management by the utility also enabled the possibility of load shedding without affecting the occupant’s comfort to reduce demand during peak usage time and avoid rolling blackouts.

HH appliances also consist of permanent devices such as refrigerators and freezers which are continuously operating with constant power consumption and a duty cycle to maintain a specific temperature to preserve the food. The consequence is that there is less flexibility in these appliances, leading to network issues when experiencing high penetration. The same implies to the On-demand load where the eCook devices fit in. It satisfies the occupant HH’s living needs which cannot be compromised, such as lighting, communication, cooking (EPC, microwave and oven, etc) and entertainment (TV and a computer). These devices are switched on/off randomly during the day depending on many factors such as occupancy, the number of HH members and the yearly season. This gives rise to the importance of studying the impact of eCook loads in the power engineering sector particularly in developing countries where national power grids are weak, and off-grid systems’ power and energy are limited. There remains an unfilled gap for research, focusing on the cooking practice and consumer behaviour in developing countries where energy consumption constantly changes from one country to another due to the type of food, ingredients used, and the duration of cooking, to name just a few. Also, cooking with electricity leads to higher peak demand when many HHs cook at the same time, on the other hand, the food cooked can vary depending on the season.

Another point is that electrification in developing countries is categorised into a Multi-Tier Framework (MTF) (Table 2-1) [12] to easily assess the availability, reliability, quality and affordability of the power. In rural areas, some HHs are categorised under Tier-1 and Tier-2 where the energy and power provided are very low and the HH power appliances ratings are only a few Watts as shown in Table 2-2. Connecting cooking devices will lead to very high peak loads as well as high energy consumption, which could last for unknown periods of time. While as an example in the UK, even though the intervention of EVs and heat pumps has significantly impacted the network, coherent policies, investments, and load control schemes are in place to prevent overloading the power system unlike those of developing countries. Furthermore, the work carried out in the eCook research area is based on off-the-shelf eCook devices that are directly connected to the power network rather than battery-operated eCooks, which give less flexibility and controllability. Off-the-shelf eCook devices are characterised by different power ratings [38]; an EPC ranges between 700-1000W for 3-7 litres capacity, a hotplate (700-2000W), an induction stove (1000-2000W) and a rice cooker (300-900W).

Table 2-1. Electrification Tiers [12].

Capacity	Tier-0	Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
Power Capacity ratings (minimum in W or daily)		3 W	50W	200 W	800 W	2,000 W
		12 Wh	200 Wh	1.0 kWh	3.4 kWh	8.2 kWh
Supported Appliances		Very low-power appliances	Low-power appliances	Medium-power appliances	High-power appliances	Very high-power appliances
Typical Supply Technology		Solar lantern	Rechargeable battery, SHS	Medium SHS, fossil fuel-based generator, mini-grid	Large SHS, fossil fuel-based generator, mini-grid, central grid	Large fossil fuel-based generator, central grid

To conclude, collating these facts, the cooking load presents a unique challenge compared to other network problems. It is critical to evaluate the network constraints when cooking with electricity as well as innovative solutions that can effectively smooth out the path to widespread adoption of eCooks, as, it is considered a critical load with very high-power consumption and less flexibility. Furthermore, from the current literature, there is a lack of understanding of the impact of eCook devices within the power engineering area.

Table 2-2. Indicative calculation of electricity consumption by Tier [12].

Appliances	Watt Equivalent Per Unit	Hour Per Day	Minimum Annual Consumption in kWh				
			Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
Task lighting	1/2	4/8	1.5	2.9	2.9	5.8	5.8
Telephone charging	2	2/4	1.5	2.9	2.9	2.9	2.9
Radio	2/4	2/4	1.5	5.8	5.8	5.8	5.8
General lighting	12	4/8/12		17.5	17.5	35.0	52.5
Air circulation	20/40	1/6/12/18		29.2	87.6	175.2	262.8
Television	20/40	2		14.6	29.2	29.2	29.2
Food processing	200	0.5			36.5	36.5	36.5
Washing machine	500	1			182.5	182.5	182.5
Refrigerator	300	6				657.0	657.0
Iron	1,100	0.3				120.5	120.5
Air conditioner	1,500	3					1,642.5
Total			4.5	73	365	1,250	3,000

2.5 eCook Barriers and Impacts

Central grid distribution networks in many developing countries face a series of challenges [28], where parts of the systems are overloaded due to the inconsistency between demand and generation. Consequently, transformers, fuses and circuit breakers operate beyond their design limits causing frequent failure and unscheduled outages as well as scheduled load shedding. In most distribution networks the power is transmitted through radial circuits to the consumers, meaning supply restoration through network reconfiguration is not viable in the case of a failure of any feeder, no power will be transmitted to the associated consumers. High power losses and phase imbalance are other factors that reduce the strength of the grid and cause regular blackouts, this can happen through connecting non-linearity high-power single-phase loads and unevenly distributing them over the three-phase power system. With the lack of generation mix, wear and tear of existing plants and power infrastructure, as well as the absence of operating reserves, the grid becomes unreliable and unstable. The energy mix situation of Malawi, Rwanda, Tanzania and Kenya is as follows:

- Malawi: The electric power is mainly generated from hydro-power stations without a reserve margin, it contributes to 97% of the total electricity supplied by ESCOM (The Electricity Supply Corporation of Malawi). The remaining 3% comes from diesel power plants [39]. However, in the past few years, there has been less power generation due to droughts causing lower water levels in rivers, wear and tear on existing power plants, and a lack of an energy mix. Consequently, rolling blackouts are routinely scheduled as the connected demand exceeds the supply of 320 MW installed generation capacity [27]. The rapid increase in the cost of electricity and gas, the lack of generation and the limited number of HHs connected to the grid, consequently, this means that firewood is still the primary cooking fuel in both urban and rural areas accounting for 50% of urban cooking fuel and nearly 100% in rural areas [39].
- Rwanda: The overall electricity generation in Rwanda depends heavily on hydro-power. As in Malawi, the power sector suffers from electricity supply shortages due to regional droughts as well as high system losses leading to an unreliable power supply and severe load shedding. Drought has also affected Kenya, Tanzania and Uganda, leaving Rwanda with no possibility of sourcing electricity from its neighbours [40]. As a solution, the Government installed diesel generators to reduce the occurrence of blackouts (from 450 in 2015 to 120 in 2018). This caused an increase in tariffs linked to the additional high cost of diesel fuel. Hence, for the lowest-income families with the lowest energy demand, the tariff increased to approximately \$0.30/kWh [27]. In fact, even though the initial capital cost

of the diesel generator is low, the diesel generator has an ongoing operating fuel cost leading to this increase. For this reason, the movement is drawn towards using LPG to replace traditional cooking fuels.

- Tanzania: Electricity makes up only 0.6% of the total energy consumption [41] where hydro-power is the dominant source of energy. As previously stated the lack of energy mix is an important issue when it comes to satisfying consumer's electricity demand leading to a blackout of more than two hours per day in the capital city of Dar Es Salaam [27]. Additionally, 73.2% of urban and 24.5% of rural areas are electrified which makes it apparent that firewood remains the main source of energy for cooking (63.5%) followed by charcoal (26.2%) [41].
- Kenya: It has an installed capacity of 2.3 GW, mainly dominated by hydro-power, though, due to poor rainfall only 38-76% of it contributes towards the generation mix [42]. This leads to more incentives tailored towards geothermal and wind power to enhance the energy power sector. Furthermore, the consequences of Covid-19 had an impact on reducing electricity consumption and peak demand which was seen as an opportunity for the Government to encourage movement towards electric cooking [27].

From these case studies, it is evident that connecting wide-scale eCook loads to the national grid is highly challenging. As a result, Sub-Sahara Africa needs to build more reliable power systems, with a prime focus on transmission and distribution. This should also centre on scheduled maintenance, reducing power outages, for a reduction from 16% a day to 10% [43], a figure which is nearer to advanced economies. Currently, this sector is ranked as one of the worst in the world and enormous sums of capital investment are required if the continent is to achieve a reliable electricity supply for all. This is estimated to be almost a fourfold increase in current investment levels, equating to $120 billion a year until the year 2040 [28], [43]. However, gaining the financial backing needed for energy projects would only be achievable if the efficiency of utilities is improved and guaranteed, along with security and stability in the financial sectors in the countries concerned.

A literature review was conducted to analyse the challenges caused by EV charging at the distribution level to transfer the knowledge obtained in the study to understand the technical limitations and the impact of eCook deployment in developing countries.

Although, before continuing it is necessary to distinguish between what is meant by the term ‘weak grid’ compared to a ‘strong grid’. In this research a weak grid is referred to power systems that produce inadequate capacity to reliably support customers with basic electrical appliances and are not capable of meeting increased generation and demand leading to rolling outages during the day [44]. On the other hand, the grid voltage level and frequency operate below the acceptable limits suggesting that the system is unable to handle the additional demand. When the system operates with low voltage and frequency, cooking takes a long time leaving the food undercooked [29].

After comparing EV and eCook loads (section 2.4), and studying the challenges arising from EV deployment in developing countries, the main network features which could be affected at the distribution level when providing eCook devices to consumers are:

2.5.1 Voltage Fluctuation

The power system has the capability to sustain the voltage at all buses within their acceptable limits during normal operation, when there is an increase in demand or after being subjected to a disturbance, such as a fault condition, constraints, or line overloading. Any of these can cause a voltage drop, which could lead to the voltage collapsing [29], [45], [46]. In this research, power flow studies are conducted to analyse the impact of eCook on the system voltage profile by taking low and high penetration levels of eCook demand.

2.5.2 Power Losses

When the current flows through the distribution line, the conductor heats up, creating power losses leading to a power drop [45]. As stated previously, power losses can be reduced by distributing the eCook load between several buses. Also, the power transmitted through the distribution system must remain within the limits, as well as the current level, since the power losses are directly proportional to the current squared.

2.5.3 Transformer Overloading and Distribution Cable Thermal Limits

Deploying a large-scale eCook load at the national grid level could threaten the performance of the transformer at the AC distribution level. Increasing the load has a direct effect on increasing the hot spot temperature of the transformer, which has a role in reducing its life cycle [45]. Practically it should not exceed the limits specified by the manufacturer. Not only are the distribution transformers affected, but also other electrical equipment such as circuit breakers (CBs), fuses and cables.

Other network issues for consideration are the thermal ratings of the conductors at the distribution level and to avoid exceeding the maximum temperature for which a conductor is designed to withstand. Economically, voltage deviation beyond the limits imposes penalties on the utility and researchers recommend connecting the non-linear loads to the strong buses rather than those considered weaker [45]. Furthermore, reliability and power quality are two other important factors for investigation when studying the operation of the power system.

2.5.4 Reliability

Reliability refers to the ability to produce adequate capacity to support customer demand to satisfy their needs, as well as ensure stable and reliable power without uninterrupted supply from the generation, transmission or distribution to satisfy consumer demand [47]. In this research power availability and energy shortage are assessed as key indicators of power system reliability for customers since eCook creates a massive increase in both power and energy demands which is a concern.

2.5.5 Power Quality

The power quality in the distribution network is referred to the diversion of the electricity attributes from their nominal values [48], [49] which can be of concern when connecting eCook loads to the distribution system, as the non-linearity of the eCook may cause harmonics as well as voltage sag as they operate with pre-heat and series of on/off cycles. The increase in eCook loads results in a rise in the peak demand which is also accompanied by a decrease in the reserve margin. The system's power quality can be analysed by calculating the voltage unbalance factor (VUF) which is the ratio of the negative and positive voltage sequence [50]. The result should be within the acceptable limits defined by the country's grid code.

2.6 Literature Review on Demand-Side Management Techniques and Technologies

2.6.1 Current Use of DSM in Mini-grids of Developed Countries

DSM can be regarded as part of large-scale power system operation, as it plays an important role in smoothing out the daily peaks and reducing energy consumption to achieve energy efficiency improvements by employing sophisticated technologies and techniques to encourage and enable legitimate changes in the end-user behaviour and their energy practices, that can manage the grid impact and ultimately the price of energy to the consumer [51], [52]. However, to date, research has tended to focus on DSM strategies that fulfil the requirements of the developed world, with somewhat less focus on its role in achieving energy access targets in the developing world. The former, are designed to operate in parallel with smart grids with appropriate modern information and telecommunication devices to ensure grid reliability and reduce operational costs. In a well-designed DSM program, it can address Energy Efficiency, Energy Conservation and Demand Response [52], [53], combining these three leads to a significant reduction in energy consumption, leading to the grid owner/operator deferring reinforcement costs and the consumer experiencing a more efficient and cost-effective service (Figure 2-2). In general, DSM is used for: peak clipping, valley filling, load shifting, strategy conservation, strategy growth and flexible load shaping [54], [55].

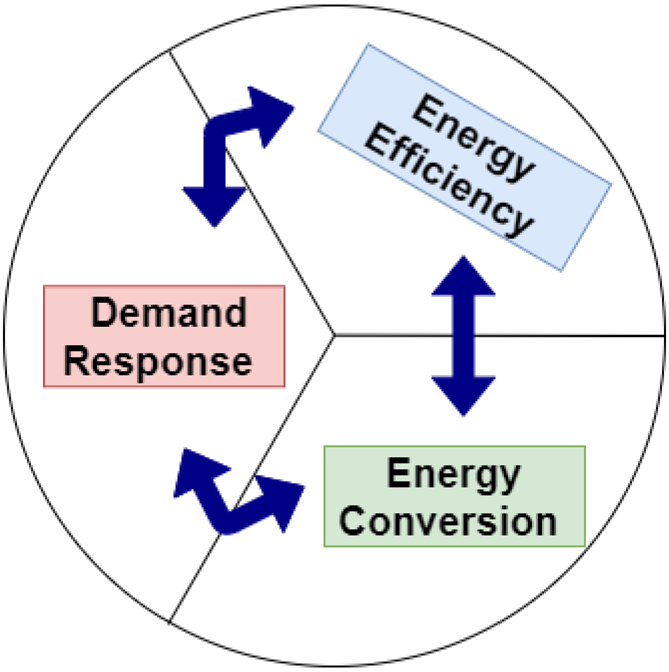

Figure 2-2. Demand-side management strategies [52].

Energy efficiency refers to the permanent installation of energy-efficient technologies (e.g. replacing incandescent light bulbs with compact fluorescent bulbs) or the elimination of energy losses in existing systems [52]. It has been a policy priority in many countries (European, Japan, USA) to eliminate system energy losses by encouraging the utilisation of energy-efficient technologies at the residential level as well as in the industry sector [52], [56] as being a key component in supporting carbon reduction targets. The

Netherlands has successfully applied this by integrating it into the Dutch industrial plan and promoting implementation in HHs. It issued an energy premium scheme to encourage consumers to purchase energy-efficient refrigerators, freezers, washing machines and dishwashers, etc. Japan, California, Mexico, and Brazil have also included it in their plans for promoting energy efficiency.

Energy conversion strategy is the engagement of people to use less energy in their homes by making behavioural choices or changes that could last for a short duration or may evolve into a habit [52], [57], [58]. However, effective behaviour change programmes need to be put in place to raise awareness by educating individuals on the implementation and the importance to both the utility and the consumers' end. The implementation of such a program may be limited as it involves cooperation and conformity.

Effective mechanisms are also deployed to enable the success of levelling the daily energy consumption by incorporating demand response tools related to market and price signals [59] to allow load management and load shifting, through the use of advanced metering which informs end-users of their energy consumption. This allows homes to save money and shift the operation of flexible loads (EV, washing machines, dishwashers) from high-demand hours to non-peak hours without affecting the users' comfort level. Although, this is a more expensive option as it includes information and communication technologies.

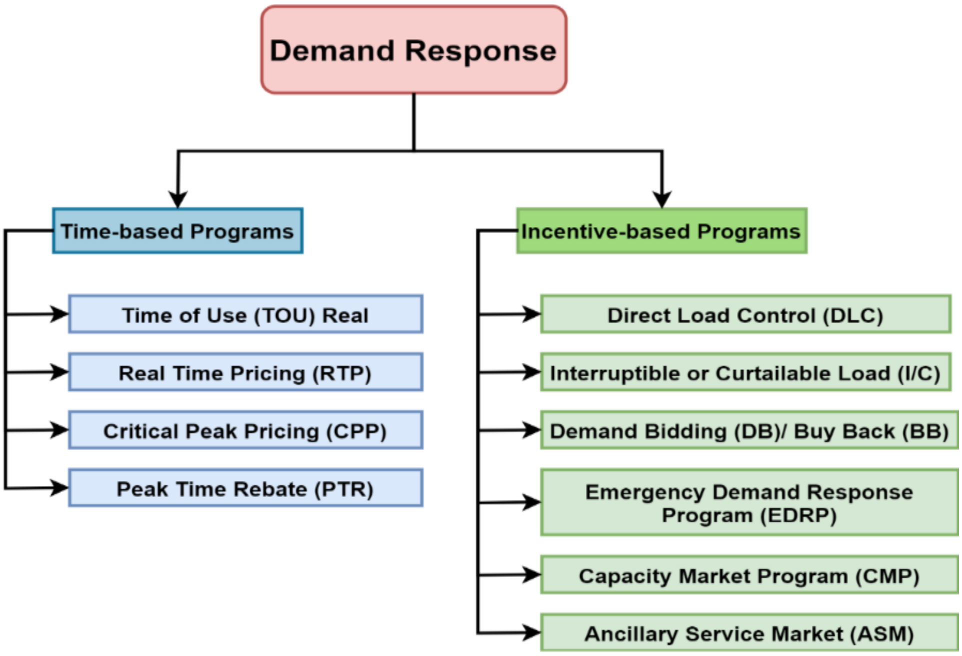

Figure 2-3. Type of demand response strategies [60].

Many DSM tools were developed in the case of demand response to easily manage load increases in developed countries, they can be classified into two categories as shown in Figure 2-3 [60], [61]: Time-based programs and incentive-based programmes. Time-based programs relate to the engagement of consumers through behavioural changes and time-variant pricing which range from time-of-use to real pricing where the prices vary over time for different hours on different days [51]. While the incentive-based programme is a scheme particularly used by electricity companies to encourage specific actions to incentivise consumers [62].

2.6.1.1 DSM Case Studies

In developed countries, the concept of the Internet of Things (IoT) opened the pathway towards smart grids and the use of DSM [60], [63], [64], the correlation of different technologies gave rise to sustainable and efficient buildings which are one of the EU strategies for energy-efficient [65]. The “InovGrid” is a project implemented in Portugal that integrated smart buildings to encourage more sustainable ways of energy management. Although, applying this concept is restricted to the economic aspects as some buildings may be characterised by poor performance and, the costs of the rehabilitation could reach the costs of demolition and new construction, which makes it unfeasible. In Germany [66], a detailed study was undertaken to investigate the potential of DSM to reduce the curtailment of renewable energy resources (RERs) through integrating flexible electrical loads (electric boilers and heat pumps in district heating). The flexibility of heat pumps and their advantages in reducing CO_2 emissions attracted support from the UK Government, resulting in the increasing popularity of home energy management systems aimed at achieving efficiency gains and energy conservation [67]. Ventilation and air conditioning are some of the dominating loads in hot regions such as Kuwait, where an energy-efficient program was implemented to oversee the issue of power shortages [68]. The program aimed to spread awareness of energy efficiency and integrate DSM techniques without affecting the comfort of occupants, such as global temperature adjustment (GTA), variable air volume systems (VAVS), and chilled water storage systems (CWS) to enable energy-saving and load shifting. Verrilli et al [69] developed a direct load control-based DSM algorithm for heating control in micro-grids considering time-varying renewable generations, and thermal comfort in the buildings. Sweden, Canada, Australia and the USA [70]–[73] investigated these appliances and implemented algorithms to identify their benefits related to DSM, saving energy and cost.

The uptake of EVs offers a potential pathway towards reducing the CO_2 emissions emitted by traditional cars, however, their uptake places a significant strain on existing low voltage networks. The advancement in smart charging technologies made them more flexible and supported by the UK policy [74].

The DSM solutions listed in this section, whether applied to large-centralized grids or off-grid mini-grids, operate effectively in countries where there are large densities of population, economic activity and large electricity consumption. In addition, there must be the correct environmental action plans, policy measures and regulatory frameworks in place, by contrast, the lack of these presents additional challenges to the implementation of DSM in developing countries.

2.6.2 Current Use of DSM in the Mini-Grids of Developing Countries

The DSM strategies and technologies used for rural mini-grids in developing countries (see Table 2-3 and Table 9-1 in Appendix 1) mostly target appliances that have more flexibility and do not affect HH comfort and less research has been undertaken in exploring techniques to reduce the cooking peak load and inspire people to cook with electricity [51].

Table 2-3. DSM strategies and technologies.

DSM Strategies	DSM Technologies
Efficient appliances and lights	Current limiters
Commercial load scheduling	GridShare
Restricting residential use	Distributed Intelligent Load Controller
Price incentives	Conventional meters
Community involvement, consumer education, and village committees	Prepaid meters
	Advanced metering systems with centralized communication

For example, DSM has been used to increase energy efficiency through reduced consumption in Zimbabwe [75], Ibadan (Nigeria) [76], and Bangladesh [60], where CFLs and incandescent bulbs were replaced with LEDs in domestic HH to explore the benefits of such a substitution. The impact of productive energy use during off-peak hours was studied in rural Bangladesh and Lake Victoria in Tanzania [77]; both projects allowed an increase in energy consumption when demand was low, which resulted in a positive impact on revenue. Energy metering and price incentives are other common approaches applied to mini-grids to reduce peak demand and shift to off-peak time. A project was rolled out in Senegal by ENERSA [77], where energy was sold in blocks to restrict energy and power consumption. The energy utilised was monitored using smart meters, which allowed HHs to plan and budget for their energy consumption. The subscription to the energy blocks lasted six months, which gave ENERSA a better insight into future demand.

However, in this thesis, the main research focuses on how to balance energy demand with generation to accommodate higher levels of cooking energy demand. Some authors have found that there is less willingness on behalf of the consumers to shift this type of load and that eCooks are the least favourite appliances used in DSM, due to their negative characteristics [78]. Capturing such complex sets of interactions needs a broader perspective; this requires a sophisticated modelling framework to enable the transition toward eCook by exploring concepts for “smart” eCook devices (this has been explored in chapter 5).

2.7 Conclusion

This chapter has presented a thorough literature review, identifying key openings and opportunities for future research contribution. This is achieved through investigating energy access and cooking practice in developing countries and previous publications on eCook. Mainly those of the MECS consortium which includes data capture, market assessments and eCook device prototyping to give a clear vision of how people cook, and the associated costs. Furthermore, work was conducted to highlight the challenges of EV charging stations seen on a low voltage distribution network in most developed countries, and to apply the knowledge gained to give a better understanding of the technical limitations and the impact of eCook deployment in developing countries. To clarify how the eCook research challenges differ from other network demand problems, a section in this chapter compared and evaluated the different load demands with respect to eCook loads. To conclude, most studies for the feasibility of eCook deployment only centred on a limited number of areas and no single study exists in the wider engineering scales leaving many questions unanswered:

- What are the technical network constraints limiting eCook deployment?

- Is the existing network infrastructure capable of supporting extra load?
- How ‘fit for purpose are existing mini-grids to accommodate increasing eCook demand, or indeed what design considerations or interventions would be required to make them so?

To address these research gaps identified in the electric cooking sector, off-grid systems, particularly mini-grids, are regarded as promising solutions to meet HH electricity needs in rural areas. This part of the research is elaborated upon in the next chapter where a novel impact assessment methodology was developed to aid understanding of the technical and techno-economic implications of additional direct eCook demand in rural mini-grids, which is then applied to Use Case studies.

3 METHODOLOGY FOR ASSESSING THE TECHNICAL VIABILITY OF ELECTRIC COOKING ON A HYBRID PV/DIESEL MINI-GRID - AND RURAL TANZANIA CASE STUDY SIMULATION

This chapter lays out a methodology [79] that could be used by mini-grid developers to assess the design readiness and future design requirement to accommodate eCook. While mini-grids in developing countries continue to grow in popularity, typically their designs are not yet sufficiently developed to accommodate large power appliances. Moving towards clean cooking using electricity will cause technical risks for mini-grids in terms of voltage drop, voltage unbalance and capacity shortage. In this chapter, these parameters are studied on a mini-grid network modelled in OpenDSS/MATLAB as a simulation platform, where the selected mini-grid topology is hub and spoke. Two network studies are considered, the first investigates the limitations of the mini-grid in terms of the generation capacity available to supply the demand for different levels of eCook penetration, while the second focuses on the network constraints for different eCook penetrations. In general, the results show that voltage drop and voltage imbalance issues can be reasonably and affordably addressed by using cables of a larger cross-sectional area (CSA). The main issue prohibiting higher penetrations of eCook centres on generation capacity requirements, which led to a techno-economic analysis being conducted in chapter 4 to assess future mini-grid sizes as well as targeting economic and environmental objectives and meeting the overall demand on a generically representative mini-grid in a rural region in East Africa.

3.1 Developed eCook Mini-grid Network Study Methodology

Despite their advantages, it is important to examine the technical challenges which could arise when introducing direct eCook loads (where the eCook appliances are directly connected to the power supply) to mini-grids in their current form. For instance, the users' base-load profile is a key element in determining the system's critical parameters such as component sizes and overall network design. However, post-installation, demand may continue to increase over time as new consumers and appliances connect to the mini-grid. Unless this anticipated demand growth is properly factored into the initial mini-grid design, it can potentially lead to capacity shortages and violation of voltage and thermal constraints, ultimately leading to system outages and curtailment of demand. Some mini-grid utilities in developing countries use large CSA cables to mitigate any future demand growth and to comply with grid standards for main grid integration (if and when it arrives). Mini-grid developers in some countries such as Tanzania and Nigeria may be provided with subsidies and grants through a finance mechanism [10] to prepare for this.

In this research work, the literature review that was conducted in section 2.5 allowed to develop a methodology to investigate "how fit for purpose" these types of mini-grids are to accommodate increasing direct eCook demand, or indeed what design considerations or interventions would be required to make them so. The methodology illustrated in Figure 3-1 can be used by mini-grid developers to assess the system's performance and cost, which will give an insight into the existing problems and future design requirements to move towards electric cooking.

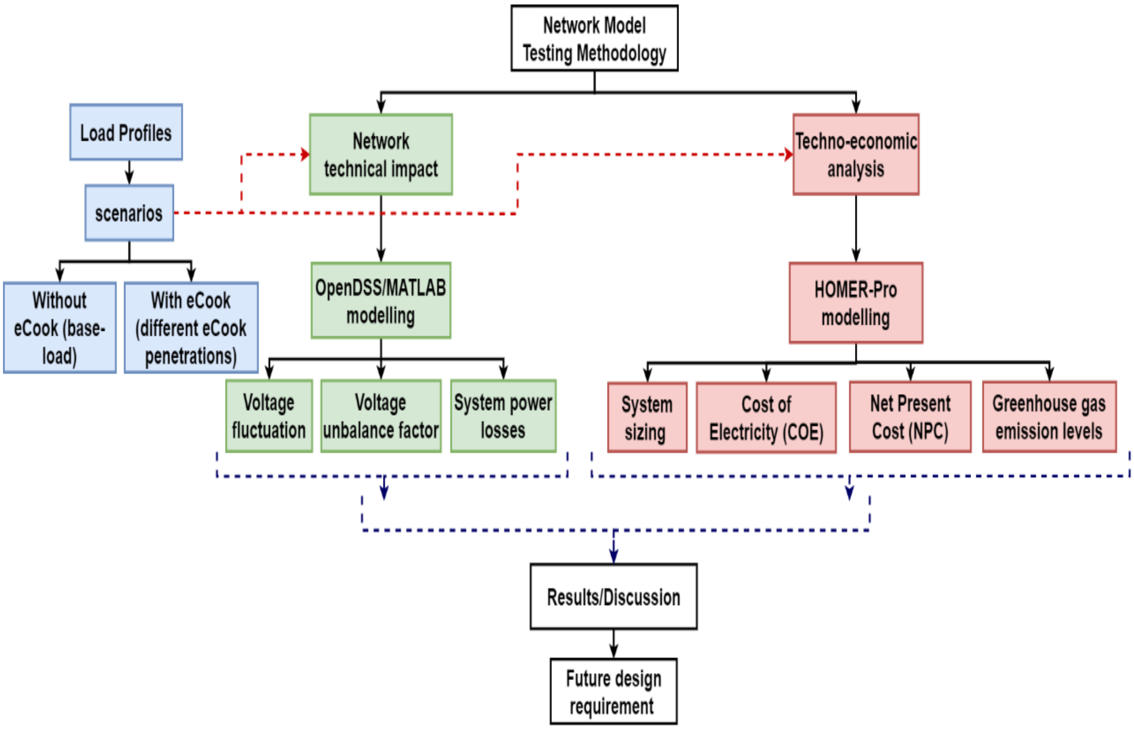

Figure 3-1. Network model methodology with/without eCook demand.

The methodology is divided into two main studies:

- Network technical impact: in this part, a mini-grid network was modelled in OpenDSS/MATLAB (R2021a) [80] as a simulation platform. OpenDSS was used to support distributed resource integration and to build the AC three-phase mini-grid distribution feeder to solve sequential-time power flow. Allowing the investigation into the impact of direct eCook on technical issues affecting network constraints such as voltage drop, power losses, VUF as well as the limitations of power demand. While numerous MATLAB functions were used to program the mini-grid's control algorithm and generate meaningful plots of voltage and power loss results from OpenDSS power flow network simulation. The common object model (COM) interface capability of OpenDSS is used to interface with MATLAB to observe the effect of the control algorithm in the min-grid (more detail on the mini-grid model and the control algorithm can be found in section 3.1.2.3 and 3.1.2.4, respectively). The model was tested by taking five eCook scenarios (0%, 20%, 50%, 80% and 100% penetration).
- Techno-economic analysis: a key area for investigation is determining the sizes of mini-grids required to accommodate this new direct eCook demand.

HOMER-Pro (version 3.14.4) [81], which is an optimisation software tool used to simulate the operation of hybrid min-grids for an entire year to provide the least-cost mini-grid system design. In this research study, the software was used to assess and identify the optimal sizing and cost to accommodate the different levels of the direct eCook scenarios considered in this research, the Cost of Electricity (COE), system's Net Present Value (NPV), etc. This was followed by calculating the system cable sizes needed.

The key findings paved the way, highlighting the specifications needed for future eCook mini-grids. The rest of the chapter gives a more detailed description of the steps considered in these two studies and the main results.

3.1.1 Demand Modelling

One-minute intervals of daily non-eCook and eCook load data were generated using the CREST demand model by a group of researchers in the MECS team [82]. The CREST tool is open-source and developed by Loughborough University for LV network analysis [83]. The model uses a high-resolution bottom-up approach to build representative individual end-user daily load profiles based on occupancy data as a core variable to decide whether the appliances are switched on/off by the occupants, as well as input data, collected from interviews or audits on electric appliances, electric needs, and consumer habits. It uses a first-order Markov chain technique to create a stochastic sequence of discrete random variables of dwelling occupancy to generate HH load profiles using probabilistic methods to account for demand diversity and allows the use of different appliances and their usage pattern depending on the timing of the occupancy activity. The original model, however, was completed by inferring occupancy from the UK time-use surveys and for this purpose, researchers from the MECS consortium adjusted the tool to represent individual low-income HH electricity demand representative of HHs in remote rural areas of Sub-Saharan Africa [6].

3.1.1.1 Non-eCook Load Profile

The non-eCook load (i.e., base-load) are derived using the CREST model, the appliance ownership and utilisation habits are taken from the ESMAP (Energy Sector Management Assistance Program) Multi-Tier framework [12], where two HH categories are considered in this research. In the first category, the HH consumption is somewhere between Tier-1 (relatively lower baseload demand) (Table 3-1) and Tier-2 (relatively higher baseload demand) (Table 3-2). While in the second category, the HH consumption is strictly within Tier-2. These give an average daily energy consumption per HH of between 50–200 Wh.

Table 3-1. Appliance characteristics within Tier-1 [6].

Appliances	Power (W/appliance)	Quantity	Hours/day
Lights	1	2	Few hours
Phone Charger	2.5	1	2
Radio	2	1	2
AC TV	20	1	1

Table 3-2. Appliance characteristics within Tier-2 [6].

Appliances	Power (W/appliance)	Quantity	Hours/day
Lights	1, 1, 2, 4, 4	5	Few hours
Phone Charger	2.5	2	2
Radio	4 (1W standby)	1	4
Security Lights	5	1	Overnight
Fan	20	1	4
AC_TV	20	1	2

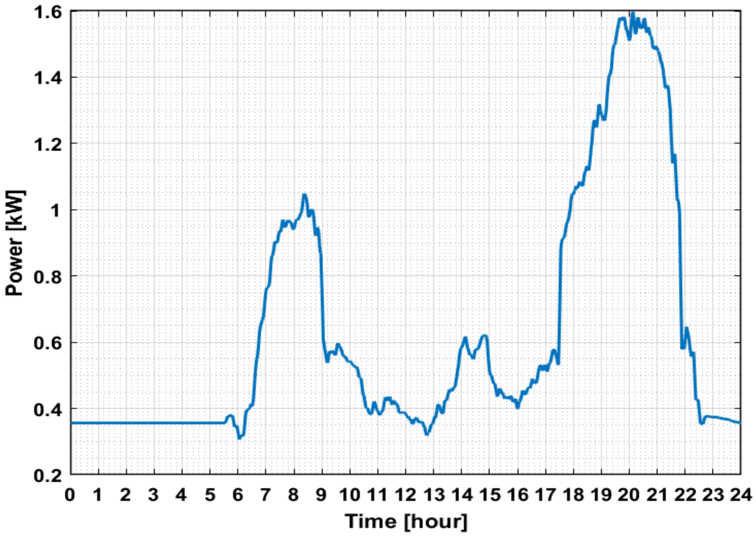

Figure 3-2. Aggregated non-eCook load for all 108 HHs.

Figure 3-2 shows a daily aggregated non-eCook load profile for the 108 HHs connected to the mini-grid. There are two distinct peaks as is typical of most domestic load profiles: a morning peak between 6 a.m.–10 a.m., and an evening peak between 4 p.m.–10:30 p.m.

3.1.1.2 eCook Load Profile

Figure 3-3 illustrates the aggregated eCook load for various levels of eCook penetration (20%, 50%, 80% and 100%) and the base-load. Note that 100% eCook penetration refers to the power consumption of all 108 HHs connected to the mini-grid, which use eCook devices exclusively when cooking their meals, as well as other non-cooking related HH appliances during the day. This gives three distinct peaks: morning, midday and evening (being the highest).

The HH load profiles are generated using the CREST model it is assumed that HHs are 100% transitioning to direct eCooks (EPC and hotplate) which means that all the HH's food is cooked with electricity. The data used for the cooking practice were collected during cooking trials which took place in Tanzania as part of the MECS programmed activity—for more information refer to the "eCook Tanzania cooking diaries report" [25]. The data were input into the CREST model to generate representative HH electric cooking load profiles using a 1 kW hotplate for breakfast and lunch, while for dinner the HH could use either or both a hotplate and a 1 kW EPC, where the HH's energy consumption is around 1.75–2.2 kWh per day for cooking only.

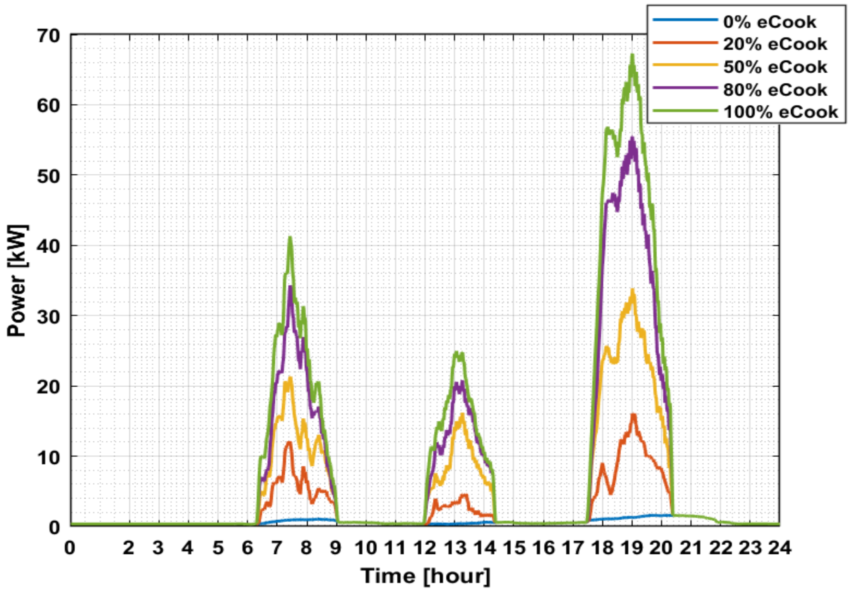

Figure 3-3. Aggregated HH load profiles (eCook + non-eCook load) for different eCook penetrations.

Table 3-3. eCook contribution concerning the peak load.

eCook Scenarios	Peak Demand [kW]	eCook Share [%]	Overall Daily eCook Energy Share [kWh]
0%	1.59	0	0
20%	16.07	90.01	53.71
50%	33.89	95.30	121.08
80%	55.49	97.13	185.86
100%	67.29	97.64	226.68

Table 3-3 shows the daily peak demand and the proportion of overall peak demand made up by each of the eCook penetrations under consideration. From the results shown in

Table 3-3 regardless of the level of eCook penetration, it accounts for more than 90% of the peak demand. This is not surprising as eCook adds a massive uplift in both power and energy demands due to its high-power consumption requirement compared to the very low power consumption from Tier-1 and Tier-2 customers.

3.1.2 Synthesising the Hybrid Mini-Grid Network Model

3.1.2.1 Mini-Grid Definition

As the term “mini-grid” varies within current literature, there is a need to clarify its definition within the context of this study. Bringing together both the IEEE standard definition [84] and the ones in [85], [86], the term mini-grid used henceforth in this research relates to a network isolated from the main grid where local distributed generation is used to supply local demand. Power is conventionally generated from either a single energy source or from multiple sources such as hydro turbines, photovoltaic (PV) panels, diesel generators and wind turbines to meet local residential, commercial and industrial demands. For an AC village mini-grid, which is considered in this research, the power capacity ranges between 1 kW and 300 kW.

3.1.2.2 Mini-Grid Topologies

Mini-grids can consist of AC, DC or AC/DC generation and distribution systems. This section introduces both the AC and DC system layouts, with the advantages and disadvantages of each.

The **DC Mini-grid** is commonly used in off-grid systems, the various components of the PV system are connected to the DC bus (Figure 3-4): the charge controller is connected to the PV array and system batteries to regulate their charging/discharging, and the inverter converts from DC to AC to serve any AC consumer loads, whilst the DC consumers are coupled to the DC bus. The diesel generator is connected to the AC side and directly powers any AC loads when it operates [87].

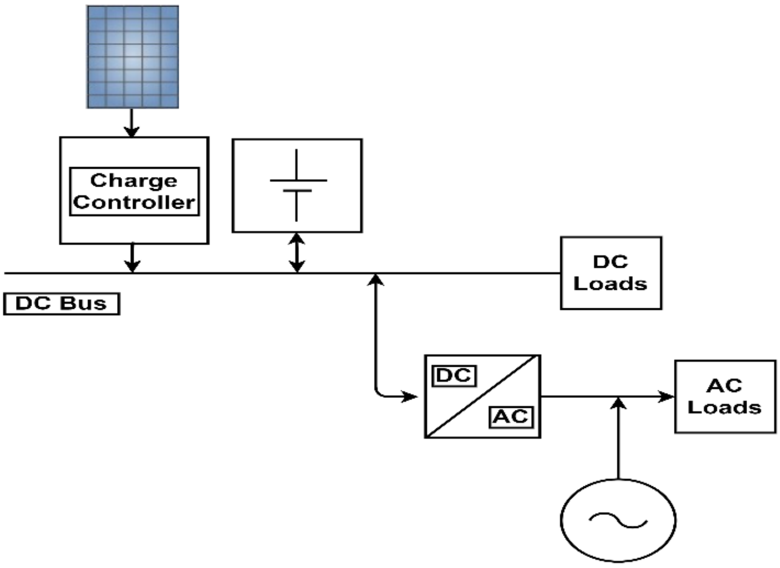

Figure 3-4. DC-hybrid PV/diesel mini-grid system layout.

The charge controller, with an in-built DC/DC converter, can also be used to step down the voltage from the PV array to the system batteries. Two types of charge controllers are available: a maximum power point tracking (MPPT) charge controller using a DC/DC buck converter and a pulse-width modulation (PWM) charge controller. The advantage of using a DC-coupled system is that it is highly efficient in discharging the battery at times when there is low or no PV available (at night), although, the system becomes more complex in the set-up when multiple parallel PV strings are needed [88].

The **AC Hybrid Mini-grid** is generally used for larger systems. It uses a grid-tie inverter that can ensure the inverter and generator output can be synchronised. The PV inverter is used to convert the DC power output from the PV to AC, a sophisticated battery converter is connected between the battery and the AC bus to manage the charging/discharging of the battery. The backup diesel generator can be used during periods where PV and/or battery capacity is insufficient to supply the demand (Figure 3-5) [87]. This configuration provides modularity, enabling the uprating of the grid by the addition of any new equipment. It is slightly more efficient during sunshine hours as there will only be one conversion step (DC/AC) needed for AC supply for direct use of PV power. However, two conversion steps are needed for charging the battery, which can lower the efficiency. In general, this setup is widely considered more appropriate for meeting peak demand during sunshine hours at an acceptable levelised cost of energy, since the marginal cost of generation is zero [88].

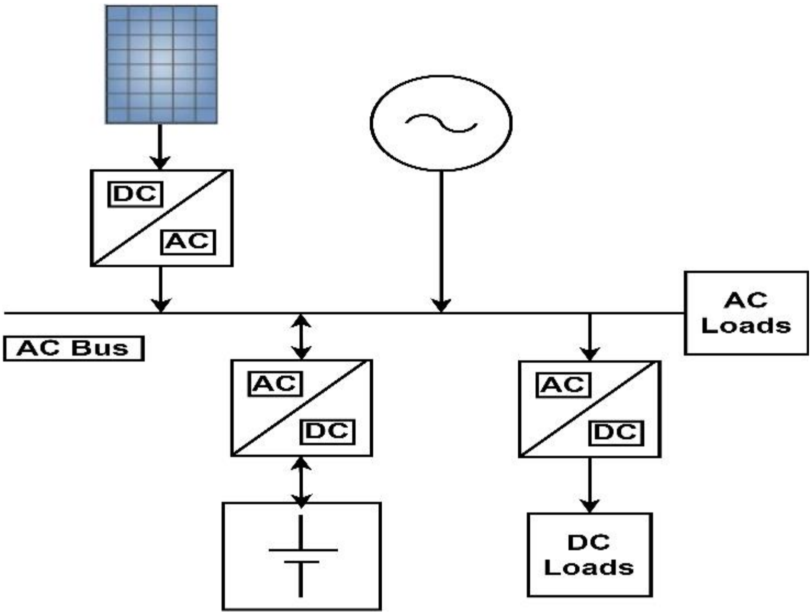

Figure 3-5. AC--hybrid PV/diesel mini-grid system layout.

3.1.2.3 The PV/Diesel Mini-grid Design Model

The hybrid mini-grid shown in Figure 3-6 which forms the basis of the model developed for the studies conducted and presented in this chapter, was developed as a composite of those designed and installed by practitioners and based on mini-grid design methods available in the literature. It was modelled according to IEEE norms and is capable of interconnecting to the main grid when it arrives. In general, for an AC three-phase mini-grid system, the distribution voltage is 400 V and the overhead cables run guyed wooden poles to serve single-phase customers along the line. The poles are typically spaced between 50 m apart. At the national grid level, the utility uses certain conductor sizes for example 50 mm^2, 100 mm^2 and 200 mm^2 [27], [89], [90]. Therefore, from these power network specifications, an AC hybrid mini-grid supplying 108 consumers was modelled in OpenDSS, which is interfaced with MATLAB. The system operates at 400 V at the distribution level and 230 V at the residential level. The mini-grid is sized to 30 kWp PV, 9 kW diesel generator, 41.4 kWh battery, 8 kW battery converter and 10 kW PV-inverter. The mini-grid here is much larger in terms of its sizing compared to a standard mini-grid design for 108 customers without any eCook. For example for a rural mini-grid connected to 100 HHs and small business, the size required to meet the demand would be approximately 6 kWp PV and 7 kW diesel generator [91], so, the type of mini-grid used in this study is 5 times greater in terms of PV size, however, it will accommodate around 20% eCook during a sunny day. Also, it will provide an opportunity for future research (presented in chapter 5) to be carried out which will consider the concept of demand-side flexibility.

In OpenDSS the parameters and the location of the PV, the diesel, and the battery are defined. The battery's generic model in OpenDSS is characterised using lithium-ion battery features (kWh, kW and % efficiency of charge/discharge); the battery's SoC is set to charge from 20% to 80% to safeguard battery health, prolong its life and minimise charging losses [92]; the round-trip efficiency of the battery is 95.3% [93]. For the electric network, the following parameters were included: the cable sizes, lengths, bus connection, resistance and reactance. The 108 consumer loads presented in section 3.1.1, were allocated at their respective nodes and the daily load patterns were read from CSV files to represent the variation in power with time, where each of the HH load profiles accounts for demand diversity. Also, basing the model on individual loads, it provides representative reactive power consumption of each load through the assignment of a 0.95 power factor.

For each of the eCook penetrations considered in this study, the cooking load was allocated starting with HHs which are furthest from the power substation in order to consider the worst-case scenario, where HHs with high demand further from the substation will lead to higher voltage drop and higher power losses. This forms the basis of the OpenDSS modelling, after which, MATLAB software was used to develop a generic controller function for the energy dispatch strategy of the mini-grid to control the operation of the generators (PV\diesel) as well as the battery.

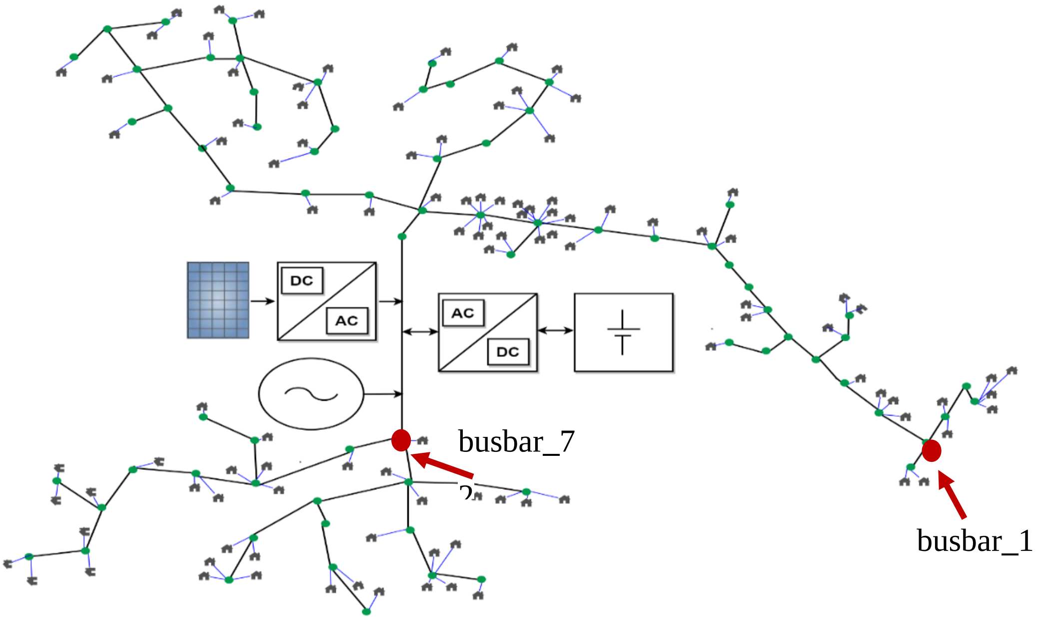

Figure 3-6. OpenDSS hybrid mini-grid layout.

The PV output power was calculated directly from the daily irradiance and temperature patterns imported from the HelioClim service for Tanzania [94] with a time resolution of 1 min.

3.1.2.4 Typical Load Following Dispatch Strategy for Hybrid PV/Diesel Mini-grid

The load following (LF) dispatch strategy is used to control only the normal operation time of the generators (PV and diesel) and the battery in OpenDSS, in this research no network security aspects were considered. Under the LF strategy, the diesel generator provides enough power to meet the load although it is not used to charge the battery. The battery only charges when there is excess power from renewable energy resources [95].

Figure 3-7 outlines the principle of the operation for the LF dispatch strategy in a flowchart which can be classified into three categories [89].

- When the output PV power is equal to the load power during the day. Here, the PV array has a higher priority to supply the entire demand and does not charge the batteries, and the generator remains off-line.
- The excess PV power will be used to charge the batteries if they are not fully charged, in this case, the diesel generator remains off-line.

- In the case where the PV output power is less than the demand during periods of no sunlight or low solar radiation, the battery starts to discharge. The battery continues to supply the maximum power allowed by the converter, and then finally the lowest priority is given to the diesel generator to meet the difference in demand not provided by the battery. If the battery's SoC becomes too low, it switches to idling mode and the diesel generator is brought online to meet the net load (load minus renewable power). The generator only provides enough power to satisfy the net load.

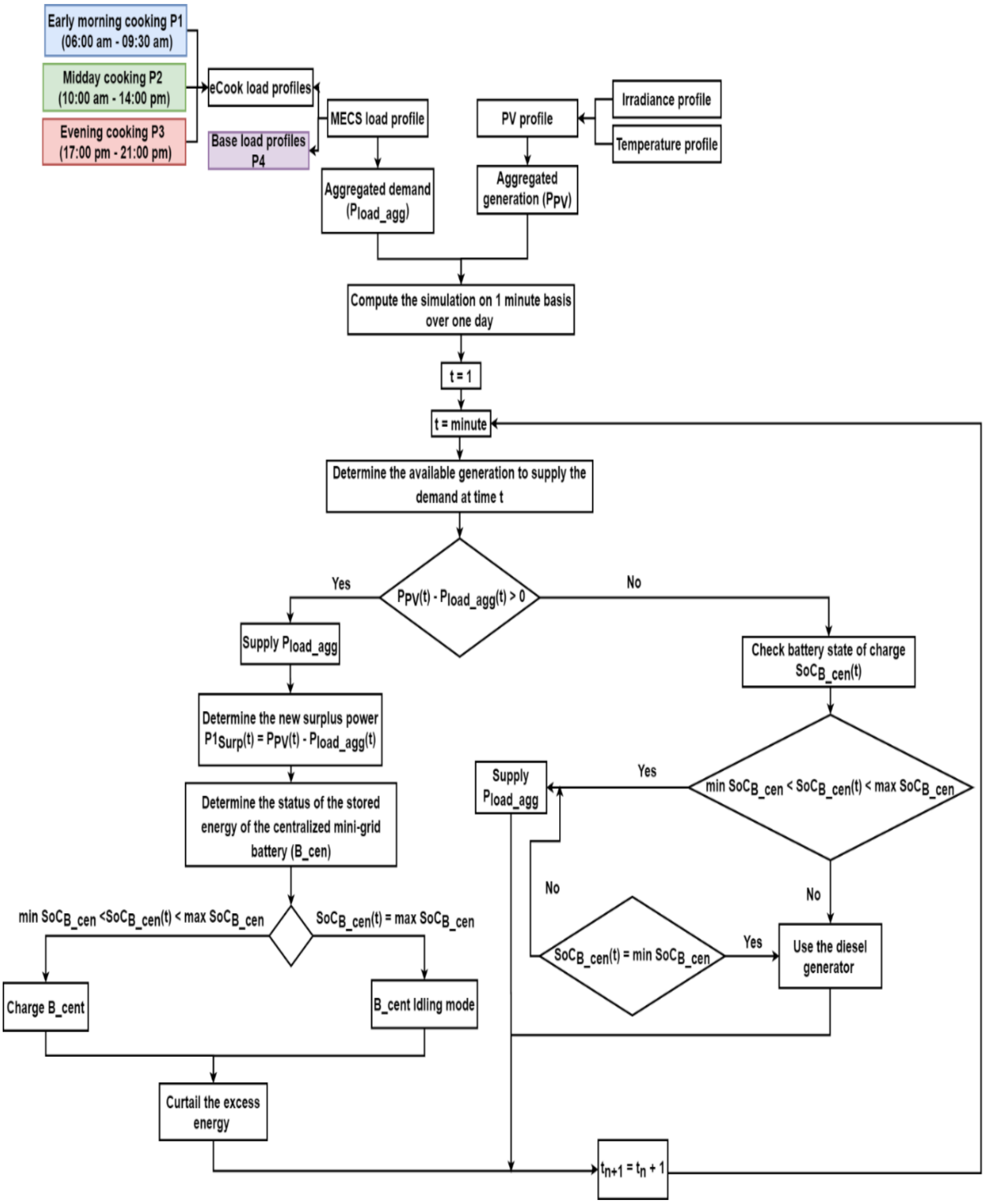

Figure 3-7. Load following energy dispatch strategy flowchart.

3.2 Technical Impact on the Network

This section of the chapter focuses on the limitations of the mini-grid in terms of the generation capacity available to supply the demand as additional direct eCook load is connected, with the likely impact of increasing eCook adoption on the mini-grid considering different aspects such as voltage drop, power loss and voltage unbalance. Two Use Cases concerning direct eCook and the availability of co-located generation are considered in the following sections.

3.2.1 Use Case 1 (Limited Diesel Generation Capacity)

In Use Case 1 the base mini-grid model in Figure 3-6 with 30 kWp PV, 9 kW diesel generator, 41.4 kWh lithium-ion battery, 8 kW battery converter and 10 kW PV-inverter was simulated over one day. The model was tested with different eCook penetrations ranging from non-eCook base-load to 20%, 50%, 80% and 100% eCook penetration (where the 100% eCook refers to all the 108 HHs using only eCooks for cooking as a worst-case scenario). This allows the evaluation of the eCook demand met and not met without network reinforcement as penetration increases. For the distribution and service cables, the CSA is set to 50 mm^2 and 16 mm^2, respectively.

When connecting different levels of eCook to the mini-grid without any reinforcement, this imposes a constraint on the grid, which translated into an increase in the daily energy shortage due to generation limitations. The system can meet the 0% eCook scenario and around 20% eCook (Figure 3-9), however, as the number of eCook devices increases, demand cannot be met resulting in an increase in the daily energy shortage; for 100% eCook, the energy shortage is approximately 42% as shown in Figure 3-8. For 50%, 80% and 100% eCook, the mini-grid fails to provide enough power to meet the aggregated load—this occurs in the morning and the evening as illustrated in Figure 3-9. In the case of 20% eCook (22 HHs using eCooks), all the daily demand is supplied by the available generation; the early morning and evening demand is met by both the battery and the diesel generator while at midday there is sufficient power generated by the PV.

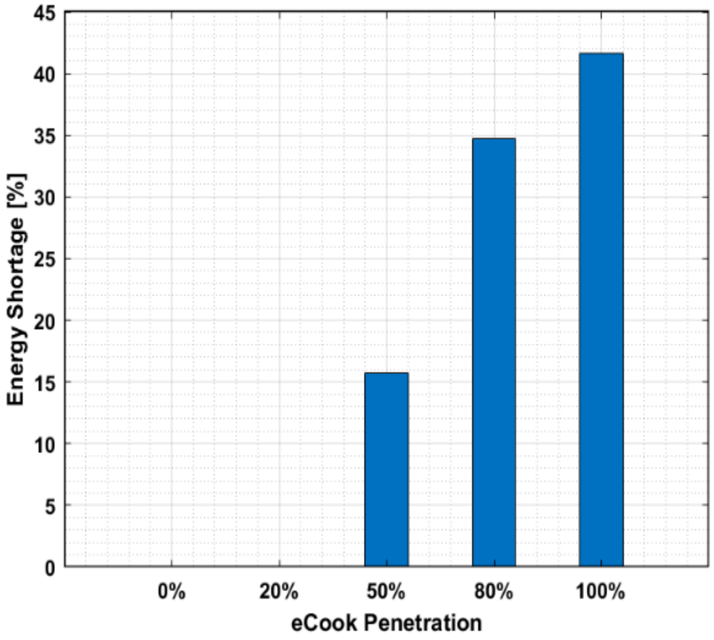

Figure 3-8. Energy shortage.

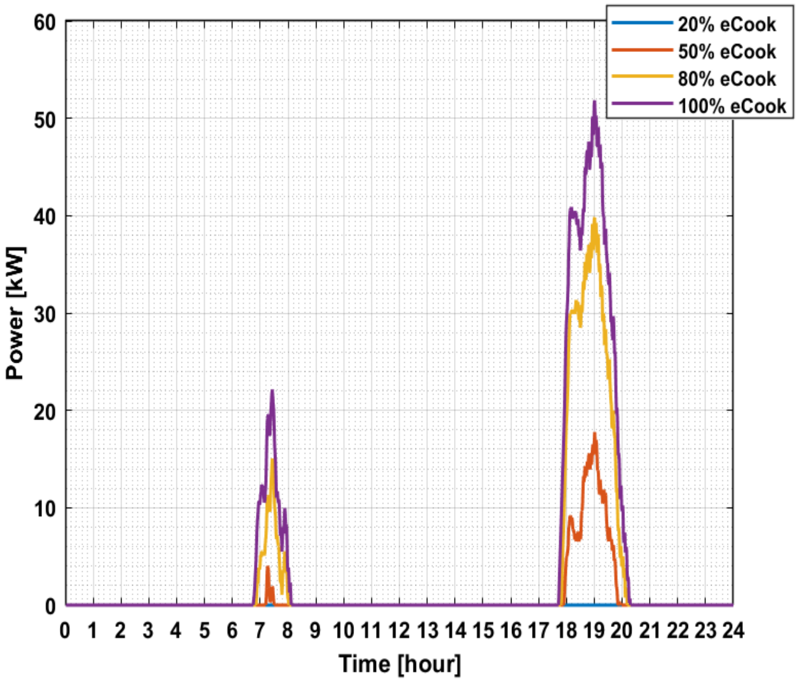

Figure 3-9. The aggregated power was not met.

3.2.2 Use Case 2 (Significant Diesel Generation Capacity)

To ensure all demand is met as more eCook loads are connected, in this Use Case, the 9 kW diesel generator was replaced with a 110 kW generator. This was executed to determine how “fit for purpose” the mini-grid was in terms of the network cable size to accommodate increasing eCook demand. The remaining network parameters are the same as specified in Use Case 1. The purpose of this analysis is to demonstrate a possible voltage drop and VUF that may appear when connecting different eCook penetrations. Throughout this study, the maximum voltage drop and VUF allowed are 5% and 2%, respectively. These follow international normalities and are in line with referenced documents [82], [89], [90], [96] of mini-grid design as well as national grid standards to mitigate any technical and investment risks when the main grid arrives.

3.2.2.1 Voltage Fluctuation

Figure 3-10 and Figure 3-11 show the 24-h voltage fluctuation before and after connecting 100% eCook load at busbar_1, respectively, which is located approximately 0.8 km from the substation (the far end in the distribution feeder) where a high voltage drop will be seen (Figure 3-6). The maximum voltage drop is around 0.9982 pu with the base-load (seen at phase C), and 0.9406 pu when connecting 100% eCook (seen at A and C), which exceeds the 5% allowed voltage drop limit considered in this case study. It is evident that as the eCook demand increases the performance of the mini-grid is affected by the introduction of these new and increased demand peaks for the system to accommodate.

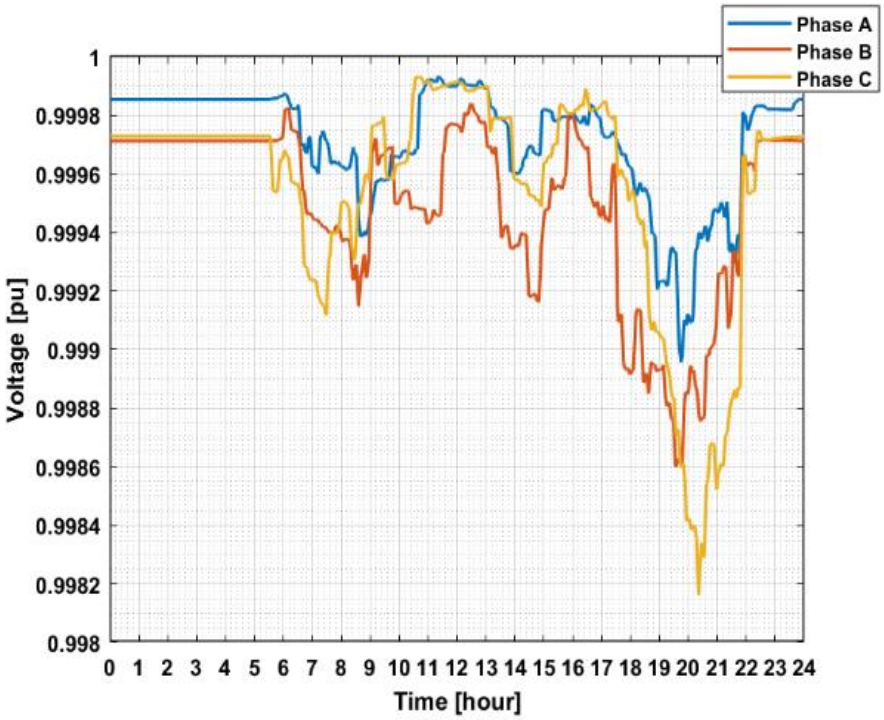

Figure 3-10. The three-phase voltage pattern at busbar_1 before adding 100% eCook.

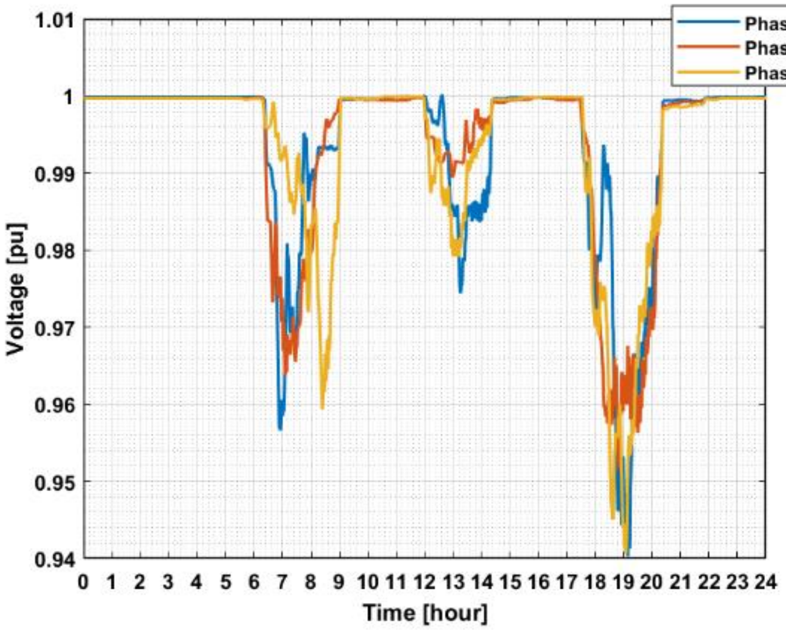

Figure 3-11. The Three-phase voltage pattern at busbar_1 after adding 100% eCook.

In Figure 3-10 and Figure 3-11 the mini-grid three-phase voltage is slightly unbalanced. To analyse the voltage level at the load busbars, the symmetrical voltage components are calculated by taking the unbalanced three-phase system values and converting them into three balanced, three-phase systems [97]. Once the solutions are determined, the maximum voltage drop at the positive sequence is recorded in Table 3-4 when connecting various penetration levels of eCook.

Table 3-4. Maximum voltage drops for different eCook penetrations.

eCook Scenarios	Maximum Voltage Drop [%]			
	Positive voltage sequence	Phase A	Phase B	Phase C
0%	0.13	0.11	0.151	0.194
20%	3.37	4.225	3.321	4.483
50%	4.22	5.362	3.851	4.914
80%	5.05	6.146	4.707	5.624
100%	5.33	6.605	4.884	5.978

From the simulation results for different eCook penetrations, the positive sequence voltage fluctuates within 5% for both 0%, 20% and 50% eCook, which is still within the allowed range. However, as the level of eCook increases, the voltage drop starts to exceed the 5% threshold and as expected this happens during peak time, although the voltage drop at the positive sequence voltage and each of the three-phase voltages (A, B and C) remains within 5% to 10% [89], [98] nominal line-to-neutral voltage limit specified for low voltage networks. For a three-phase mini-grid, the 50 mm^2 distribution and 16 mm^2 service lines are enough to provide adequate power quality at the load level, yet there could be an issue with future demand growth.

3.2.2.2 Voltage Unbalance Factor

Maintaining the power quality at a mini-grid level is a major concern due to the use of non-linear devices from residential users and the increase in eCook penetration. In this chapter, voltage unbalance is quantified and analysed, since it is one of the main power quality issues at the distribution level. For a three-phase system, the VUF is calculated using [50]:

$$\mathbf{VUF} = \frac{|\boldsymbol{V_n}|}{|\boldsymbol{V_p}|}, \tag{3-1}$$

where V_n and V_p are the negative and positive sequences, respectively [46].

The maximum VUF the network experiences for the different eCook penetrations are shown in Table 3-5. The findings reveal that adding eCook load causes the VUF to dramatically increase compared to the 0% eCook level, though, remaining within the allowed limit of 1% to 2% [46], [99].

Table 3-5. Maximum voltage unbalance factor [%] for different eCook scenarios.

eCook Scenarios	Maximum Voltage Unbalance Factor [%]
0%	0.035
20%	1.192
50%	1.119
80%	1.201
100%	1.222

3.2.2.3 System Losses

Power losses in the mini-grid are directly proportional to the mini-grid demand profile. At low eCook levels, most of the feeder lines are not susceptible to large line losses. However, as demand increases, this results in a rise in power losses which directly contributes to a voltage decrease for the consumer. As shown in Figure 3-12, there are no significant effects of power losses for the feeder system in off-peak hours.

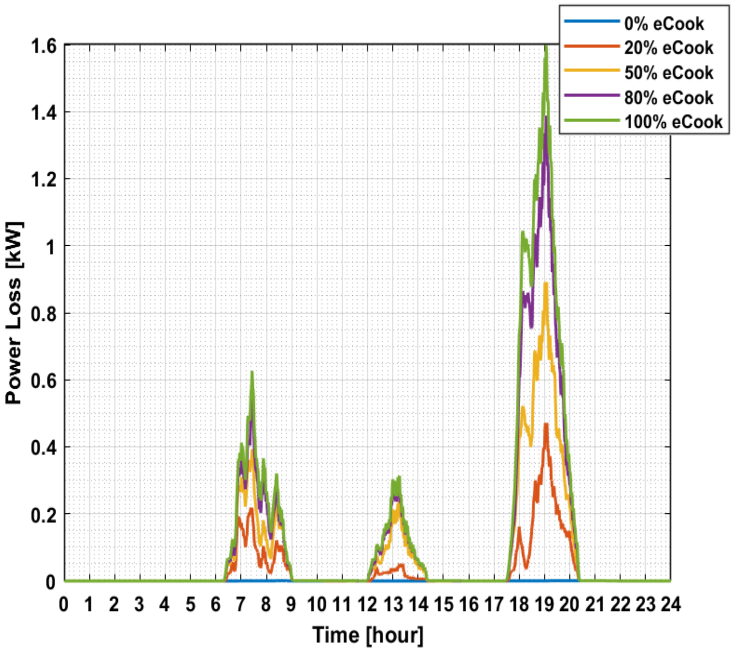

Figure 3-12. System power loss for Case two for different eCook penetrations.

3.3 Discussion and Recommendation

The results of Use Case 2 'Significant Diesel Generation Capacity' show that mini-grids characterised with 50 mm^2 and 16 mm^2 CSA distribution and service cables, respectively, adequately support high levels of eCook penetrations (maximum of 108 HHs) without causing any serious network constraint issues that would require network reinforcement. This will be the case for mini-grid developers such as PowerGen which is a leading renewable energy and mini-gid developer across Africa [100], where systems are characterised by an ABC (Aerial Bundle Cable) cable of 50 mm^2 and single-phase 16 mm^2 ABC. These are the same as those specified for the LV network [82] as they are provided with a connection subsidy. However, some mini-grid developers who do not benefit from this grant are restricted to using small CSA cables, enough to support the base-load and reduce the system's cost, This type of mini-grids will restrict the connection of high appliances such as eCooks. Numerous other ways could be used to improve the voltage regulation at the distribution level such as increasing the voltage level at the generator, reactive power support devices, and fast load shedding. However, applying these methods to a mini-grid with high eCook penetrations may not be effective as the second main concern limiting eCook deployment constitute the limited generation capacity required to supply the additional eCook load. This is why there is a need to explore the concept of network demand management and ‘smart’ eCook management (this will be the subject of chapter5) to maximise eCook utilisation and make use of any PV surplus daily energy generation.

Extrapolating this further in the future, it should be observed that the network study findings do not consider two important scenarios; the base-load demand growth (new customer and appliance connection) and the diversity of eCook due to the lack of information in the literature. This could be a constraint to the system, so, it is important to determine the tipping point for this transition to be possible. It is therefore recommended to:

- Compare different mini-grid categories in terms of capacity and cable sizes to investigate network constraints and the maximum eCook penetration a system can accommodate without any further reinforcement. Additionally, it is unrealistic to assume that a large percentage of HHs would convert to eCook at the same time or cook all the food only with electricity—fuel-stacking where HHs use a combination of different clean fuels (such as LPG with eCook) for different forms and stages of cooking, maybe a more viable transitional scenario, that future work will consider (following the methodology presented in this chapter). Access to electric cooking at this level in mini-grids remains a daunting task for many low-medium-income HHs in developing countries due to the energy resources available for cooking, cooking preferences, economic development, lifestyles, cultural behaviour and traditions, housing structures, together with, limitations on existing infrastructure, and crucially, still to be developed infrastructure such as rural mini-grids.
- Evaluate the eCook ownership rate at a mini-grid level, along the time horizon, which will be relevant to mini-grid developers and utilities, providing them with valuable statistics to enable more accurate decision-

making affecting mini-grid design, reinforcement, business models and long-term planning to accommodate eCook demand as it grows.

- Solve the barriers concerning the uptake of eCook such as the affordability of electricity, lack of supply and social acceptability, as well as the capital costs of network infrastructure.

3.4 Conclusion

The simulations and analysis focused on determining daily capacity shortage, voltage drop, voltage unbalance and power losses for various eCook penetrations. The results from Use Case 1 shows that a mini-grid with 30 kWp PV, 9 kW diesel generator, 41.4 kWh lithium-ion battery, 8 kW battery converter and 10 kW PV-inverter can accommodate around 20% eCook, and as the eCook penetration increases, demand cannot be met, leading to an energy shortage which equates to approximately 42% for 100% eCook penetration. However, the findings from Use Case 2 signify that mini-grids designed with oversized distribution and service cables such as in the case of this research (using 50 mm^2 and 16 mm^2 CSA distribution and service cables, respectively), both the voltage drop and the VUF remain within the thresholds. Hence, the main barriers constitute the limited generation capacity required to supply the additional eCook load, and the high COE.

The proposed methodology in this chapter is also used in chapter 4 to conduct the tecno-economic case studies, which will also be a useful tool for mini-grid developers in their planning for the deploying of eCook-based mini-grids for rural communities. The results are further analysed and discussed to highlight the main barriers preventing direct eCook deployment on rural mini-grids and present suggestions for future work that addresses new design specifications for the next generation of eCook mini-grids.

4 ASSESSING THE TECHNO-ECONOMIC FEASIBILITY OF ECOOK DEPLOYMENT ON THE HYBRID PV/DIESEL MINI-GRID

From chapter 3, the main issue prohibiting higher penetrations of eCook centres on generation capacity requirements, which led to a techno-economic analysis [79] being conducted in this chapter to assess future mini-grid sizes as well as targeting economic and environmental objectives and to meet the overall demand on a generically representative mini-grid in a rural region in East Africa.

This chapter is organised as follows, section 4.1 conducts a techno-economic analysis to identify the optimal sizing of eCook mini-grids for feasible eCook deployment in terms of size and cost for different eCook penetrations as well as cable sizing for both the distribution and service cables. Section 4.2 presents a brief discussion of the findings and recommendations for the next generation of eCook mini-grids. Finally, section 4.3 is the conclusion.

4.1 Mini-Grid Techno-Economic Analysis

In this section, the mini-grid component ratings and cable sizes required to upgrade the systems to accommodate different levels of eCook scenarios were calculated, as a means of demonstrating the future mini-grid design requirements; as well as conducting a techno-economic analysis to analyse the impact of eCook load penetrations on the COE and NPC.

4.1.1 System Sizing and Cost of Energy

For future mini-grid planning and design, a techno-economic analysis was conducted using HOMER-Pro to determine the optimal mini-grid sizes to accommodate each of the eCook penetration scenarios under consideration, with Tanzania taken as the mini-grid location. It should be recognised that the diesel fuel price fluctuation was not considered in the analysis as there is insufficient data presented in the literature, since it is difficult to accurately forecast the events in world fuel prices. Additionally, it is hard to predict, how individual countries will react to fuel prices, in the future, by either imposing duties or granting subsidies on diesel for their domestic market.

The input data used comprises the initial capital cost and replacement cost of each of the mini-grid components (see Table 4-1); the fuel price of $ 0.8/L, which represents the price of diesel for the year 2016 in Tanzania [101] and the lifetime of the project is taken as 20 years. To calculate the PV output power, HOMER uses the mini-grid location to import the solar resources data from the NASA surface metrology and Solar Energy.

Table 4-1. Mini-grid component cost data [102], [103].

Component	Initial Capital Cost	Replacement Cost	Lifetime
PV array size	406.25 $/kWp	406.25 $/kWp	25 years
Diesel generator	500 $/kW	500 $/kW	15,000 hours
Lithium-ion battery	555 $/kWh	555 $/kWh	10 years
Converter	446.75 $/kW	446.75 $/kW	10 years
PV-inverter	286 $/kW	286 $/kW	15 years

The inflation rate and the nominal discount rate fluctuate and can vary from one country to another, so in this research to evaluate the NPC and the COE, the inflation rate and the nominal discount rate used are 6% and 10% respectively which are considered standard figures for business planning [102]. The annual fixed operation and maintenance (O and M) cost accounted for 2% of distribution capital expenditures (CAPEX) [104].

The proposed optimal mini-grid sizes for the eCook penetration scenarios are presented in Figure 4-1, where the PV array is sized based on the energy consumption profile, and location, as well as ensuring there is sufficient energy to fully charge the battery during the day, under all conditions, and to meet the evening demand, as the mini-grid operates with the LF energy dispatch strategy. This means, that the battery will be charged with the surplus generated from the PV, and when required the diesel generator is activated to provide enough power to meet the load.

Another aspect to consider is that, when sizing a mini-grid, it is important to have a high renewable contribution to supply the demand as the diesel generator is more cost-effective when operating as a backup, rather than using it as a base-load generator [105]. Even though the initial capital cost of the diesel generator is low, the diesel generator has an ongoing operating fuel cost. In addition, fuel availability cannot be assured as most of the mini-grids in developing countries are located in rural areas where the supply chain of diesel can be temperamental and fuel prices volatile. When more renewable energy is available the COE and NPC are reduced since the marginal cost of generation is zero, and with smaller amounts of diesel used, this also leads to less CO_2 emissions.

The PV-inverter is typically sized to meet the full load under all conditions, in some min-grids the inverter will be under-sized relative to the PV array size which means that the maximum power output of your system (in kW) will be dictated by the size of the inverter [106] although, results in lost energy production during peak production hours. Regardless of the output of the solar panels, the power output will be clipped by the inverter, so that it does not exceed the inverter’s rated capacity. Under-sizing the PV-inverter has a number of advantages: reducing inverter cost and make better of the inverter’s AC output. On the other hand, the PV-inverter could also be over-sized by taking a 1.2 ratio or 80% inverter (AC) to 100% solar panels (DC) [107]. In this case, there will be an energy production (kWh) gain during peak hours which can be used to charge the battery. The main disadvantage is the increase in the relative cost of the PV-inverter leading to an increase in the total system cost.

The results in Figure 4-1 present the solution with the lowest cost to serve the load under the model’s conditions. It is evident that the PV array does not require an inverter of approximately the same capacity, although, this leads to a larger PV size which requires a larger installation area. To reduce the PV size, the HOMER models were simulated again to calculate the optimal mini-grid sizes when fixing the ratio of DC capacity (solar panel DC power rating) to the inverter’s AC power rating (DC/AC ratio) to 1.2 [108]. The results are shown in Figure 4-2.

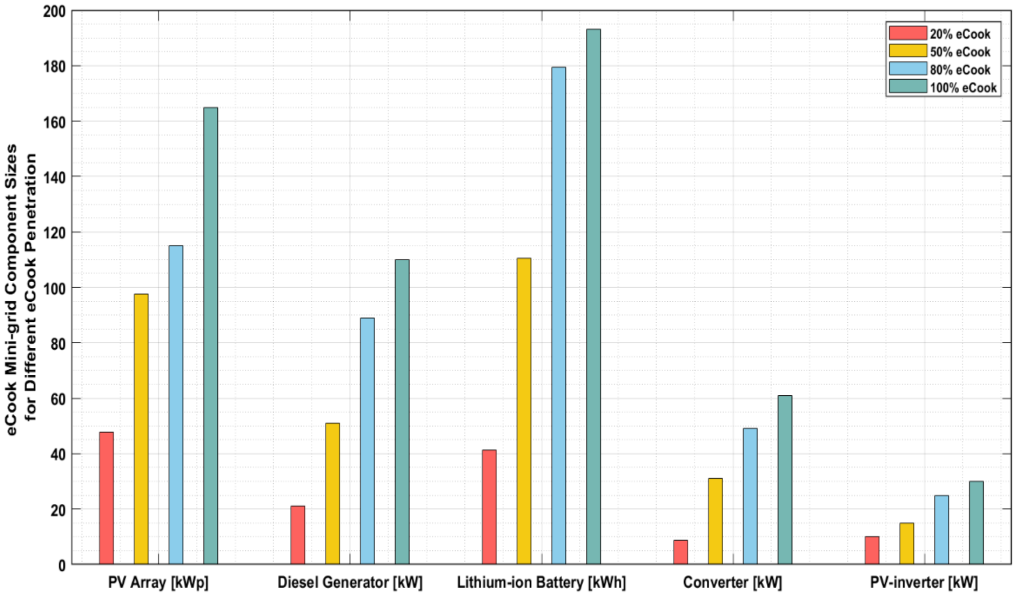

Figure 4-1. Component sizes for eCook mini-grid deployment scenarios (without considering 1.2 DC/AC ratio).

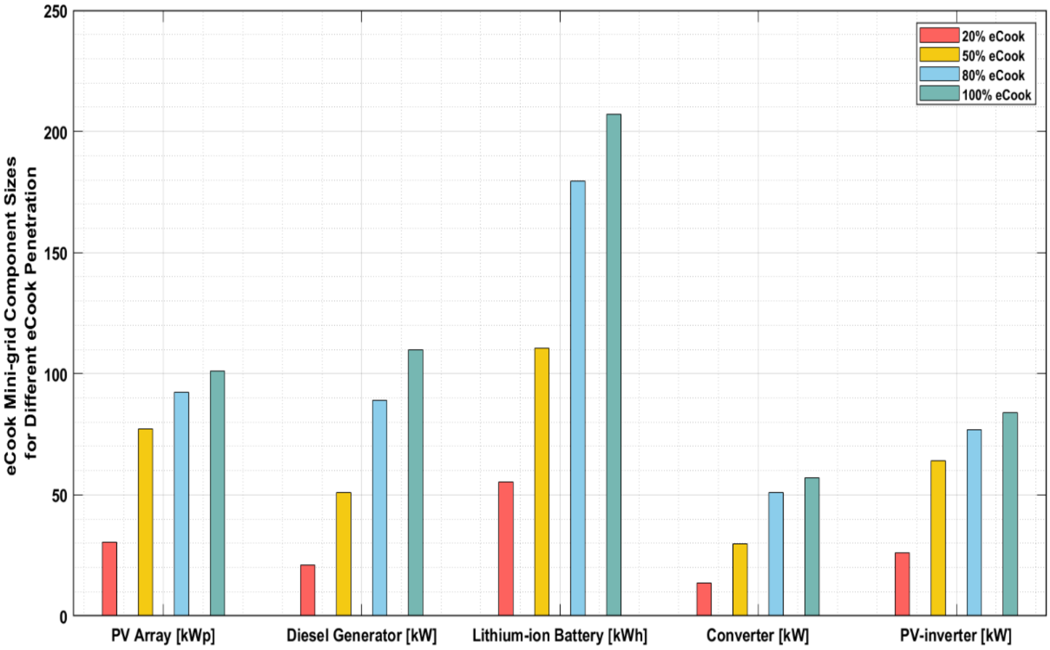

Figure 4-2. Component sizes for eCook mini-grid deployment scenarios (when considering 1.2 DC/AC ratio).

4.1.2 Conductor Sizing

To calculate the optimal cable sizes needed for the distribution and service cables, it was important to establish the expected load and peak time of the mini-grid, as well as understand its characteristics [109]. All the calculations were carried out in MATLAB by applying directly the following equations, for a single-phase line, the CSA can be calculated using:

$$\mathbf{A_{min}} = \frac{\mathbf{I_T} \times \boldsymbol{\rho}_{\mathbf{ambient}} \times \mathbf{L}}{\mathbf{V_{sys}} \times \frac{\mathbf{V_{d\%}}}{\mathbf{100}}} \times \mathbf{10^{-6}}, \qquad \textbf{(4-1)}$$

where A_{min} is the CSA in (mm^2), $\boldsymbol{\rho}_{\mathbf{ambient}}$ is the resistivity of the material in ohm-m (W-m) at ambient temperature, I_T, is the total current flowing in the cable with a maximum length of L in m, V_{sys}, is the system phase to neutral voltage in Volts and $V_{d\%}$, is the acceptable voltage drop in %.

The resistivity of a material is dependent on temperature and this is calculated using [110]:

$$\boldsymbol{\rho}_{\mathbf{ambient}} = \boldsymbol{\rho}_{\mathbf{ref}} \left(\mathbf{1} + \left((\mathbf{T_{ambient}} - \mathbf{T_{ref}}) \times \boldsymbol{\alpha}\right)\right), \qquad \textbf{(4-2)}$$

Where $\rho_{ambient}$ is the resistivity of the material in ohm-m (Ω-m) at ambient temperature, ρ_{ref} is the resistivity at the reference temperature T_{ref}, α is the temperature coefficient of resistance for conductor material, $T_{ambient}$ is the ambient temperature. The values used in (4-2) are shown in Table 4-2.

Table 4-2. Parameter for conductor sizing.

Parameters	Value
ρ_{ref} [Ω-m]	2.65 10^{-8}
T_{ref} [degree C]	20
$T_{ambient}$ [degree C]	30
α	0.00429
ρ_{ref} [Ω-m]	2.65 10^{-8}

In any typical mini-grid, consumers are located at irregular intervals along the distribution line rather than being uniformly distributed. To calculate the CSA of both the distribution and service lines, the product of power demand and the distance from the supply for each consumer must first be calculated, and then the product for all "M" consumers can be summed. Furthermore, the mini-grid distribution circuit model can be simplified to a three-phase “wye” connection configuration, while the service lines are single-phase two-wire, illustrated in (4-3) and (4-4):

For distribution lines (wye connection)

$$\mathbf{A_{min}} = \boldsymbol{\rho}_{\mathbf{ambient}} \times \frac{\sum_{n=1}^{M} \mathrm{L_n(m)} \times \mathrm{P_n(W)}}{3 \times \mathrm{V_{sys}}^2 \times \cos\theta \times \frac{\mathrm{V_{d\%}}}{100}} \times \mathbf{10^{-6}}, \tag{4-3}$$

For service lines (single-phase, two-wire line)

$$\mathbf{A_{min}} = \mathbf{2} \times \boldsymbol{\rho}_{\mathbf{ambient}} \times \frac{\sum_{n=1}^{M} \mathrm{L_n(m)} \times \mathrm{P_n(W)}}{\mathrm{V_{sys}}^2 \times \cos\theta \times \frac{\mathrm{V_{d\%}}}{100}} \times \mathbf{10^{-6}}, \tag{4-4}$$

The optimal CSA for both the distribution and service conductors required for a typical mini-grid characterised by each of the eCook penetration scenarios and taking 5% as the voltage drop threshold was determined from (4-3) and (4-4). The results are recorded in Table 4-3.

Table 4-3. Distribution/Service CSA cables for eCook mini-grid penetration scenarios.

eCook Scenarios	Calculated CSA [mm^2]		Available CSA [mm^2]	
	Distribution	Service	Distribution	Service
20%	43.51	12.74	50	16
50%	68.23	26.83	70	35
80%	84.39	43.94	95	50
100%	89.24	53.38	95	70

4.1.3 Cost of Energy

In [102], simulation studies were conducted in HOMER to assess the techno-economic feasibility of different levels of eCook penetration and deployment in mini-grids. The results reveal that in the case of accommodating a certain percentage of eCook load, there is a need for a larger mini-grid capacity size to meet the demand, although show a continuous decrease in the COE due to the increase in the annual total electric load served (Eserved). This demonstrates that as more energy (kWh) is used, the upfront cost is divided between the many users. However, the system’s costs were calculated assuming that the distribution network is strong enough to support extra loads without the need to upgrade it in terms of cables. Hence, no additional upfront cost was included. When planning the construction of an eCook mini-grid there is a necessity to study the impact of additional cable costs. In this section, an economic analysis is conducted in HOMER to investigate the mini-grid cost for the eCook scenarios when:

- Use Case-a: Reinforcing the mini-grid only in terms of the generation and storage capacity while the distribution upfront cost is fixed throughout the analysis, using the component sizes obtained from Figure 4-1.
- Use Case-b: The same as specified in Use Case-a however, the cost analysis is carried out when taking the component sizes in Figure 4-2.
- Use Case-c: Refers to the cost of the system when upgrading both the cables, the generation and battery capacity (PV, diesel, battery, converter and PV-inverter) to the sizes in Figure 4-1 and Table 4-3.

The results for each Use Case are provided in Table 4-4. Comparing Use Case-a with Use Case-b; installing a large-sized PV-inverter reduces the PV array size, so less area is needed to install the system. This, however, leads to a slight increase in the COE and the NPC due to the extra cost imposed when replacing the PV-inverter.

The results of Use Case-c validate that the extra cable cost causes an increase in the COE and the NPC due to the increase in the initial capital cost. Directing our analysis to the 100% scenario, the COE and the NPC increase by approximately 16% compared to those of Use Case-a. Another point worth mentioning is that the simulation results of the COE in all three cases are significantly higher than the COE tariff for the domestic customers connected to the national grid in Tanzania, which is approximately \$0.1/kWh [111]. Therefore, there is a need for additional investment and innovative policies to be put into effect to speed up the process, as well as to give a crucial workable timescale. Sustainable Energy For All issued a report providing a comprehensive analysis of commitments to energy access for electrification and clean cooking [112]. The report also highlights the impact of COVID-19 on public budgets and private investments and points out that most of the investments are not being awarded to the countries with the greatest needs and that there is a necessity for greater investment to achieve universal access by 2030.

Table 4-4. Comparison of the economics of the different cases.

	Use Case-a		**Use Case-b**		**Use Case-c**	
eCook Scenarios	COE [$/kWh]	NPC [$]	COE [$/kWh]	NPC [$]	COE [$/kWh]	NPC [$]
20%	0.782	212,746	0.803	218,386	0.782	212,708
50%	0.535	328,138	0.563	345,219	0.617	377,874
80%	0.482	453,611	0.507	477,175	0.552	518,944
100%	0.461	528,427	0.486	557,309	0.535	613,398

4.2 Discussion and Recommendation

Energy Cost Barrier: Mini-grid deployment in developing countries remains significantly expensive in rural communities due to the limited ability or inability to pay, as the up-front capital costs are an important factor in the cost of the system. As illustrated in Table 4-4 (Use Case-a), a mini-grid for a 165 kWp PV, 110 kW diesel generator and 193.2 kWh battery, supplying a 100% eCook demand, the COE is $0.461/kWh. Therefore, for a HH with a cooking energy consumption of between 1.75–2.2 kWh per day, customers would be required to pay approximately $24–30/month, which would account for almost all the HH income, for low-income HHs on a monthly salary of $25–30, and so this is clearly uneconomical and impracticable. It should be observed that the simulations conducted in HOMER do not consider any subsidy which may have a further impact on reducing the COE and lowering tariffs. To encourage the deployment of more mini-grids, the Tanzania Rural Energy Agency provides grants of $300–600 per connection under its results-based financing scheme, equating to a subsidy of $30,000–60,000 for a 100 HH connection mini-grid [91]. However, this scale of subsidy is not enough to reduce the COE to a value close to the existing tariff provided by the national grid, and so:

- Further subsidies and grant support are needed to make it more attractive to the developer as well as to the customer.
- A methodology could be developed for eCook-ready mini-grids integrating DSM techniques to promote the uptake of daily productive usage seeking to reduce the COE and boost the utilisation rate of eCook mini-grids. Another benefit is that, on days when there is low production of PV power, the diesel

generator is used more efficiently, at almost maximum power, due to a more stable load profile.

Smoothing out the daily aggregated load profile increases the utilisation rate of mini-grids which correlates highly with the load factor ratio. The load factor [113] reflects how well the energy is used based on daily, monthly, and yearly profiles. It is defined as the ratio of the average load divided by the maximum (or peak) load in a given time period, which can then be used to measure the utilisation rate or the efficiency of electricity usage, where a low load factor indicates the energy usage is low compared to that available, and so much of the generation capacity remains spare; resulting in a high COE. Conversely, a high load factor indicates energy usage is more "efficient" in this respect and subsequently results in lower COE. Improving or increasing the load factor, therefore, requires the average load and peak load to be as near as possible. This can be achieved either by peak shaving to effectively reduce the peak demand or by increasing the average electricity consumption to maximise the use of the power available. In the context of eCook demand, it may be possible to shift some of the demand during peak hours to off-peak hours to achieve an improved load factor and hence lower COE. While there are non-technical and socio-cultural factors to consider when considering this, from a technical perspective there is merit in simulating the use of DSM techniques to enable this, which may involve a move towards using battery-operated eCook to offer a more flexible eCook demand (this will be the subject of chapter5).

4.3 Conclusions

This chapter applies the methodology developed in chapter 3 to simulate the connection of graduated levels of direct eCook penetration to evaluate future design requirements of mini-grids needed to accommodate a transition towards universal uptake of eCook, in line with SDG 7 targets.

It is therefore evident that the eCook mini-grid design should be characterised by a high renewable contribution towards eCook demand, as it is preferable over non-renewable solutions due to the advantage of saving fuel and the reduction in greenhouse gases, NPC and COE. The sizes of such mini-grids for different eCook penetrations are reported in Figure 4-1 and Figure 4-2 although, there is still a need to reduce the energy cost further to make it more attractive to the consumer. As illustrated in this research, for a 100% eCook penetration with a system size of 165 kWp PV, 110 kW diesel generator and 193.2

kWh battery, the consumer would be required to pay approximately $24–30/month which is not feasible due to a low income. However, different methods could be incorporated such as fuel stacking, boosting the utilisation rate and integrating smart DSM techniques making it more cost attractive. DSM strategies and technologies are already being used in mini-grids to manage the operation of the system, although, there remains a need for more innovative and sophisticated techniques to accommodate large power appliances such as eCooks, while minimising capacity upgrades and network reinforcements. The main takeaway from the literature review on DSM in chapter 2 (section 2.6), is that battery-operated eCook with an innovative charging management concept (which is the topic of the next chapter) would maximise the utilisation of electricity from the daily PV power and offset peak demand to a different time, by charging the batteries during off-peak hours to provide flexibility of demand. The prospect of a more rigorous and systematic payment scheme is also necessary as well as the need for Governmental support, tailored policies, and regulatory frameworks to be put in place.

5 DEVELOPMENT OF A SMART BATTERY CHARGING STRATEGY TO MAXIMISE PV/DIESEL HYBRID MINI-GRID ECOOK CAPACITY

In this chapter a methodology has been developed to assess PV/Diesel/Hybrid mini-grids when adopting battery-operated eCook instead of direct eCook, this led to modelling a novel smart battery charging strategy to maximise mini-grid eCook capacity [114], which offers a practical DSM solution for the accommodation of increasing eCook demand.

Here the batteries are considered to be synonymous with eCook appliances, such as EPC, induction cookers, hotplates or rice cookers, that can be connected to and supplied from a battery, which may or may not be fully integrated within the device. Connecting many battery-operated eCook can have an impact on the operation of a hybrid PV/diesel mini-grid network; however, they also offer some flexibility in the demand that could potentially be used to accommodate increased eCook capacity if managed appropriately. Without appropriate management and control of these devices, the network could experience voltage fluctuations, system power losses and increased peak demand if all or most of the connected battery-operated eCook charge during a relatively “narrow” window of sunlight hours. However, this chapter focuses on maximising the number of eCook devices accommodated by the mini-grid, in keeping with increased consumer uptake, by regulating the charging rate (C-rate) of the battery-operated eCooks themselves. The impact of varying the C-rate on the network constraints is assessed through a range of contextualised case studies. This entailed modelling an innovative smart eCook battery management system (‘smart’ EBMS) that actively monitors the state of the grid and decides on the battery-operated eCook ’s C-rate set-point required to address the network constraints. The results demonstrate that the ‘smart’ EBMS can alleviate the impact of conventional battery-operated eCook charging on the mini-grid network, as well as increase the quality of the charging service (QoS).

5.1 Introduction

The research work in chapter 3 shaped a methodology that could be used by mini-grid developers to assess the design readiness and future design requirements to enable users without supported batteries. The results support the argument that there is merit in simulating the potential role and impact of DSM in maximising eCook while minimising the upgrading of generation capacity. DSM strategies and different technologies are already being implemented in mini-grids to manage their operation, accommodate more demand as customer behaviour and energy requirements change, as well as to deal with new customer connections, enabling more efficient use of power systems [115]. However, there remains a need for more innovative and scalable techniques to facilitate the uptake of large power appliances such as eCook, while minimising the need for capacity upgrades and network reinforcements.

The battery-operated eCooks represent a “flexible load” that can be used to maximise the utilisation of electricity from the daily PV power and offset peak demand at different times of day, by charging the battery-operated eCooks during off-peak hours to balance both generation and demand. The main contribution of this chapter is to provide an initial scoping study of both the challenges and opportunities when adopting battery-operated eCooks, as well as developing an innovative smart eCook battery management system to maximise eCook demand within the network constraints. The remainder of this chapter is organised as follows. Section 5.2 outlines the battery-operated eCook charging methods. Section 5.3 presents the hybrid PV/diesel mini-grid network model that forms the basis for both the simulation and the studies conducted in this chapter. Section 5.4 highlights the technical limitations constraining the wide-scale deployment of battery-operated eCooks. The proposed smart eCook battery charge management system approach and the simulation results are presented in section 5.5. Section 5.6 evaluates the quality of charging service provided to HHs via battery-operated eCooks. Section 5.7 provides a summary of the conclusions.

5.2 Battery-operated eCook Charging Methods

The choice of method for battery charging depends mainly on the type of battery and its application. Typical methods can be mainly classified into constant voltage (CV), constant current (CC), and a combination of CC-CV [116]–[118]. The first is frequently used with lead-acid batteries, as the method adopts a predefined constant voltage, varying the charging current throughout the charging process until the current drops to almost zero. In contrast, the CC charging mode is widely used for nickel-metal hydrate batteries and nickel-cadmium batteries, as well as lithium-ion batteries, where a constant current is supplied by varying the charging voltage. In the case of CC, at the start of the charging process, the battery system utilises much higher power until the battery voltage reaches a pre-set voltage. If this high power is not managed well by the charge controller, the battery will overcharge. This may cause gassing and overheating issues, leading to system damage and a decrease in the battery life cycle, due to a higher rate of current injection under lower charging conditions. However, drawing excessive power can be avoided with the CV charging method. Hence, it is more efficient to use the CC-CV in the application of lithium-ion batteries as it improves the performance and life of the battery, limits the charging current and voltage-protecting from over-voltage and over-current, controls the injected power, and reduces thermal stress, as well as enabling rapid charging. The lithium-ion battery is charged in two main stages: in the CC mode, a constant current is applied by the battery controller until it achieves 70–80% of its SoC and the battery's cell voltage reaches a certain voltage level. This is followed by the CV charging mode, where the current level is reduced until it reaches zero while maintaining a constant voltage level. This protects the battery from damage due to overcharging.

Since the generic storage model available in OpenDSS is unable to handle the CV charging mode, only CC charging is considered in this study. MATLAB has been used to develop the CC functionality (more detail on this can be found in section 5.3.2). This is considered sufficient to understand the charging/discharging behaviour of the eCook batteries, the technical impact on the grid, and the advantages of using this control strategy.

Furthermore, the behaviours of batteries are highly dependent on the C-rate. The C-rate can be defined as the measure of the rate at which a battery is charged/discharged, relative to its maximum capacity—the shorter the charge/discharge time, the higher the current required [119]. When using a high C-rate, the charging speed is improved, although it accelerates degradation and causes more rapid deterioration of both the capacity and the power capability of the battery. More importantly, this could result in negative impacts on the distribution network (voltage fluctuation and new system load peaks). In the case of a lower C-rate in battery charging, high-capacity utilisation is achieved with fewer negative effects on power network performance. However, if the C-rate is too low, this will slow down the battery-charging speed. Hence, the main challenge is to select a suitable C-rate that can equilibrate the battery charging speed and capacity utilisation, without violating network constraints. For lithium-ion batteries, a charge of 0.8 C or less is recommended to prolong battery life [120], however, this will depend on the manufacturer and the application (for example, Mastervolt recommends a maximum of 0.3 C [121]). This chapter, therefore, analyses the effect of five different C-rate values on the performance of the mini-grid network.

From the authors' point of view, the main questions for consideration when connecting eCook batteries to the mini-grid network are:

- What are the technical network constraints that can occur when deploying battery-operated eCooks?
- What is the most suitable battery-operated eCook C-rate capable of maintaining the network constraints within the thresholds, during the charging window?
- What are the alternatives and solutions to enable uptake and maximise the number of battery-operated eCooks connected to the network, without violating network constraints?

The remainder of the chapter will focus on addressing these questions by conducting a technical assessment and developing contextualised case studies, to explore the concept of a "smart" eCook management system.

5.3 Mini-Grid Network Modelling with eCook Batteries

5.3.1 Modelled Mini-Grid Network with eCook Batteries

In this chapter the same PV/diesel hybrid mini-grid (Figure 5-1) modelled in chapter 3 (section 3.1.2.3), is used to understand the charging/discharging behaviour of battery-operated eCooks, the technical impact on the grid and their advantages. In chapter 3 the PV-inverter is under-sized relative to the PV array size although adequate to accommodate the network baseload. However, it results in a loss of energy production during peak production hours. Therefore, to explore most of the generated daily PV output power needs and make good use of the excess daily PV energy generated, the 10 kW PV-inverter was replaced with one of 25 kW, and the size of the centralized battery used in the previous study in chapter 3 was reduced from 41.4 kWh to 27.6 kWh. Hence, the mini-grid network studied in this chapter includes a 30 kWP PV, 25 kW PV-inverter, 27.6 kWh centralized battery, and 8 kW converter. In terms of the distribution and service cables being the same, the CSA is set to 50 mm^2 and 16 mm^2, respectively. Through, the test and trial, the surplus mini-grid daily energy was enough to connect 47 battery-operated eCook to the mini-grid, so the batteries were allocated to 47 HHs (43% of total HHs) connected to the mini-grid network (starting with those connected HHs furthest from the power station). As shown in Figure 5-1, the shaded HHs have batteries available to support their cooking.

The daily non-eCook (i.e., baseload) and the eCook load profiles used throughout the simulations are the same as those in chapter 3 (section 3.1.1). These were generated using the CREST [122] demand model by a group of researchers in the MECS team [82].

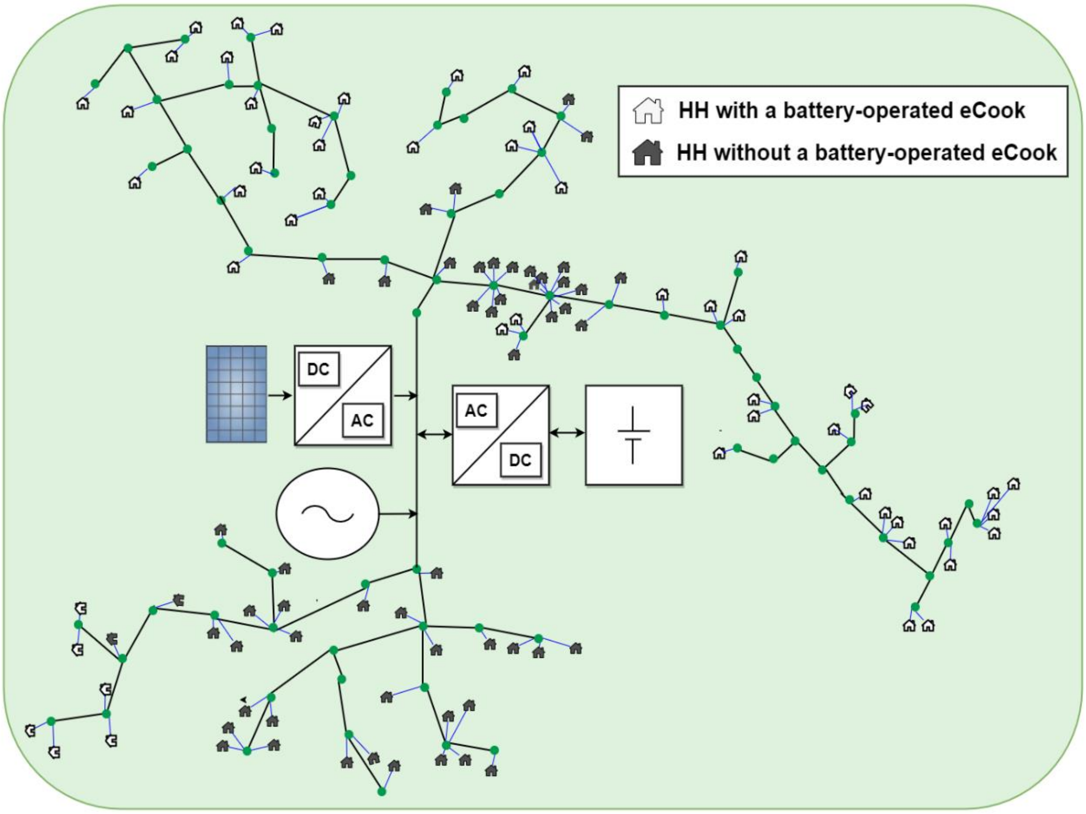

Figure 5-1. OpenDSS hybrid PV/diesel mini-grid layout (the grey-shaded HHs have eCook batteries).

The report by M. Leach and R. Oduro [123] was used as a reference for the steps followed when calculating the battery-operated eCook capacity. The average daily cooking energy consumption (breakfast + dinner) is 1.6 kWh and is based on the characteristics of the lithium-ion battery in Table 5-1; the battery capacity is calculated at 6 kWh. Here, the batteries are sized to meet only the morning and evening cooking demand, while at midday, the PV power generation and the backup diesel generator are used to enable the HHs to cook food (thus limiting the battery-operated eCook size). To improve the battery's performance during its mid-life design, additional factors are considered in the system sizing; these values are highly sensitive to the depth of discharge (DoD), C-rate, and temperature. These factors are the batteries' lifetime ageing and life cycle; also, in the case of a hot climate, where the average temperature is around 33° C, the life cycle of a lithium-ion battery reduces to 20% of its rating under ambient temperature, due to internal chemical reactions. Hence, it is important to limit the DoD to 80% or less to prevent harm to the battery-operated eCooks, prolong their life and minimise charging losses. For these reasons, in this chapter, the minimum and maximum SoC are set at 20% and 80%, respectively [124]. The round-trip efficiency of the battery and the bidirectional converter efficiency were also considered in the calculations.

Table 5-1. Assumption of lithium-ion parameters.

Description	Lithium-ion
Autonomy (days)	≈ 1.5 day
Battery voltage	24 V
Round-trip efficiency	≈90 %
Additional battery capacity for decay over time	10%
Lifetime of the battery	2000 cycles at 100% DoD (depth of discharge)

5.3.2 The Mini-Grid Network Central Controller and Distributed eCook Battery Charge Controller Algorithm

As shown in Figure 5-2, the mini-grid's central controller instructs the generators to control and manage their behaviour, while the battery's charge controller optimally regulates the voltage and current flowing to and from the batteries, preventing them from overcharging and under-discharging. The battery-operated eCook charge controllers are controlled through a centralized controller that allows planning of the battery charging strategy and input charging power. This approach can provide more flexibility in grid load allocation and have a better ability to provide systematically coordinated charging for large-scale battery-operated eCook populations.

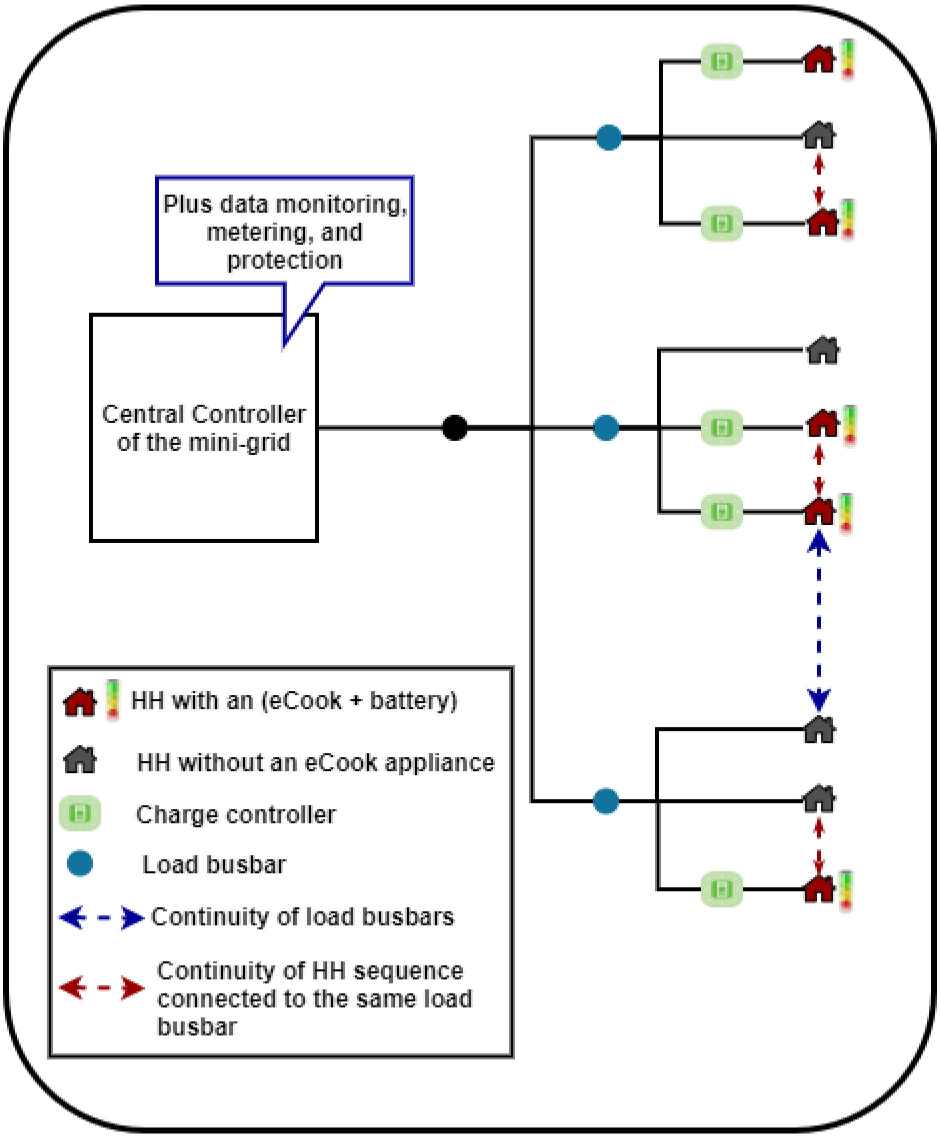

Figure 5-2. A simplified diagram showing the mini-grid components.

Figure 5-3 illustrates the principles of operation for the central controller and the battery-operated eCook charge controller algorithms, which were developed in MATLAB (a more detailed flowchart can be found in Appendix 2). These can be summarised in the following steps:

- Once the PV output power is equal to the aggregated load power (baseload plus midday cooking demand (P2), since midday cooking happens during the PV window generation), the PV array has a higher priority to fulfil the entire demand (Figure 5-3). The second priority is given to the centralized mini-grid battery and the last priority is to the backup diesel generator.

- The excess PV power ($P1_{Surp}$) is used to charge the centralized battery using (5-1) if it is not fully charged, then the new surplus network power ($P2_{Surp}$) is calculated using (5-2), which will be used to charge the battery-operated eCooks.

$$\mathbf{P1_{Surp}(t) = P_{PV}(t) - (P2(t) + P4(t)),} \tag{5-1}$$

- Where P_{PV} is the PV power at time t, P2 is the aggregated cooking demand at midday and P4 is the aggregated base-load.

$$\mathbf{P2_{Surp}(t)} = \begin{cases} \mathbf{P1_{Surp}(t) - P_{B\_cen}(t),} & \textbf{when} \quad \mathbf{min\ SoC_B \leq SoC_B(t) \leq max\ SoC_B} \\ \mathbf{P1_{Surp}(t),} & \textbf{when} \quad \mathbf{SoC_B(t) = max\ SoC_B} \end{cases} \tag{5-2}$$

- Where P_{B_cen} is the charging power of the centralized battery at time t, min SoC_B and max SoC_B are the minimum and maximum SoC of the centralized battery respectively, while SoC_B (t) is the battery's SoC at time t.

- The battery-operated eCooks are charged by a so-called uncontrolled charging method where the centralized controller determines which battery is charged. At this stage, the only control that is assumed to be available is the ability (at any given time) to charge the batteries safely, avoiding under or over-charging using a conventional charge controller when there is a surplus generation of power from the PV. Limited power also implies that only a limited number of battery-operated eCooks can charge simultaneously. The logical flow for charging battery-operated eCooks is, first, to find the number of batteries (N) that could be charged, depending on the available surplus PV power. In the case where there is enough power to charge one or more batteries, the charging takes place, starting with those HHs with the lowest SoC levels. If there is no excess power, the battery-operated eCooks are put into idling mode.

- A minimum SoC is required before the power discharging takes place. The battery-operated eCooks at each HH level start to discharge to meet the early morning (P1) and evening (P3) cooking demands. When the batteries are in discharging mode, they follow the HH demand curve. In this case, the discharging current is limited to the maximum current rating of the inverter.

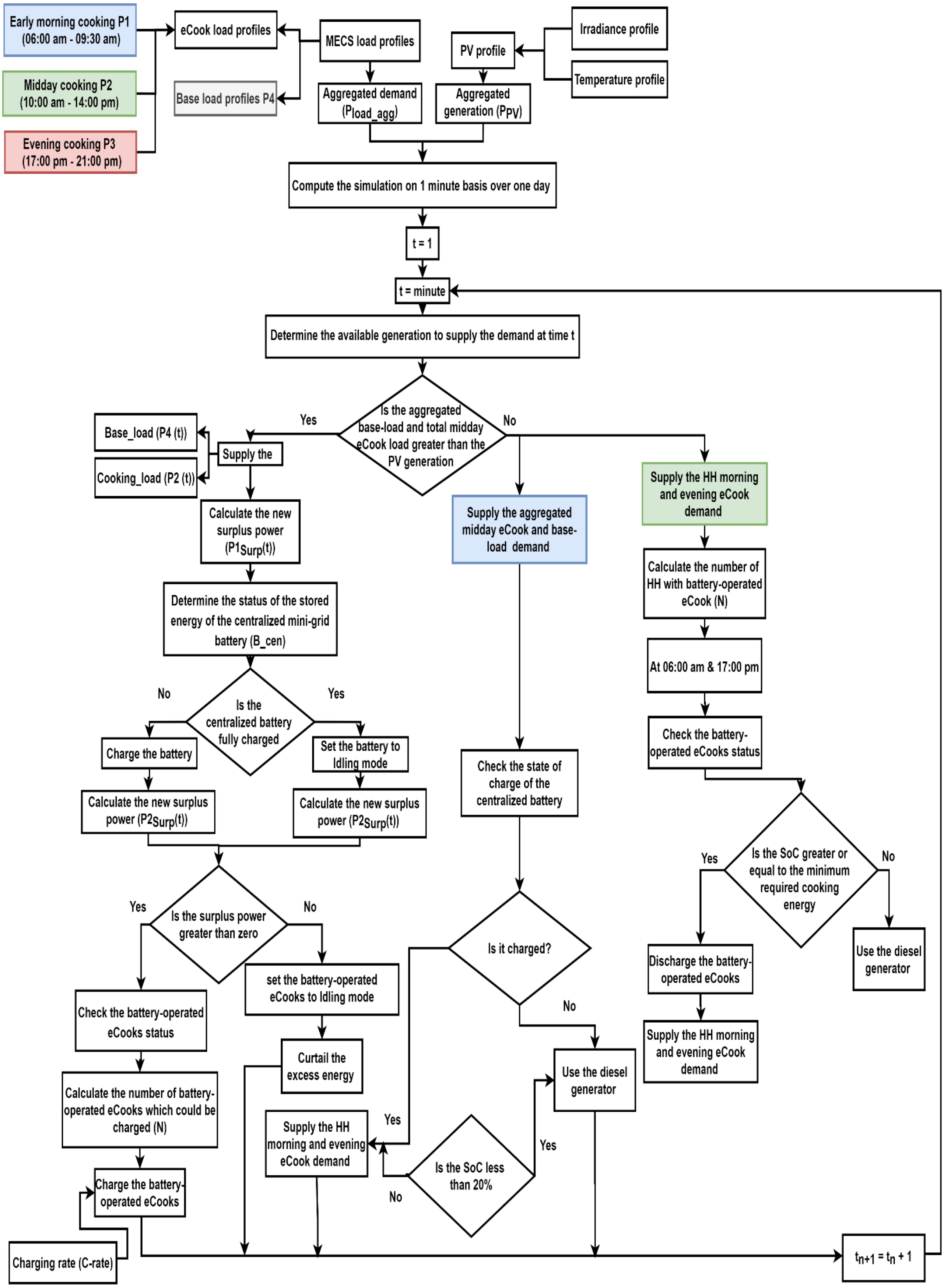

Figure 5-3. The mini-grid central controller and the battery-operated eCook charge controller algorithm.

- If the SoC of the battery-operated eCook is not sufficient to cook breakfast or dinner, the backup diesel generator is brought online to meet the cooking netload.

5.4 Developed Scenarios and Simulation Studies Assessing the Impact of Different C-Rates on Network Constraints

This study assesses the impact of varying the C-rate on the network constraints (Figure 5-4) as key controllable parameters when charging the battery-operated eCooks. The findings of this study are beneficial in moving forward toward developing a smart eCook battery charge management system, to prevent significant network reinforcements or upgrades.

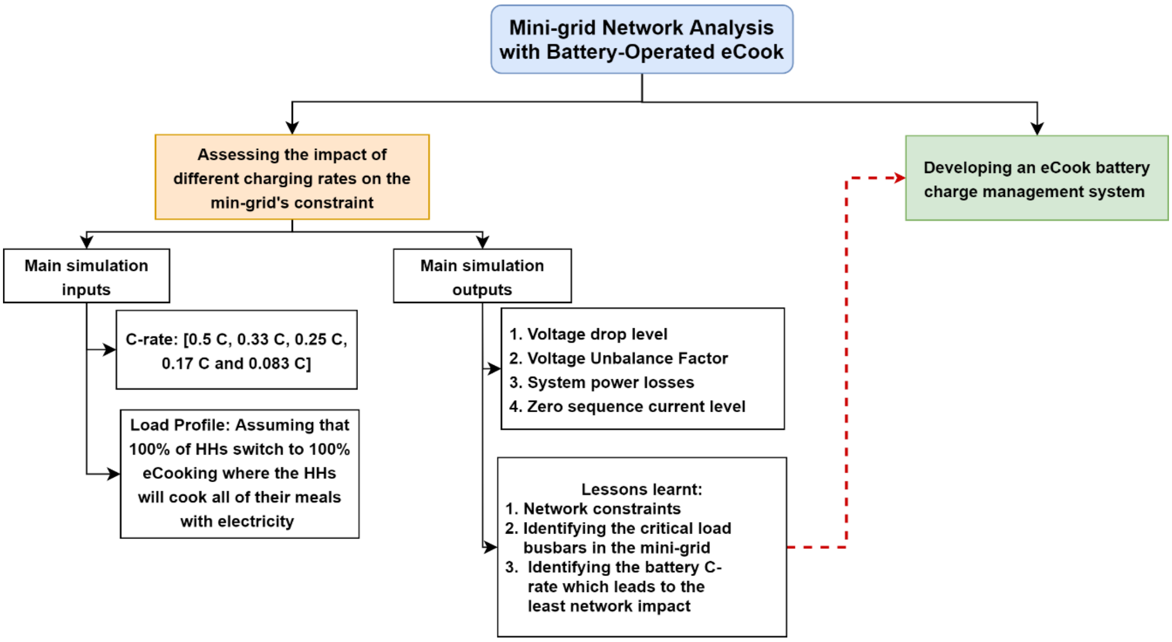

Figure 5-4. Assessing the C-rate impact on network constraints.

The study investigates the impact of different battery-operated eCook C-rates on the performance of the distribution network. As mentioned in section 5.2, at a high C-rate, the battery-operated eCooks will successfully charge more rapidly; however, the network could experience high voltage fluctuations, system power losses and additional demand when the battery charges during sunlight hours.

The network model and the battery-charging algorithm were tested on five different case studies where, in each domestic situation, the battery-operated eCooks are charged at different C-rates, these being 0.5 C, 0.33 C, 0.25 C, 0.17 C and 0.083 C, respectively, and where the input charging power is 3 kW, 2 kW, 1.5 kW, 1 kW and 0.5 kW, respectively.

The choice of battery C-rate value allows the performance of the mini-grid to be assessed in terms of both fast and slow charging, as well as providing a wider range of results and establishing a better understanding of the technical impacts. It should be noted that some battery-operated eCooks could charge faster, as they are partially charged while waiting in the queue since attention is focused on those with the lowest SoC. The network studies are carried out to evaluate the C-rate with the least network impact on the voltage drop constraint, VUF, system power losses and zero-sequence current level.

As highlighted in Figure 5-4, in this section, it is assumed that HHs with battery-operated eCooks have transitioned to 100% eCook—meaning that all the HH food is cooked with eCook, where a hotplate is used for breakfast and lunch while, for dinner, either or both the hotplate and an EPC are used. This cooking pattern is considered the worst-case scenario (in terms of high demand level), which emphasises the need to study and understand the upcoming trends and challenges.

As mentioned in chapter 3, in this study the maximum voltage drop and VUF are 5% and 2%, respectively. These values follow international norms and are in line with reference documents [82], [89], [90], [96] of mini-grid design, as well as national grid standards to mitigate any technical and investment risks when the main grid arrives.

5.4.1 Simulation Results/Discussion and Recommendations

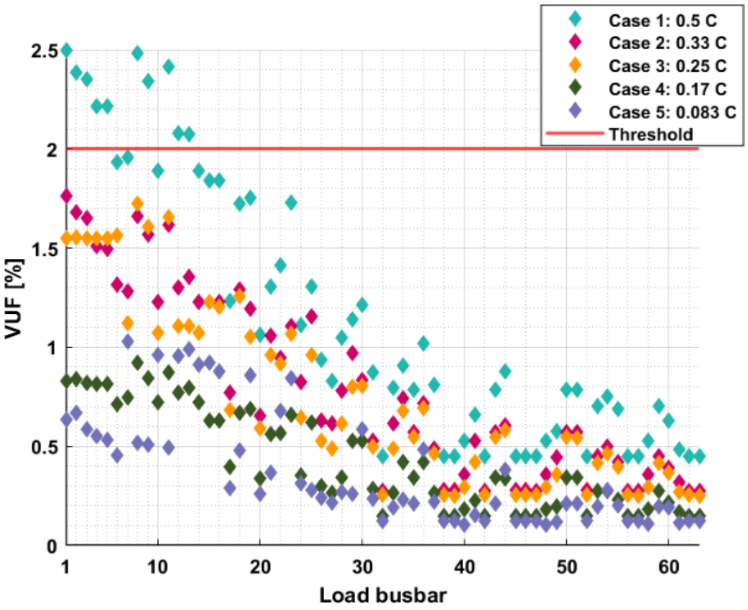

Figure 5-5. The maximum VUF value that occurs throughout the daily network simulation at each load busbar.

Figure 5-5 illustrates the maximum VUF level throughout the simulation at each load busbar of the residential feeder; on the x-axis, the busbars are arranged in descending order regarding their distance.

The results show that the level of the C-rate has a significant impact on the performance of the grid. At a high C-rate (case 1, case 2 and case 3), the network experiences more stress at the load busbars that are furthest from the power source, particularly those busbars at the end of the feeder connected to HHs with battery-operated eCooks. The VUF goes beyond the allowed limit of 2% for case 1, due to the unequal distribution of these batteries along the distribution line, where each phase experiences different voltage drops. In Figure 5-5, it is seen that some of the 0.33 C have lower VUF than 0.25 C, as the VUF level depends on the SoC and C-rate as they decide on the duration of the charging period, the number of batteries being charged simultaneously, the phase connection, the location of the batteries and their concentration within a particular zone in the mini-grid. The same things apply to case 4 and case 5.

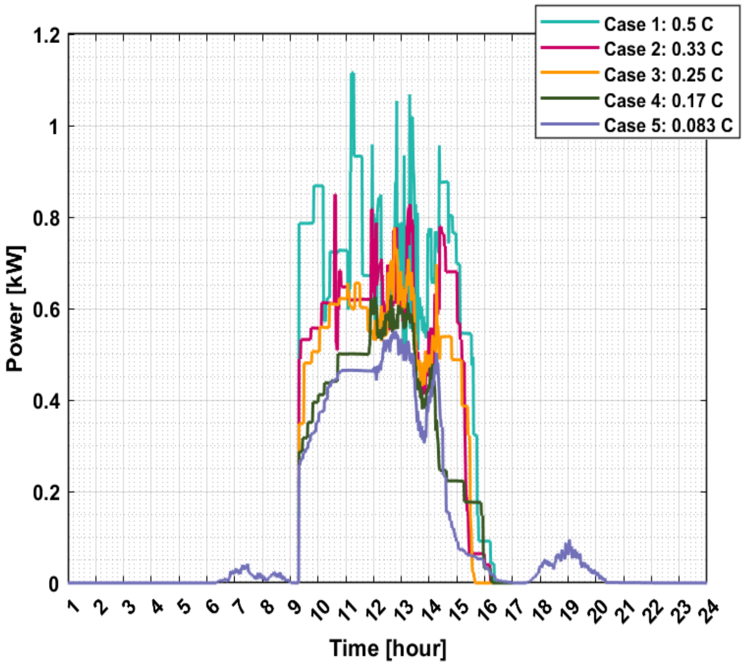

Figure 5-6. The total system power network losses.

The battery-operated eCooks are characterised by a high single-phase power rating, leading to an imbalanced system impedance, meaning that during the charging process, a phase imbalance occurs, whereas a high flow of current through the distribution lines causes an increase in system power losses (Figure 5-6), leading to a higher voltage drop at the end of the feeders. Consequently, the zero-sequence current (Iz) becomes higher in parts of the grid where the feeder length is significant (between approximately 0.8 km and 0.38 km), which could result in damage to the grid's infrastructure when the operational and network constraints are exceeded.

At maximum VUF, the voltage drop for each case was recorded and plotted in (Figure 5-7-Figure 5-11). From the findings, it is shown that the voltage drop exceeds the allowed limit (5%), particularly those busbars connected to charging battery-operated eCooks that are at a distance from the substation. It is noticeable that the case studies with high C-rates (case 1, case 2 and case 3) experience a high voltage drop at phase C, compared to phases A and B, due to most of the charging eCook devices being connected to phase C. The VUF and voltage drop levels depend mainly on the number of batteries charging simultaneously, their distribution along the feeder, and the SoC level. Any changes to these arrangements could initiate more severe network constraint violations.

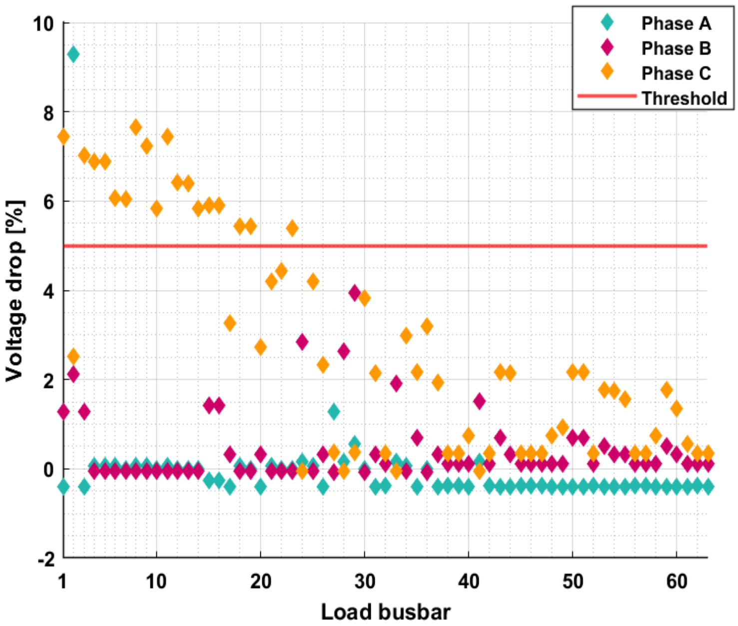

Figure 5-7. The load busbars' voltage drop (%), was obtained at maximum VUF for case 1 (0.5 C).

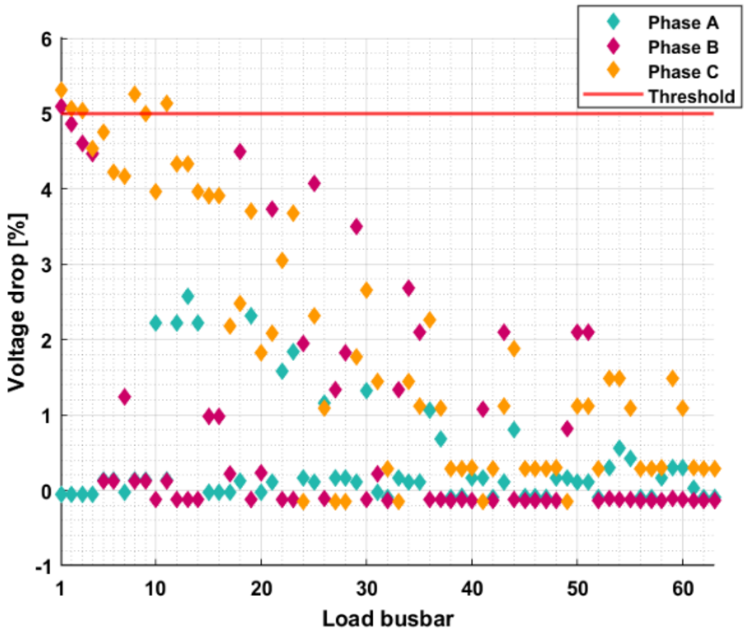

Figure 5-8. The load busbars' voltage drop (%), was obtained at maximum VUF for case 2 (0.33 C).

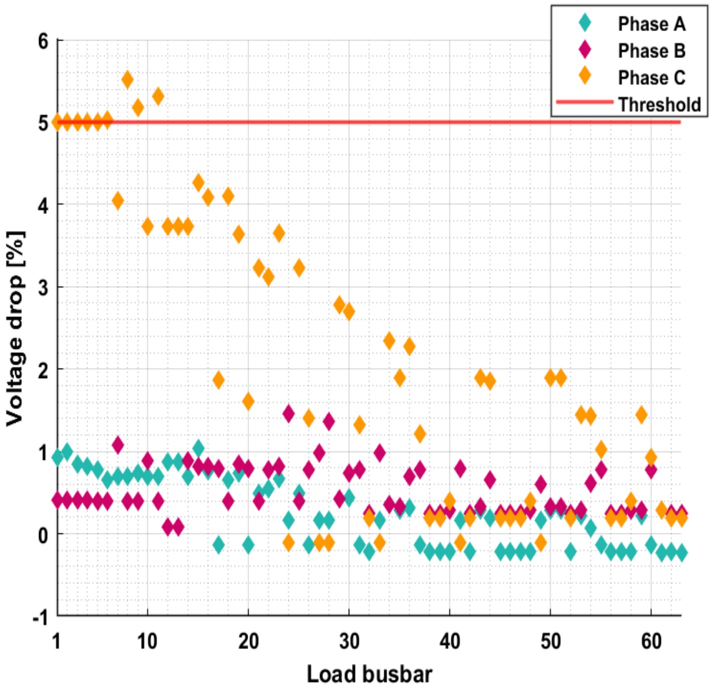

Figure 5-9. The load busbars' voltage drop (%), was obtained at maximum VUF for case 3 (0.25 C).

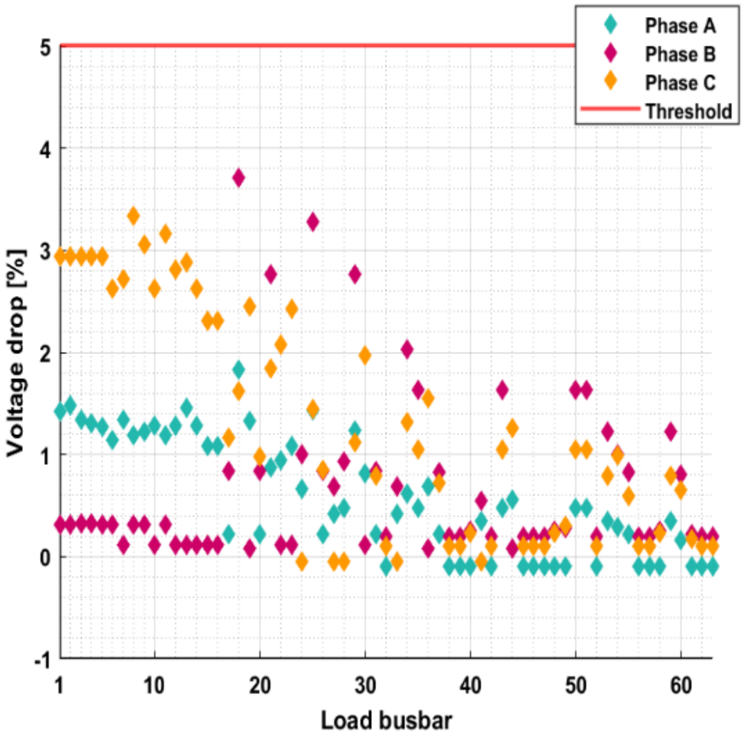

Figure 5-10. The load busbars' voltage drop (%), was obtained at maximum VUF for case 4 (0.17 C).

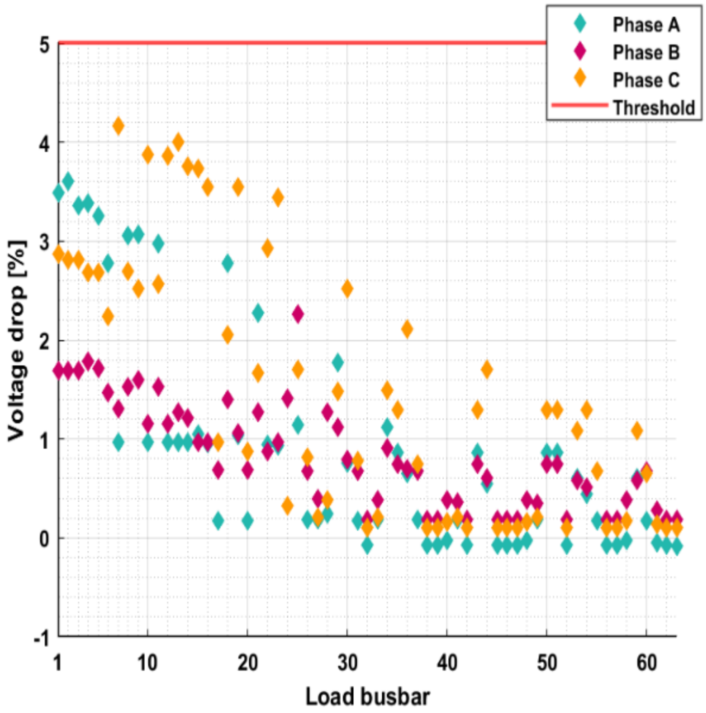

Figure 5-11. The load busbars' voltage drop (%), was obtained at maximum VUF for case 5 (0.083 C).

For a C-rate of 0.17 C and 0.083 C, the voltage drop level remains below 5% (Figure 5-10-Figure 5-11) and the network starts to operate within its constraints, with less current required to charge the battery-operated eCooks, resulting in lower system power losses when compared with high C-rate charging. Therefore, fewer VUF and voltage drops are experienced, and the network operates within the allowed limits (2% and 5%, respectively).

The simulation results show that over a typical day, the network experiences excessive voltage drops in phases A, B and C in case 1, case 2 and case 3 (Table 5-2). However, it also shows that this can be avoided by using a low C-rate, as indicated in cases 4 and 5. Naturally, the trade-off here is a longer charging period, as illustrated in Figure 5-12, which demonstrates the charging time for 30 battery-operated eCooks, connected to the mini-grid, out of a total of 47. From the results, the average charging time in case 5 (4.65 hours) increases by approximately six times the average charging time of case 1 (0.79 hours); therefore, it is evident that a high C-rate reduces the charging time, but it does not present a better solution from the perspective of the network’s constraints.

Table 5-2. Maximum voltage drops for different case studies.

Cases	Maximum Voltage Drop (%)		
	Phase A	Phase B	Phase C
1	9.289	6.940	7.567
2	6.760	5.555	5.315
3	5.605	5.296	5.522
4	4.567	4.961	3.683
5	3.853	3.320	4.160

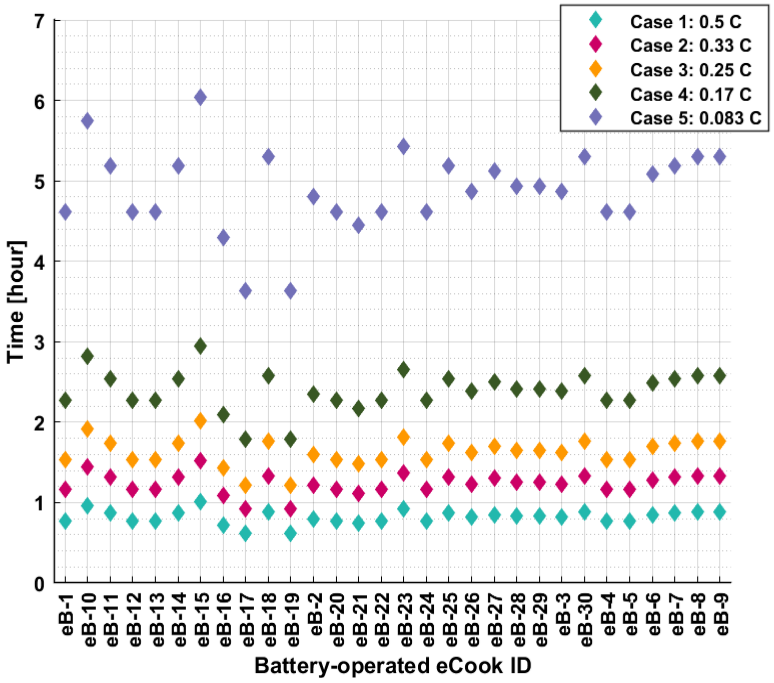

Figure 5-12. The charging time for each battery-operated eCook, with respect to each charging rate.

To conclude this section, the main observations and recommendations obtained from the results are:

- The battery-operated eCooks are considered to be flexible loads with respect to the charging power, by changing the C-rate value.
- Using high C-rate causes a high voltage drop and VUF; therefore, there is the opportunity to utilise lower C-rates for charging battery-operated eCooks, to maintain the network constraints within the limits, and to charge a wider distribution of HH eCook devices.
- The location of the battery-operated eCook along the feeder, and their concentration in a particular location, are two main factors to take into consideration when deploying battery-operated eCooks since, they can lead to a higher likelihood of network problems arising and can cause more pronounced phase losses.
- The number of battery-operated eCooks charged during the day depends mainly on:
    - The daily surplus PV energy, since this decides the number of battery-operated eCooks that can be charged simultaneously.

  - The SoC, decides the duration of the charging period for eCook devices.
  - The choice of C-rate value, from observations, it was noticed that fast-charging batteries on a cloudy day, when solar resources are limited, results in the cumulative charging of fewer batteries than when using a lower C-rate for slow charging. This is because the required charging power is relatively high; when a group of batteries are in charging mode, they are forced by the conventional charge controller to continue recharging until they reach full SoC (on the condition that there is enough surplus PV power) before allowing the other HH batteries to commence charging. This inhibits the capacity of the other batteries waiting to recharge to do so. On the other hand, slow charging enables additional batteries to charge simultaneously, as the surplus PV power can be distributed between more batteries since the input charging power is lower. In the simulation, these batteries ultimately reached an average SoC of around 54%, which is sufficient to meet the evening cooking demand.

The simulation results of the power flow studies carried out in OpenDSS/MATLAB in the next section demonstrate how the smart charging of flexible battery-operated eCook loads can be used to mitigate some of the preconceived network risks associated with uncontrolled battery-operated eCook charging.

5.5 Development of a Smart eCook Battery Charge Management System to Maximise eCook Demand

As discussed in chapter 2 (section 2.4), to keep the system balanced, the available ‘smart’ battery charging incorporates mainly cost incentive strategies that signal target market and price, to optimally schedule and manage the load e.g. EV. However, these strategies are not practical for the eCook demand since it is not possible to enforce or schedule the cooking times for the consumer. Also, another barrier is that the battery-operated eCooks are charged during a relatively “narrow” window of sunlight hours.

The previous section presented different scenarios using fixed C-rates in simulation studies to appraise the feasibility of utilising the charging rate of battery-operated eCooks as a way to manage the network constraints when eCook demand increases on a mini-grid. This section considers how a ‘smart’ EBMS would be designed to dynamically adjust C-rate set-points to maximise eCook demand while maintaining the system within its constraints and adapting to both cloudy and sunny days with the objective of maintaining an acceptable standard and quality of eCook charging service.

The ‘smart’ EBMS shown in Figure 5-13 is divided into two parts. The first part of the system should be installed at the generator site and is referred to here as the central eCook battery management system (‘smart’ C_EBMS). The second part is installed at the load busbar where at least one battery-operated eCook is connected, which is referred to as the distributed eCook battery management system (‘smart’ D_EBMS).

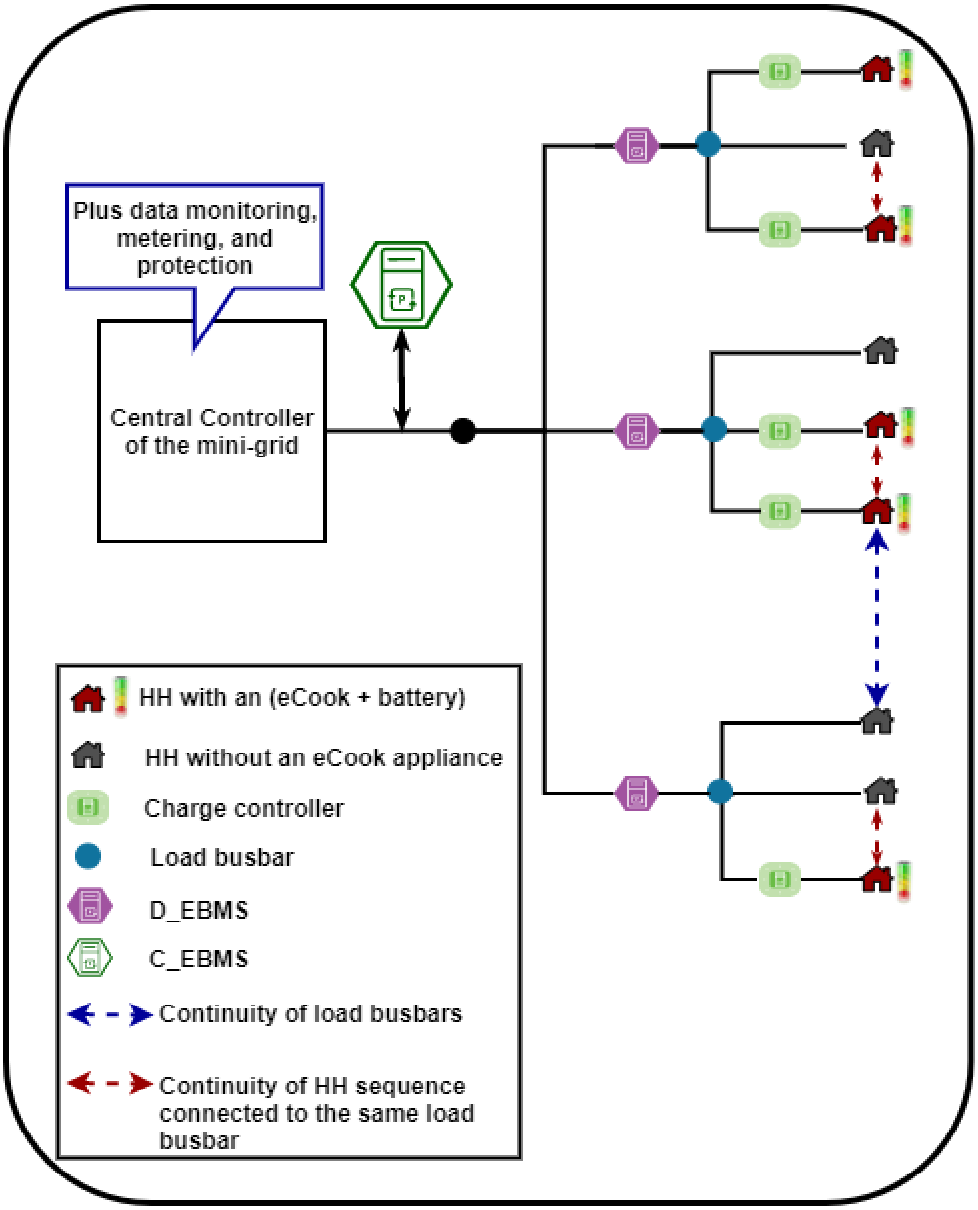

Figure 5-13. A simplified diagram showing the mini-grid components, including the two ‘smart’ EBMS types (D_EBMS and C_EBMS).

The schematic diagram in Figure 5-14 represents the command flow for the eCook smart controlled charge service. First, the centralized mini-grid charge controller decides on the number of battery-operated eCook that can be charged with respect to the available PV surplus energy. It then sends commands to the selected D_EBMS to start charging the battery-operated eCooks. As shown in Figure 5-14, once the battery-operated eCook is in charging mode, the ‘smart’ D_EBMS constantly checks the battery’s SoC—if it is less than the required/desired SoC level required to cook a meal (e.g., 54% in the case study above) the D_EBMS decides on the C-rate and allows the battery to first recharge to the appropriate C-rate level (e.g., C-rate$_{(low)}$ of 0.083 C). When the SoC reaches the required level, the C-rate is switched to a higher C-rate to speed up charging when possible (e.g., C-rate$_{(high)}$ of 0.25 C).

At this point, the ‘smart’ D_EBMS starts monitoring the state of the mini-grid by constantly measuring the VUF and voltage drops along each of the feeder circuit phases. If these values exceed their normal operational range (2% and 5%, respectively), the D_EBMS sends a signal to the battery-operated eCook forcing it to switch back to C-rate$_{(low)}$.

If the network constraints are still violated, possibly due to the battery-operated eCooks that are connected nearby indirectly contributing to the voltage drop and phase imbalance, as they may be charging at C-rate$_{(high)}$ and drawing high charging power, then the ‘smart’ C_EBMS assumes control, sending commands to the selected D_EBMS, to force the batteries to charge at a lower C-rate$_{(low)}$.

The choice of using C-rate$_{(low)}$ (0.083 C) and C-rate$_{(high)}$ (0.25 C) was through testing a range of C-rates and selecting the combination that maximises the number of batteries charged during the day on both a sunny and cloudy day, as well as reducing network constraint violations in terms of voltage drop and VUF. However, these values cannot be generalised as there is no standardised mini-grid. Therefore. future work could consider optimisation of the optimal combination of C-rates to operate in coordination with other mini-grids.

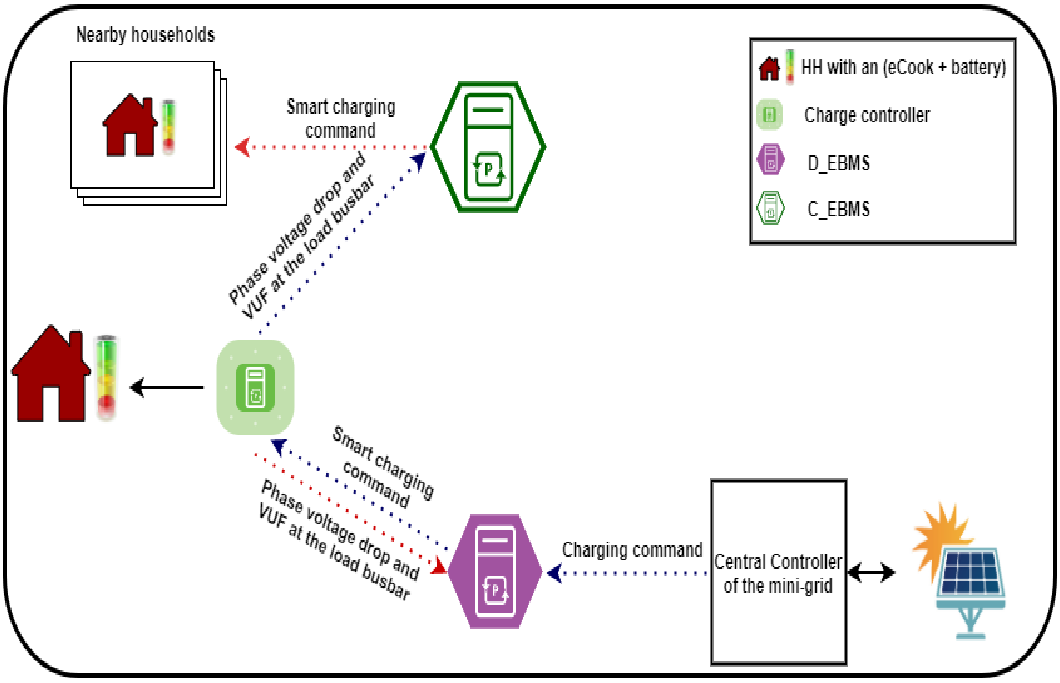

Figure 5-14. Command flow for the eCook controlled charge service.

5.5.1 Simulation Results and Discussion

The sets of simulation results are shown in (Figure 5-15-Figure 5-18) to evaluate the feasibility of the proposed 'smart' EBMS. The figures show the 24-hour VUF and the three-phase voltages (A, B and C) obtained at different load busbars of the feeder (these being the furthest load busbars of the distribution network). The results reveal that when the network constraints are violated the proposed 'smart' EBMS is put online and corrects it to maintain the output voltage and VUF within the set limits. In Figure 5-16 and Figure 5-17, when the voltage dropped below the allowed limit at 10:57 am and 11:16 am (circled in black), leading to a voltage drop of 5.12% at phase A and 5.25% at phase B respectively, the 'smart' EBMS detected the problem and adjusted the C-rate of the battery-operated eCooks to 0.083 C, allowing the voltage to recover while maintaining the charging regime. The same response is observed at 11:21 am, 12:30 am and 12:38 am, as illustrated in Figure 5-18. A snapshot of the three-phase voltage level at busbar_1 from 10:53 am to 11:26 am is tabulated in Table 5-3. It shows if the voltage level drops below 5%, the 'smart' EBMS acts to correct the voltage and maintain the mini-grid to operate within its limits.

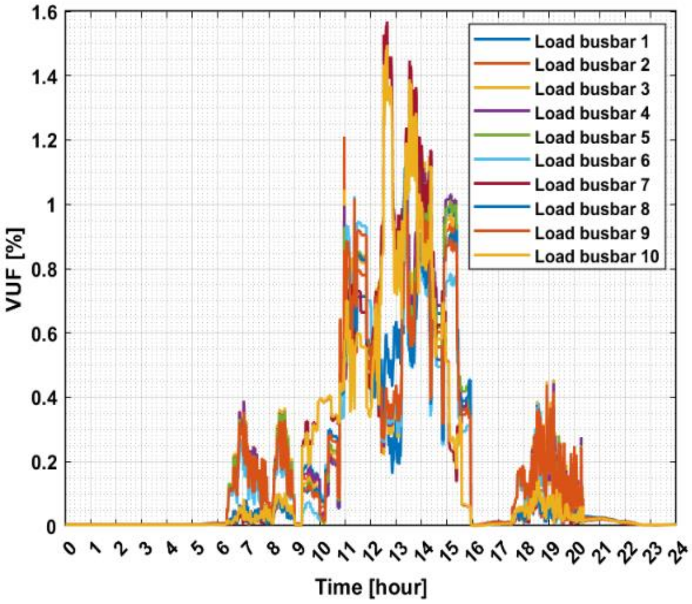

Figure 5-15. VUF daily profile at load busbars from 1 to 10.

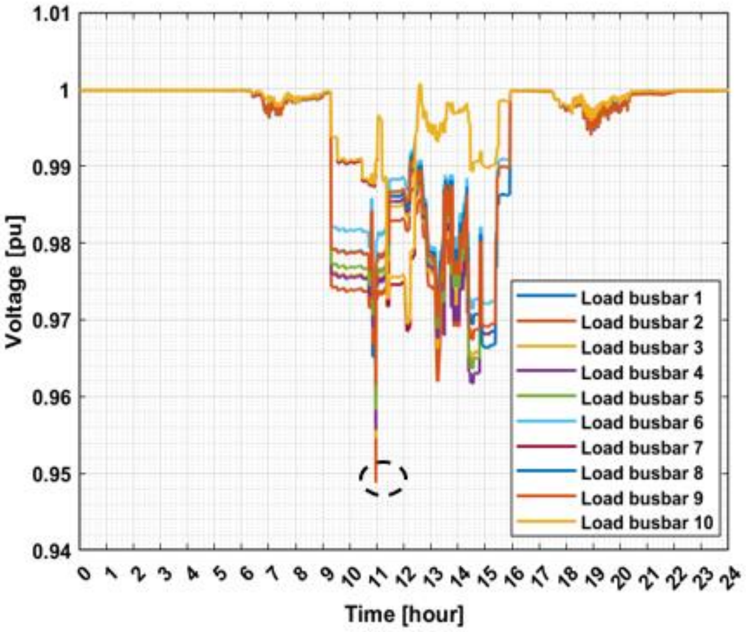

Figure 5-16. The voltage daily profile of phase A at load busbars from 1 to 10.

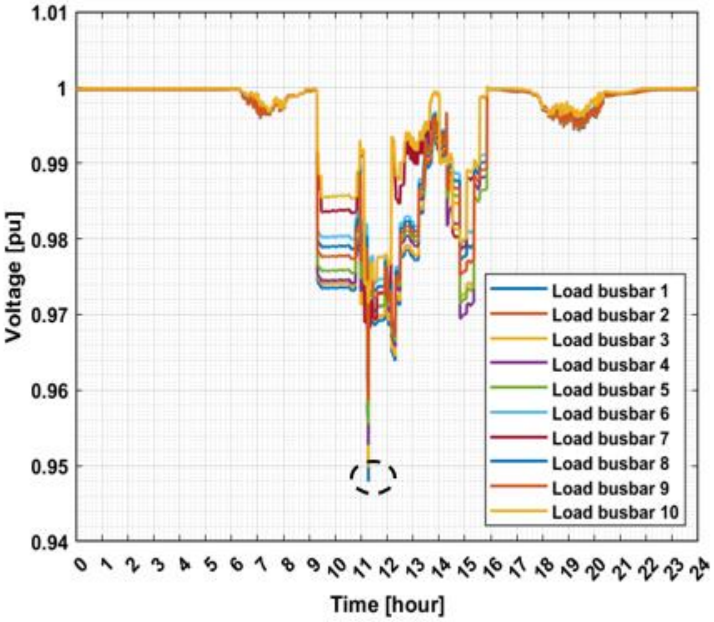

Figure 5-17. The voltage daily profile of phase B at load busbars from 1 to 10.

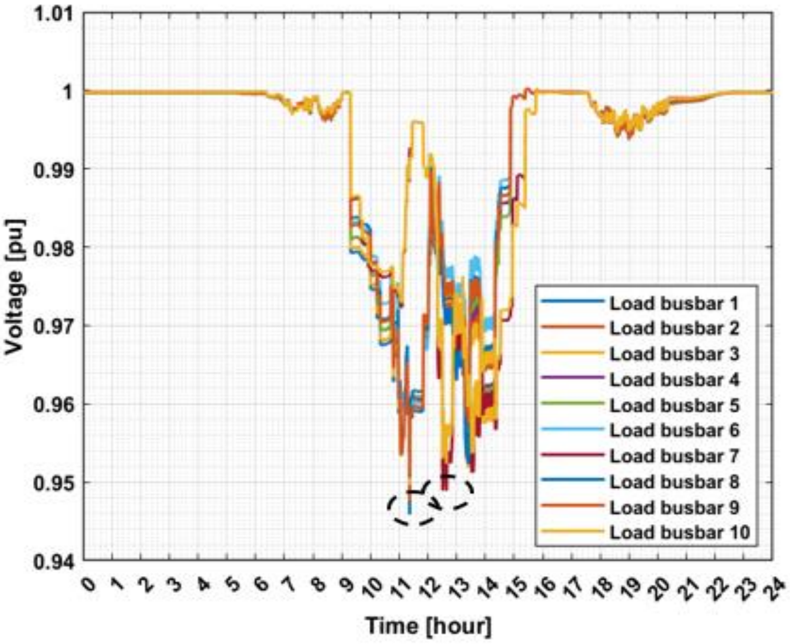

Figure 5-18. The voltage daily profile of phase C at load busbars from 1 to 10.

Table 5-3. A snapshot of the three-phase voltage level in pu at busbar_1 from 10:53 am to 11:26 am.

Time	Voltage Level		
	Phase A	Phase B	Phase C
10:53	0.9652	0.9784	0.9661
10:54	0.9652	0.9784	0.9661
10:55	0.9652	0.9784	0.9661
10:56	0.9657	0.9788	0.9660
10:57	**0.9488**	0.9877	0.9678
10:58	0.9726	0.9731	0.9588
10:59	0.9726	0.9731	0.9588
11:00	0.9726	0.9731	0.9587
11:01	0.9731	0.9730	0.9588
11:02	0.9737	0.9746	0.9541
11:03	0.9738	0.9750	0.9540
11:04	0.9738	0.9750	0.9540
11:05	0.9738	0.9750	0.9540
11:06	0.9734	0.9758	0.9552
11:07	0.9732	0.9744	0.9561
11:08	0.9732	0.9744	0.9561
11:09	**0.9732**	**0.9744**	**0.9561**
11:10	0.9731	0.9744	0.9596
11:11	0.9739	0.9748	0.9595
11:12	0.9738	0.9748	0.9599
11:13	0.9737	0.9748	0.9604
11:14	0.9735	0.9565	0.9656
11:15	0.9735	0.9565	0.9656
11:16	0.9734	**0.9479**	0.9668
11:17	0.9738	0.9700	0.9599
11:18	0.9742	0.9699	0.9599
11:19	0.9742	0.9699	0.9599
11:20	0.9742	0.9699	0.9599
11:21	0.9775	0.9705	**0.9459**
11:22	0.9759	0.9709	0.9583
11:23	0.9759	0.9709	0.9583
11:24	0.9759	0.9709	0.9583
11:25	0.9759	0.9710	0.9582
11:26	0.9759	0.9710	0.9582

Here, the voltage drop levels could exceed 7%, depending on the number of batteries charging simultaneously, their location along the feeder, their relative SoC, and their position in the queue. However, as can be seen from the analysis, the ‘smart’ EBMS successfully operated within the network constraints.

Connecting the battery-operated eCooks significantly altered the network’s operation. This section of the chapter presented this ‘smart’ EBMS control strategy as a viable option, in accommodating higher and more distributed eCook demand along with these feeders while ensuring that the VUF remains within the standard allowed limits. Another advantage of this approach is that a combination of slow and fast charging is permitted, resulting in successfully reducing the charging time, compared to case 5 (see Figure 5-19), which shows the charging time of 30 battery-operated eCooks out of a total of 47), where the average charging time was reduced by approximately 62% compared to case 5. Using the ‘smart’ EBMS also permitted an increase in the number of battery-operated eCooks to be recharged on a cloudy day to meet the evening cooking needs, with a fraction of the batteries having enough charge to cook breakfast the following day (this is further discussed in section 5.6), while on a sunny day, all 47 battery-operated eCooks are charged enough to cook both meals (dinner and breakfast where the duration of cooking on average is around 37 min and 1 hour, respectively). On both sunny and cloudy days, lunch demand is directly supplied from the PV/diesel, as well as from the centralized battery.

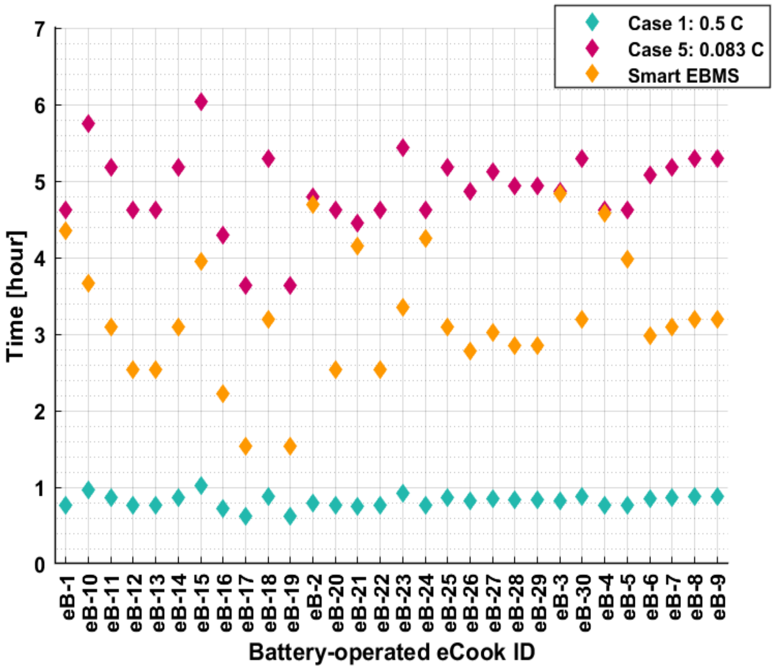

Figure 5-19. The charging time for each battery-operated eCook, with respect to each charging rate.

5.6 The Quality of Service of Battery-Operated eCook Charging

In this study, the QoS of eCook battery charging is defined, based on the number of batteries recharged daily to meet evening cooking demand. The QoS analysis was conducted for four case studies, each considered on both a sunny and a cloudy day.

- “Direct Electric Cooking” case study: an electric cooking device with no battery storage, connected directly to the mini-grid.
- “End of Feeder eCook” case study: a mini-grid network with battery-operated eCooks connected at the end of the feeder.
- “Random Distribution #1 eCook” case study: a mini-grid network, with battery-operated eCooks randomly allocated to HHs (set 1).
- “Random Distribution #2 eCook” case study: this is the same as the “Random Distribution #1 eCook” case study but it takes another set of random values (set 2).

For “Direct Electric Cooking”, on a sunny day, the mini-grid case study can accommodate approximately 20% eCook devices (representing 22 HHs with eCook); however, on a cloudy day, this decreases to 6% (7 HHs with eCook) due to the lower PV output.

Connecting battery-operated eCooks offers more flexibility and maximises the utilisation of electricity, compared to ”Direct Electric Cooking”. In fact, from the results, on a sunny day, all 47 battery-operated eCooks were recharged in each of the ”End Feeder eCook”, and ”Random Distribution #1 and #2” case studies, and were able to accommodate dinner and also breakfast demands of the following morning. This capacity is reduced on a cloudy day, as illustrated in (Figure 5-20 - Figure 5-22); these figures show the number of battery-operated eCooks for each case study that has recharged with enough energy during the day to serve the evening’s needs, as well as the number of batteries that have not charged, although they have enough energy stored as the battery size accounts for half-day autonomy. In terms of the conventional charge controller and EBSM, the total number of batteries available to serve the evening cooking demand in each case study is fewer than 47 battery-operated eCooks. It is apparent from (Figure 5-20 - Figure 5-22) that charging the battery-operated eCooks with the smart-controller EBMS offers a higher QoS, as more battery-operated eCooks are adequately recharged, ranging between 26 and 29 battery-operated eCook (55–62%) (compared to a system without the ‘smart’ EBMS charging). These are discharged during the evening, and a limited number of batteries will still have enough stored energy to supply early morning cooking demand (around 12–15 battery-operated eCooks, translating to 26–32%).

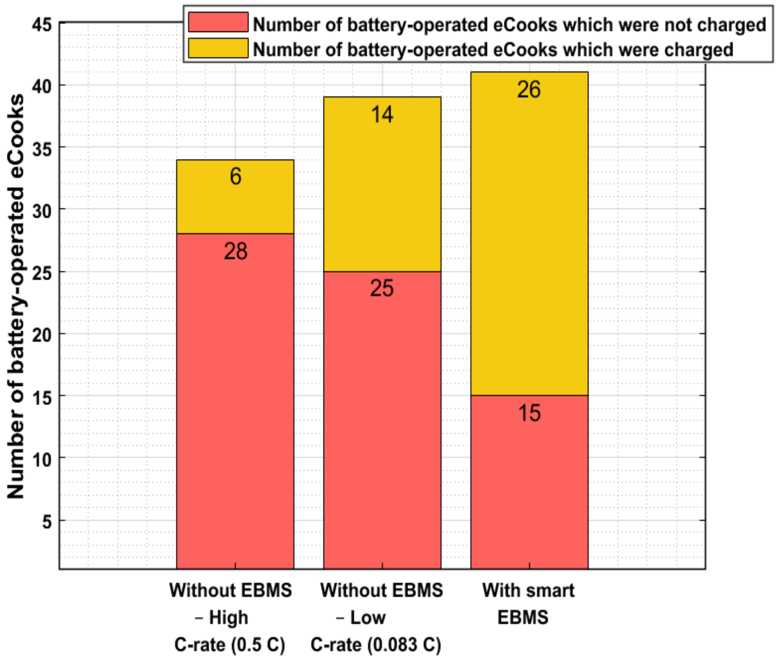

Figure 5-20. The number of battery-operated eCooks available to meet dinner-cooking demand on a cloudy day for the “End of Feeder eCook” case study.

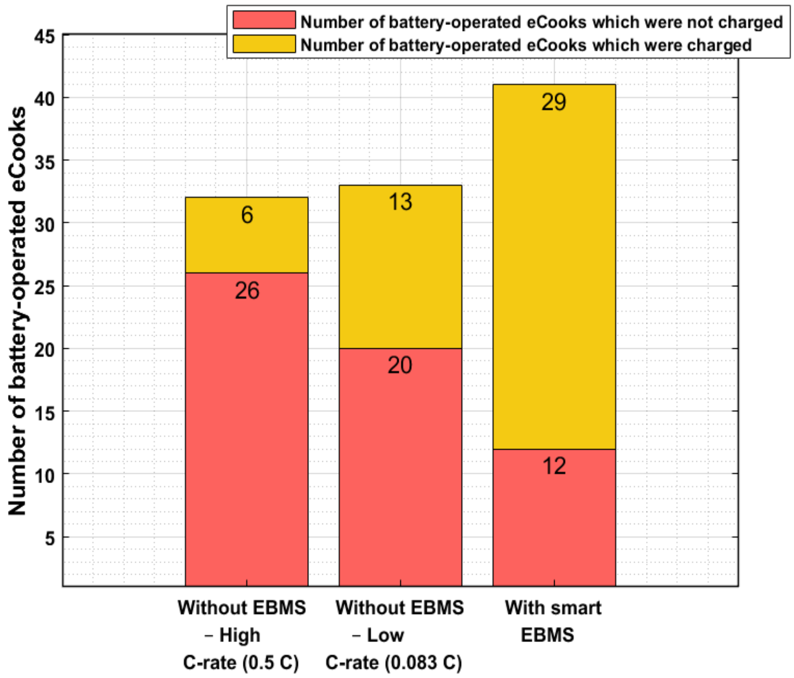

Figure 5-21. The number of battery-operated eCooks available to meet dinner-cooking demand on a cloudy day for the "Random Distribution #1 eCook" case study.

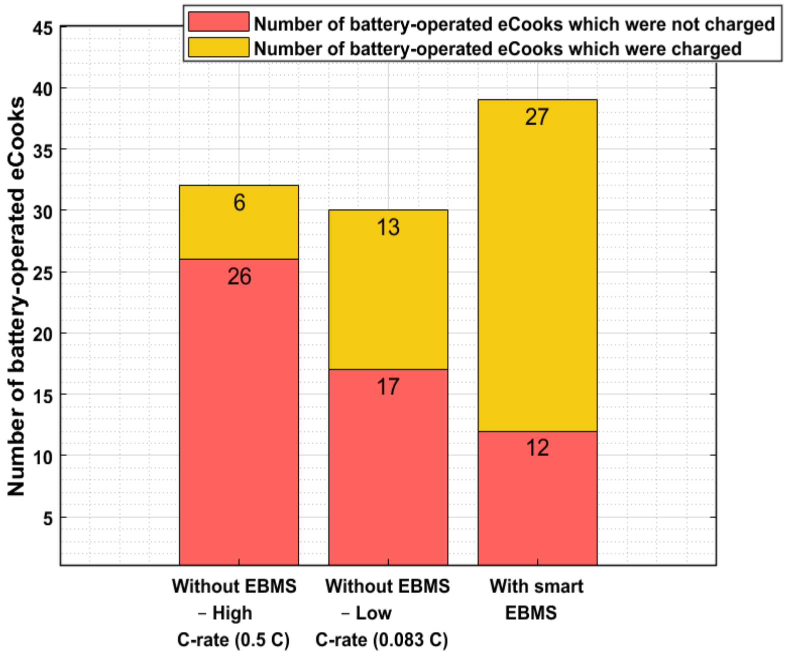

Figure 5-22. The number of battery-operated eCooks available to meet dinner-cooking demand on a cloudy day for the "Random Distribution #2 eCook" case study.

Until this point, the 'smart' EBMS performance was studied when connecting only 47 battery-operated eCooks to the mini-grid (where 43% of HHs had a battery-operated eCook), yet it is important to evaluate the maximum eCook battery penetration that could be connected to the type and size of the mini-grid studied in this chapter. Figure 5-23 and Figure 5-24 present the QoS of battery-operated eCook-charging as a percentage, showing the battery-operated eCook penetration for sunny and cloudy days, respectively. The eCook penetration is gradually increased from 40% to 100% (where 100% refers to all 108 HHs using a battery-operated eCook) in each of these cases.

It was found that on a sunny day, the PV eventually generated enough power to adequately recharge up to 60% battery-operated eCooks in the case of conventional charging without the ‘smart’ EBMS (see Figure 5-23). As illustrated in Figure 5-23, when the battery-operated eCook penetration increases beyond 60%, the QoS abruptly starts to reduce due to not receiving any or enough charging service, due to the limited PV generation capacity required to charge the additional battery-operated eCooks. In addition, when a group of batteries are in charging mode, they are forced by the conventional charge controller to continue recharging until the battery reaches full SoC, before allowing the other HH batteries to commence charging. As can be seen, when using the ‘smart’ EBMS, the charge distribution of the batteries is spread more equally, providing an improved overall QoS. As the battery-operated eCook penetration increases, it enables all 108 HHs to cook with electricity during the evening and still enables 72% to 100% of the battery-operated eCooks to provide enough power to cook breakfast the following day. Naturally, when there is a limited solar resource (Figure 5-24), this will have a direct impact on the number of battery-operated eCooks that can be adequately charged. Where the eCook demand cannot be adequately met, then fuel stacking can be used as a form of “backup” [125]. A longitudinal study is needed that captures how this scenario plays out over the course of a year, in terms of eCook availability. As the battery-operated eCook penetration increases, batteries will not normally be charged to their full capacity. Therefore, to ensure maximum utilisation of the battery-operated eCooks with the ‘smart’ EBMS, it is considered practical that the system will enable 40% to 60% of HHs to cook 100% of their evening food with electricity, as well as most of the breakfasts, on a sunny day.

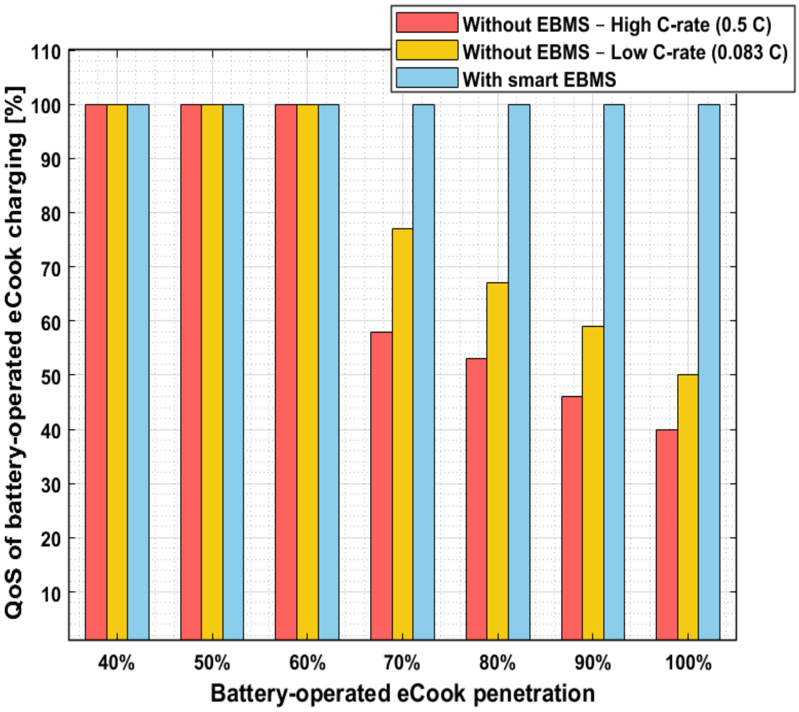

Figure 5-23. QoS of battery-operated eCook charging for different battery-operated eCook penetrations on a sunny day, with power usage in the evening.

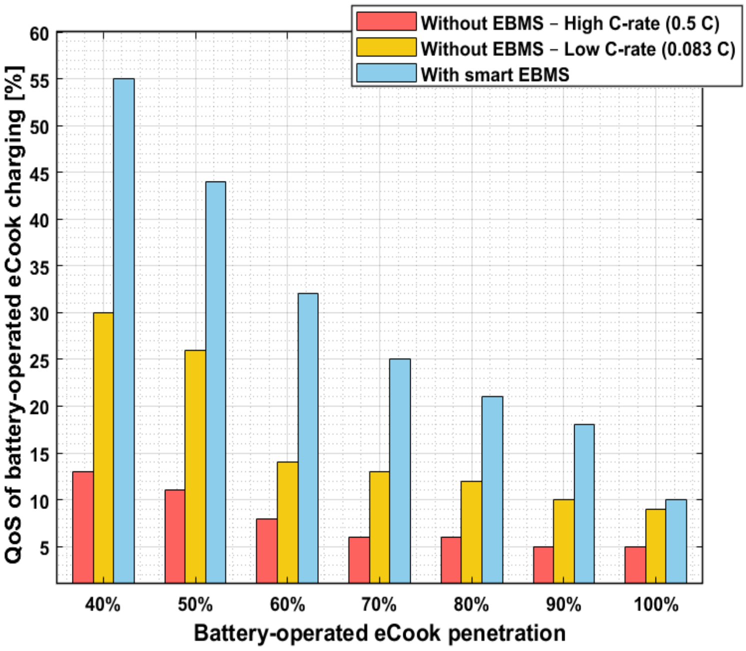

Figure 5-24. QoS of battery-operated eCook charging for different battery-operated eCook penetrations on a cloudy day, with power usage in the evening.

An alternative way to interpret these results is with the possibility of increasing battery-operated eCook penetration beyond 60% when using the ‘smart’ EBMS, by reducing the size of the battery-operated eCooks; in this scenario, 100% of the HHs’ evening meals will be cooked with electricity, while the remainder of the meals will be cooked with another type of cooking fuel. This option will encourage a gradual move toward cooking with electricity, as well as introduce health, resource, and cost-saving benefits.

5.7 Conclusions and Future Work

The network studies in this chapter aim to give a clearer idea of the technical challenges when connecting eCook battery-operated eCooks to the hybrid PV/diesel mini-grid network. Charging the battery-operated eCooks with a high C-rate causes increases in voltage drop and VUF that exceed the allowed limit of 5% and 2%, respectively. This is mainly observed in the case of the load busbars furthest from the power source. Therefore, an innovative ‘smart’ EBMS has been developed to allow C-rate adjustments to engage in voltage regulation, which operates by constantly verifying the voltage drop at each phase, as well as the VUF level. In general, the results show that the proposed ‘smart’ EBMS can ensure that the network operates within voltage constraints. Moreover, the ‘smart’ EBMS offers other significant advantages. Firstly, it enables a combination of slow and fast charging that allows a greater battery charge coverage across the network, ensuring that eCook devices are ready for use in the evenings. Secondly, it provides the best QoS compared to a network without ‘smart’ EBMS; thirdly, this approach could be used in the future, in concert with other flexible and non-flexible high-power appliances, to facilitate their uptake. However, further studies are required to evaluate the suitability and generality of the ‘smart’ EBMS strategy presented here on different mini-grid models of different scales and topologies. Further work will also consider the optimisation of the C-rate, to maximise eCook penetration over different mini-grid types and topologies.

It is apparent, even when using this ‘smart’ EBMS, there is still a need for a large battery-operated eCook size (6 kWh) to cook the daily meal with 100% electricity, which is not cost-effective. Therefore, instead of moving directly toward 100% eCooking, fuel stacking can be seen as a viable solution to facilitate the transition (with ‘smart’ EBMS smart charging working alongside fuel stacking). This emphasises the need to study and understand the upcoming trends of fuel stacking by developing a methodology to identify the lowest-cost, best-fit cooking scenario (with the optimal cooking solution incorporating eCook to a varying degree). This will be the subject of chapter 6.

6 DEVELOPMENT OF A METHODOLOGY FOR ASSESSING THE ECONOMIC AFFORDABILITY OF BATTERY OPERATED ECOOK COMPARED TO COOKING WITH CONVENTIONAL FUELS

The initial aim of this chapter is to understand and provide a comparative analysis of the cooking energy costs through a range of contextualised cooking scenarios–when cooking either with conventional fuels (e.g. charcoal, firewood) or with eCook appliances (e.g. EPC or hotplates), that are connected to and supplied from an integrated or portable battery [126]. The cooking cost for the eCook cooking scenarios is assessed with and without fuel stacking where a degree of eCook is alongside other conventional fuels. These studies offer a more realistic concept of the cooking practice to characterise the best fit for cooking scenarios and the main factors required to close the gap between the energy cost of conventional fuel and eCook (battery-operated eCook). The results suggest that to achieve this between firewood and battery-operated eCook-based cooking, three main factors need to be taken into consideration when estimating the cooking cost: the non-market cost of firewood; ensuring a low mini-grid tariff that is within a range of the national grid tariff and using an optimal battery-operated eCook size with the capability to meet the required demand. In fact, the results of the research study in this chapter show that when taking these factors into account; for the 2022 analysis, cooking 100% using a battery-operated eCook is in a range of \$29-30/month implying that there could be an opportunity for parity when the firewood cost reaches \$29/month. The same applies to the cooking prediction costs for 2030, reducing further to \$20-21/month. However, if the firewood is harvested sustainably, ensuring it is high in quality and dry, it would be difficult for battery-operated eCook to compete. It should be emphasised that this research has relevance for governments, practitioners, and researchers.

6.1 Introduction

Limited grid access, weak grid infrastructure and the perception of high energy prices when cooking with electricity act as barriers to moving towards eCooking. In terms of the mini-grid network study in chapter 5, an innovative ‘smart’ EBMS was developed to alleviate the impact of ‘conventional’ battery-operated eCook charging on the mini-grid network, as well as to increase the quality of the charging process. It actively communicates the state of the grid and then decides on the battery-operated eCook charging rate set-point required to address the network constraints. In addition to this, recent studies by ESMAP [125] and MECS [82] examined the cost of cooking with electricity (from the national grid or the mini-grid network) and the costs of traditional fuels that are required for stacking or as the baseline. The results show that there is a potential for eCooking in urban areas for grid-connected HHs due to the low tariff, as well as for peri-urban mini-grid HHs when the tariff cost is expected to fall to \$0.25–0.38/kWh by 2025. With further continuation of the research work seen in [114] which focused on the technical viability of eCook battery on a hybrid photovoltaic (PV)/diesel mini-grid, the research carried out in this chapter assesses the economic affordability of it in developing countries.

Due to the lack of research, literature is absent on HH-level battery (battery-operated eCook) cooking costs in a hybrid PV/diesel mini-grid. Therefore, it is necessary to study and understand the upcoming cost trends when cooking with battery-operated eCooks. When considering the challenges of rapid and wholesale eCook adoption of 100% in rural areas, where affordability remains a significant barrier, eCooking penetration may be more gradual, and intermediate, transitional solutions may be required. HHs in rural areas are likely to have lower spending power for cooking fuels and therefore less ability to pay for modern energy cooking services [127]. Also, there may be a reluctance to change cooking methods, as these practices have cultural relevance in many communities, and the food may not taste the same, as well as potential resistance to cooking in batches to reduce overall energy consumption. Evidence also shows that eCooking is abandoned by some communities in the winter months, reverting to more traditional methods, as this also provides heating for the homes while cooking [128]. Therefore, the solution could be to move towards fuel stacking, helping phase the transition rather than moving directly towards 100% cooking with electricity.

With such an approach, and in time, users may become aware of the benefits of the cleaner options, which may influence their decision-making. In this context, this research aims to explore the economic viability of eCooking compared with the use of predominant traditional fuels (charcoal and firewood) and, LPG which is occasionally used by low-and-middle-income HHs when these traditional fuels are not readily available. It may be argued that HHs may acquire firewood for cooking at no financial cost, however, this is not necessarily the case, as there is an indirect cost to be considered in the loss of earnings from alternative productive uses of time and effort to the task of collecting the firewood specifically for cooking.

A non-market value can be estimated and quantified by taking the value of unpaid labour for collecting firewood plus its social cost of carbon. In general terms, the cost of unpaid labour is valued by calculating the amount of time spent collecting the firewood and, the wage paid to casual employees and a person with similar skills employed in public or private sectors [20], [129]. While the social cost of carbon is the total damage to the economy and human welfare created by one extra ton of CO_2 emissions, converted to dollars [130], [131]. Using the results obtained from [20], the non-market value of firewood is estimated to range between \$0.17/kg to \$0.37/kg, where the cost corresponds to harvesting unsustainably from local forests.

The remainder of the chapter is organised as follows; section 0 outlines the methodology and the steps taken to determine the key factors to evaluate the least cost eCook scenario (considering both direct connected and (in-direct) battery-operated eCook). Section **Error! Reference source not found.** includes a brief introduction to the techno-economic modelling tools as well as the input assumptions and system constraints considered in each of the simulations, the simulation results are also present. The analysis conducted to close the affordability gap between conventional cooking fuels and battery-operated eCook are presented in sections 6.4. Finally, section 6.5 is the conclusion.

6.2 Methodology for Assessing Affordability of eCook

This chapter presents the methodology and results of a techno-economic study to provide a comparative analysis of the cost of energy when cooking through a range of contextualised cooking scenarios – cooking only with conventional fuels (charcoal or firewood), with 100% eCooks (direct eCook or through battery-operated eCooks) as well as fuel stacking. The energy mix for fuel stacking and the ratio can vary from one HH to another depending on many factors. Also, there remains a lack of cooking data concerning consumer behaviour. Therefore, it is difficult to predict conclusively the energy mix ratio, which is why it is more practical to study a ratio 50:50 (eCook to conventional) to understand the future trends in costs. The results explore only a subset of possibilities for the energy cooking mix. The cooking scenarios are summarised in Figure 6-1. They intend to provide a clear understanding of the issues surrounding the barriers associated with an eCook transition in rural areas, particularly battery-operated eCooks, and to give an indication of the key factors needed to reduce the cost of cooking with electricity.

For the ‘Direct Electric Cooking’ scenario, the hybrid PV/diesel mini-grid includes a 30 kW_P PV, 25 kW PV-inverter, 27.6 kWh centralized battery, 8 kW converter and a 9 kW backup diesel generator (more detail on the mini-grid can be found in chapter 3 and chapter 5). It connects 108 HHs with electricity to supply their baseload, while the daily surplus PV energy used to charge the eCook batteries enables 47 HHs (≈43% of total HHs) to cook breakfast and dinner with battery-operated eCooks. Whereas, at midday, the PV power generation and the backup diesel generator are used. However, for direct eCook (i.e. where an electric cooking device with no battery storage is connected directly to the mini-grid), the system capacity can accommodate approximately 20% eCook devices (22 HHs with eCook) and on a cloudy day, this decreases to 6% (7 HHs with eCook) due to the lower PV output.

To achieve and maintain consistency in the cost analysis, and to easily compare the “Direct Electric Cooking” and “Clean Cooking” scenarios (Figure 6-1) only 47 HH out of 108 HH are connected to eCook devices.

From Figure 6-1 “Direct Electric Cooking” is split into two other cooking scenarios: “Direct Electric Cooking #1”: evaluating the monthly energy cooking cost when ***upgrading only the centralized battery and the bi-directional converter***. Upgrading the battery bank will permit storage of the surplus daily PV energy for later use by the 47 HHs to cook all the daily meals with eCooks directly connected to the mini-grid (the reason for only connecting 47 HH out of 108 HH to eCook is explained in section **Error! Reference source not found.**).

“Direct Electric Cooking #2 – for PV/Storage/Diesel Hybrid”: determining the optimal hybrid PV/diesel mini-grid size when upgrading the (PV array, centralized battery, diesel generator, PV-inverter and bidirectional converter sizes) for ***an overall upgrade to mini-grid***, in addition to the monthly energy cooking cost to permit 47 HHs to cook all their daily meals with eCooks directly connected to the power supply.

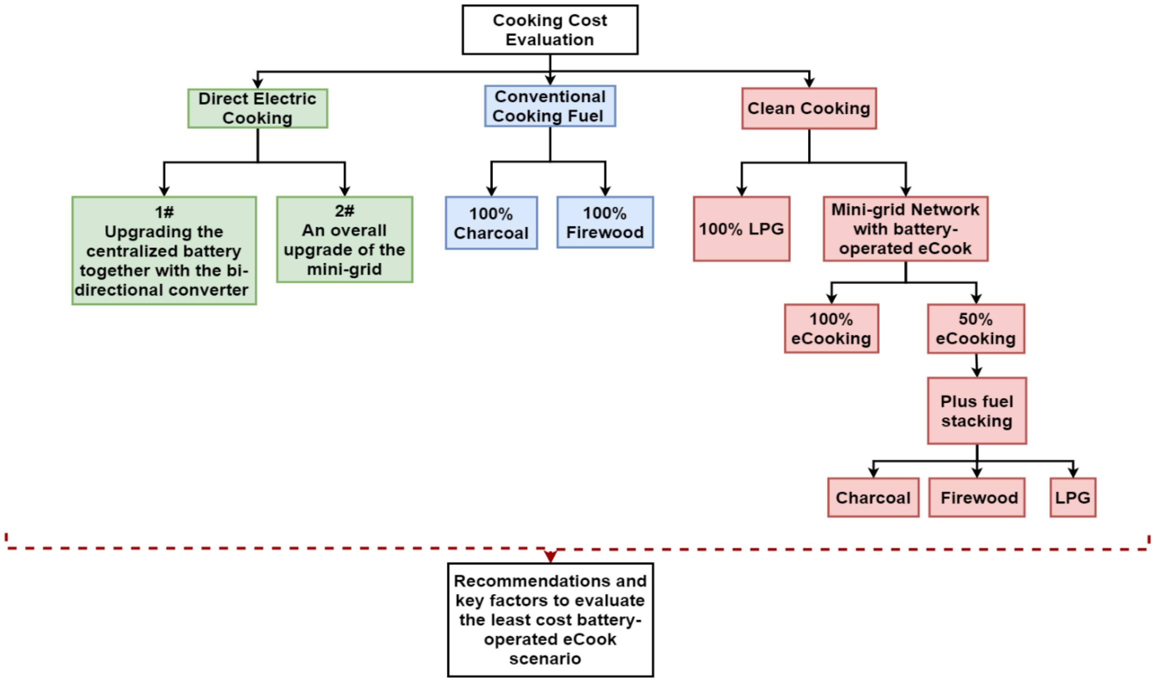

Figure 6-1. Contextualised cooking scenarios to evaluate the monthly cooking cost.

The “Conventional Cooking Fuel” scenario deals with HH cooking either with “100% Charcoal” or “100% Firewood”. While the “Clean Cooking” scenario comprises of five cooking scenarios, the first explores cooking with “100% LPG” and the second one assumes that HHs switch to using battery-operated eCook where the cost is evaluated for 100% eCooking and for the three scenarios developed when using 50% eCooking with 50% of stacking fuel, the fuel used are charcoal, firewood and LPG.

For 100% eCooking the daily average cooking demand is 2.2 kWh/day which accounts for breakfast, lunch, and dinner, yet, to cook both breakfast and dinner there is a need for 1.6 kWh. As shown in [114], the latter was used to size the battery-operated eCook, since it is only used in the morning and the evening, while the lunch demand is directly supplied by the min-grid generation. The size of the battery calculated accounts for the worst-case scenario, where the minimum and maximum SoC are set at 20% and 80% respectively.

Also, 1.5 days of autonomy and other factors mentioned in [114] were included to improve the battery's performance through its mid-life design. Therefore, for the 100% eCooking and the 50% eCooking scenarios, 6 kWh battery and 2 kWh batteries are used respectively throughout the cost analysis of this chapter.

It is important to mention that for the 100% eCook scenario, breakfast and lunch are cooked using a hotplate, while dinner is cooked on either or both a 1 kW hotplate and a 1 kW EPC. For the 50% eCooking, only an EPC is used with fuel stacking.

The main findings lead the way, highlighting the key factors to bridge the affordability gap between firewood and battery-operated eCook-based cooking. From this other cooking scenarios were evolved, and subsequently simulated, assessed, and compared alongside the "100% Firewood" cooking scenario cost (section 6.4.1). The remainder of the chapter gives a more detailed description of the steps considered in these studies and the main results.

6.3 Cooking Cost Modelling and Computation

Throughout this chapter two techno-economic tools are used, Homer-Pro Software and an eCook Modelling Tool.

6.3.1 "Direct Electric Cooking" Scenario

HOMER-Pro software [81] was used to conduct a techno-economic analysis of the various scenarios, using particular input assumptions where necessary and system constraints, to find the lowest cooking energy cost for the "Direct Electric Cooking" scenarios in Figure 6-1.

The defined input data for the mini-grid model in HOMER is summarised in Table 4-1. The lifetime of the project is 20 years and the inflation rates and the nominal discount rates used were 6% and 10% respectively, which are considered standard figures for business planning [102]. The annual fixed O and M costs account for 2% of distribution CAPEX [104]. For the non-eCook demand (i.e. baseload demand) and the eCook demand, the load profiles were modelled by a group of researchers from MECS using the CREST demand model [82], [122].

6.3.1.1 Result and Discussion

From Table 6-1 in the "Direct Electric Cooking #1" cooking scenario, a 345 kWh battery bank is required and a 24.4 kW bi-directional converter, to store the surplus daily PV energy to cook both dinner and breakfast.

Table 6-1. Proposed mini-grid component sizes to enable direct eCooking.

Scenarios	PV Array	Diesel Generator	Lithium-Ion Battery	Converter	PV-Inverter
	[kW]	[kW]	[kWh]	[kW]	[kW]
Direct Electric Cooking #1	30	9	345	24.4	25
Direct Electric Cooking #2	87.1	43	82.8	25	15

In this scenario, the required battery capacity is high as it is sized for 3 days of autonomy to try and meet most of the high early morning and evening cooking demand during extended periods of low solar resources. Any trade-offs in the availability of supply to reduce system costs are not considered in this study, although could be in future. Another reason for the high levels of storage capacity is that the PV array and the backup diesel generator generation are limited (Table 6-1). This scenario suggests that HHs will pay \$66.6/month for cooking with eCooks. Comparing this value to the cost of the "Direct Electric Cooking #2" cooking scenario \$38.94/month, it is considerably higher, which indicates that upgrading the centralized battery is not the most cost-effective solution. In fact, for such systems, it would be more practical to install mini-grids that are sized appropriately from the out-set to accommodate eCook, rather than upgrading the components later. Also, the battery cost is still considered a major barrier preventing a market breakthrough in battery-powered domestic products and appliances. In addition, for "Direct Electric Cooking #1" there remains a 1% annual energy demand which is not met by the available mini-grid generation.

6.3.2 "Conventional Cooking Fuel" and "Clean Cooking" Scenarios

For the "Conventional Cooking Fuel" and the "Clean Cooking" scenarios in Figure 6-1, the techno-economic eCook modelling tool developed by M. Leach and R. Oduro [125], [132] is used. The model is a numeric simulation model of cooking by a HH linked to a system design for a battery-supported eCooking device. It is written using VBA language in Excel and running the VBA macro allows to estimate the monthly costs of cooking in various scenarios – when cooking only with conventional fuels (charcoal or firewood), LPG, or incorporating battery-operated eCook with/without varying levels of fuel stacking. For the financial analysis, the cost is spread over 5 years, representing a more practical way of implementing eCook in the near term with a Pay-As-You-Go (PAYGO) business model, and with a discount rate of 10%. The fuel cost range and the electricity tariff in Table 6-2 and Table 6-3 contain inputs to the model that were taken as a baseline based on the data published in [125], [133]. The data shown in Table 6-3 highlights the most recent data collected from the cooking diary studies which tracked the energy use, cost and cooking practices of a total of 20 HHs in Tanzania where the HHs are connected to a solar-hybrid mini-grid.

All of the "Mini-grid Network with eCook Batteries" scenarios (Figure 6-1) were first simulated with the national grid tariff and then with the mini-grid tariff to compare both cost trends and the impact of the high mini-grid tariff when moving towards eCooking. It should be noted that the results in section 6.3.2.1 assume that the wood is harvested sustainably, with replanting and regrowth, which justifies the low cost of firewood.

Table 6-2. Conventional fuel cost.

Charcoal ($/kWh)		**Firewood ($/kWh)**		**LPG ($/kWh)**	
Low	High	Low	High	Low	High
0.01	0.02	0.007	0.012	0.078	0.16

Table 6-3. Electricity tariff.

Mini-grid Electricity tariffs ($/kWh)		**National grid tariff**		
		Electricity tariff		Lifeline tariff* and monthly allowance
Low	High	Low	High	Lifeline tariff: $0.04/kWh allowance: 75 kWh
0.46	0.74	0.1	0.2	

* Lifeline tariff means that HHs are provided with a minimum unit of electricity per month at a low cost

Furthermore, in this chapter, the monthly cost of each scenario is calculated for the years 2022 and 2030. The techno-economic eCook modelling tool assumes that the eCook component costs are expected to reduce gradually over time, and the prices of traditional fuels are expected to increase (at 3% per year), for more detail on the eCook modelling tool refer to [18]. The techno-economic analysis of each of the cooking scenario results is presented and discussed in section 6.3.2.1.

6.3.2.1 Results and analysis

Figure 6-2 shows the monthly cooking costs in $ based on the cooking scenarios in Figure 6-1. The first two involve cooking 100% with conventional fuels showing that both are available at a low cost; for 100% charcoal, the cost ranges between $8-17/month while 100% firewood is much less ($5-9/month). Moving towards clean cooking, cooking 100% with LPG becomes the best cost-competitive option ($11-22/month) compared to eCooking as it has the lowest cost. The results of cooking 100% with electricity requiring a 6 kWh battery demonstrate that the monthly cost is considered the most expensive compared to the other cooking scenarios, which is seen as a cost barrier for low-and-middle-income HHs. However, a gradual transition towards eCooking helps to reduce the size of the battery to 2 kWh along with the monthly cooking cost. Using a mix of 50% firewood with 50% eCook is seen as the most cost-effective of the three combinations of fuel stacking scenarios when the electricity source is either from the national grid or the mini-grid - with a cost of $24-26/month and $45-62/month respectively. A mixture of 50% charcoal and 50% eCook is the second most cost-effective option with the cost of using the national grid supplied electricity at $26-32/month compared with mini-grid supplied electricity at $47-67/month. Pairing 50% eCook with 50% LPG instead of conventional fuels increases the cost to $28-35/month when using the national grid tariff and to $49-71/month when using the mini-grid tariff. The data shows that in an off-grid context characterised by a high cost of electricity, transitioning to eCooking with and without fuel stacking is more challenging. Hence, there is a need for further investments and policies that result in the cost reduction of mini-grid electricity prices to achieve greater parity with national grid-supplied electricity.

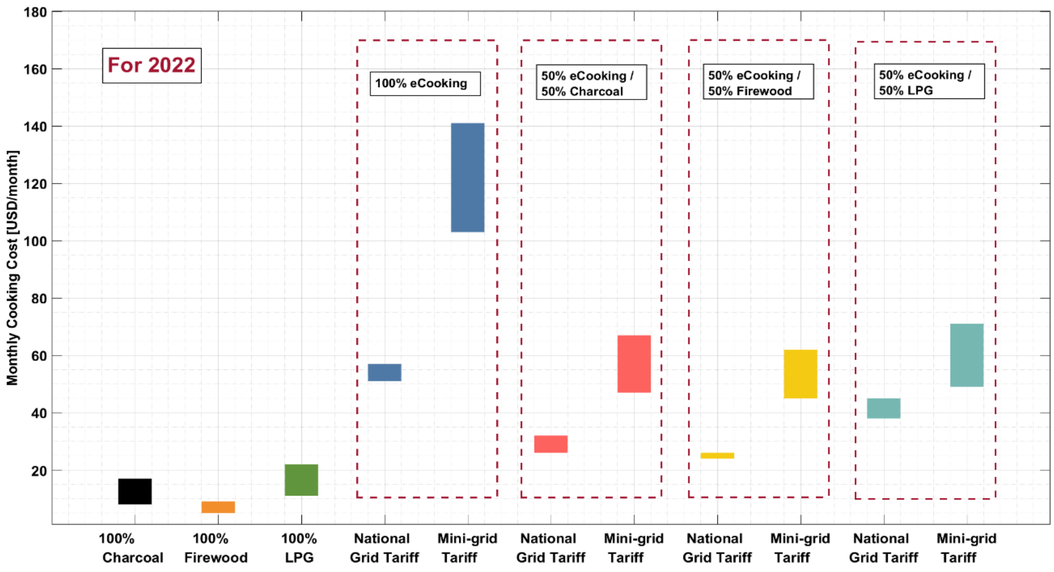

Figure 6-2. Monthly cooking cost of the contextualised cooking scenarios under study calculated for 2022.

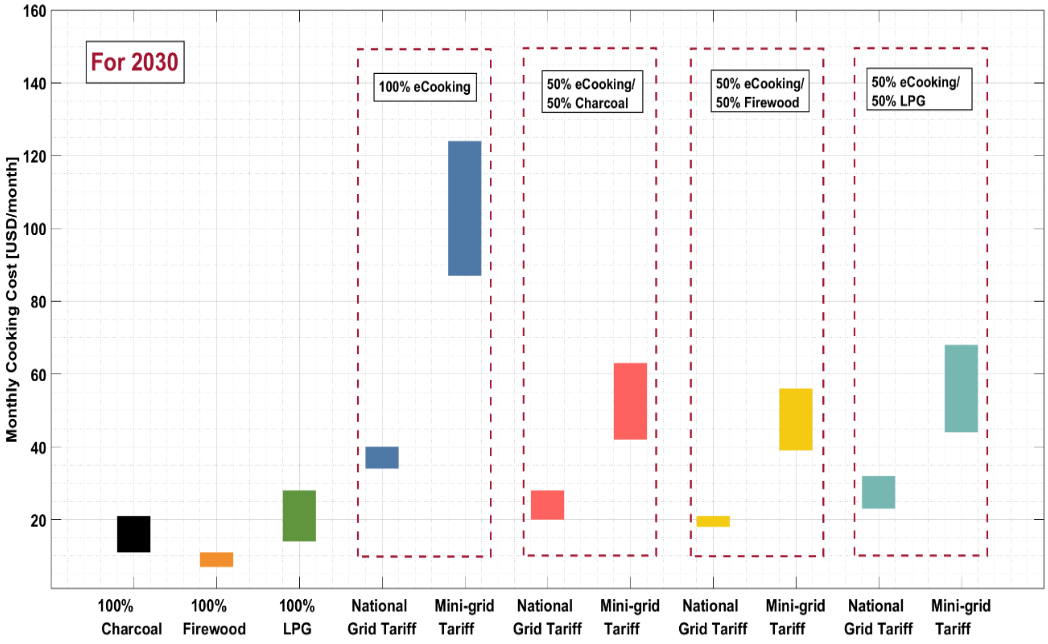

Figure 6-3. Monthly cooking cost of the contextualised cooking scenarios under study calculated for 2030.

By 2030 it is projected that the cost of firewood, charcoal and LPG will rise as illustrated in Figure 6-3, however, cooking with 100% firewood and stacking firewood with electricity remains the cheapest option. It cannot be ignored, however, that cooking with firewood leads to a high level of emissions if it is not harvested sustainably.

As previously mentioned, LPG presented itself as the cheapest option for clean fuels. The reason behind this is that some Governments offer microloans for the initial upfront costs of LPG equipment, subsidised refill costs and set transport costs for delivery to rural areas. However, there is still much scepticism by the public surrounding the safety concerns of LPG.

The main key findings from these analyses are:

- Cooking with firewood is the cheapest option, although at this stage of the analysis, there is no commercial value included in the price of the firewood. Adding this to the estimated cost, as this becomes scarcer due to overharvesting and even due to climate change impacts, could significantly change the results.
- The battery size for 100% eCooking is costly, accounting for the worst-case scenario as mentioned in section 6.3.2. This leads directly to an increase in the initial investment cost as well as the monthly cooking cost. To further reduce the battery capacity, instead of sizing the eCook battery to account for a minimum SoC of 20% and a maximum SoC of 80%, it would be more practical to take a minimum and maximum SoC of 20% and 100% respectively. Also, a one-day autonomy was selected instead of 1.5. This gives an eCook battery size of 3 kWh for 100% eCook and 1.25 kWh for 50% eCook.
- It is important to reduce the mini-grid tariff to a value close to the national grid tariff as well as to increase the lifeline tariff allowance to maintain the cooking electricity consumption within the specified value.

The following section presents results that include a comparative analysis when incorporating these key points in the cooking cost evaluation.

6.4 Closing the affordability gap between conventional cooking fuels and battery-operated eCook

6.4.1 Developed Scenarios to Bridge the Affordability Gap

This section intends to characterise the condition under which eCooking with a battery-operated eCook can be more cost-efficient than firewood cooking and so addressing the affordability gap. As highlighted in section 6.3.2, the results show that firewood is the least expensive cooking fuel option used by most low-and-middle-income HHs, so the target is for the monthly cost of battery-operated eCook to reach a level that is equal to or less expensive than firewood to become an attractive option. To achieve this target, four additional cooking scenarios are simulated and examined using the techno-economic analysis. The eCook modelling tool (introduced in section 6.3.2) was used. The additional scenarios are as follows:

- Scenario 1: Here cooking is done with 100% firewood and at this stage of the analysis the non-market cost is included which ranges between \$0.17-0.37/kg this translates to \$0.04-0.086/kWh (when the wood is harvested unsustainably).
- Scenario 2: This explores the price of cooking with 100% eCook with a 3 kWh battery. The cost, in this case, was calculated using only the national grid tariff since in the previous results, it was noticed that this was lower than the mini-grid tariff.
- Scenario 3: This is the same as scenario 2, with an increase in the monthly allowance for the lifeline tariff from 75 kWh to 100 kWh with a lifeline tariff of \$0.04/kWh.
- Scenario 4: The cooking price when using a mix of 50% eCook with a 1.25 kWh battery and 50% firewood. It also takes into account the non-market price of firewood and the 100 kW lifeline tariff allowance.

6.4.2 Result Analysis and Discussion

When examining the results displayed in Figure 6-4, a high monthly cost occurs when cooking with firewood cooking where the full non-market cost (value of unpaid labour and environmental impact) of fuel is included. In this case for 2022, the cost of cooking with firewood ranges between \$29-64/month.

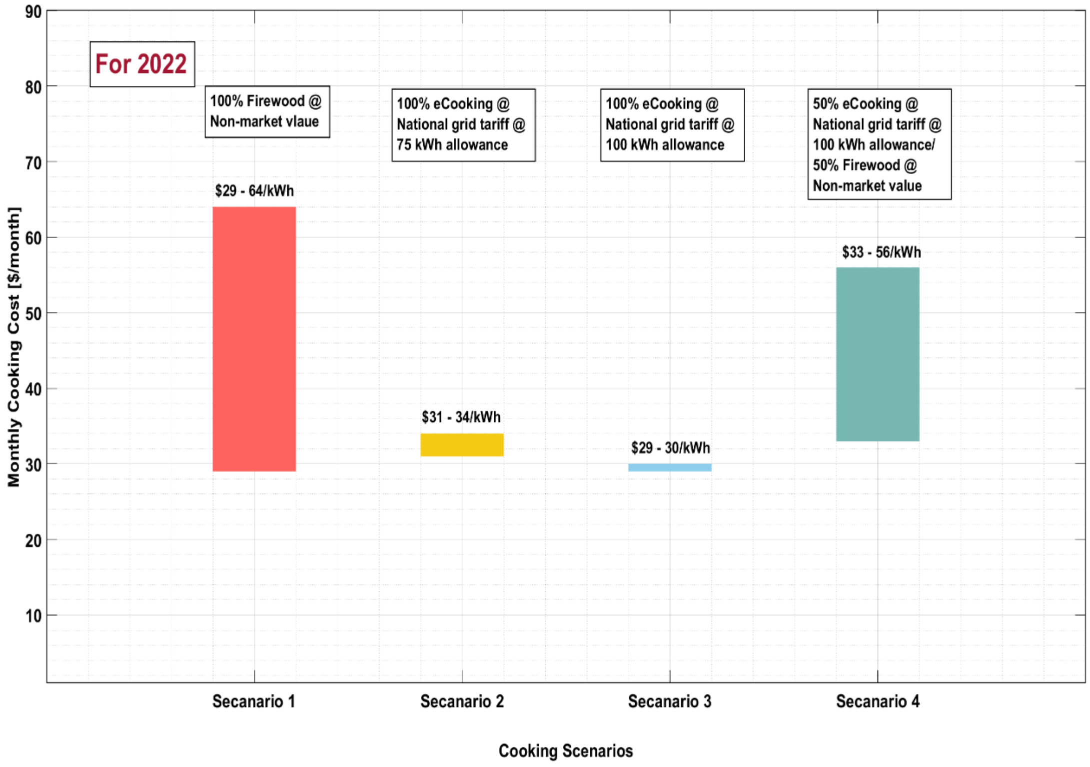

Figure 6-4. Monthly cooking cost of the contextualised cooking scenarios to close the affordability gap by 2022.

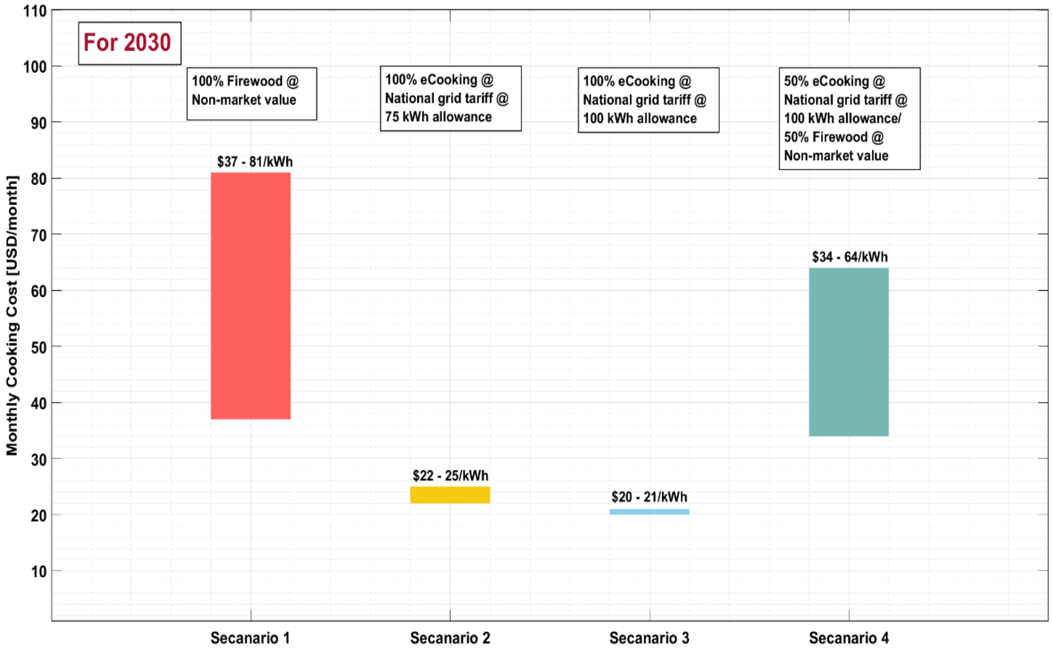

Figure 6-5. Monthly cooking cost of the contextualised cooking scenarios to close the affordability gap by 2030.

Nevertheless, 100% eCooking is between \$29-30/month for scenario 3. The overlapping bars in Figure 6-4 imply that it could be an opportunity for parity, when the firewood cost reaches \$29/month if, 1) the battery cost is affordable, 2) there is an increase in the lifeline allowance and 3) the non-market price of firewood is taken into consideration. The same applies to the cooking prediction cost for 2030. Also, the 100% eCooking cost of scenario 3 reduces further to \$20-21/month. However, if the firewood is harvested sustainably, ensuring it is high in quality and dry it would be difficult for battery-operated eCook to compete with it (see section 6.3.2.1). Under the fuel stacking scenario (50% eCooking and 50% firewood) for both points in time; 2022 and 2030 for scenario 4, it becomes the least favoured option compared to scenarios 2 and 3 when the non-market value is included in the firewood cost.

6.5 Conclusion

To achieve widespread uptake, battery-operated eCooks must be seen as accessible and highly desirable products by the low-middle-income HHs. From the analyses in this chapter, it is apparent that 100% eCooking becomes cost-competitive with firewood when including these three main factors; (1) accounting for the non-market cost of firewood, (2) ensuring a low mini-grid tariff that is in a range of the national grid tariff, (3) an optimal battery-operated eCook capacity sufficient to meet the required demand. The following section presents a further discussion on this topic and provides the overall conclusion of the thesis. In addition to evidence-based recommendations for rural eCook to move forward to cooking with electricity. Furthermore, potential improvements and future works that can follow this research are also discussed here.

7 CONCLUSION & FUTURE WORK

> *"No book can ever be finished. While working on it we learn just enough to find it immature the moment we turn away from it."*
>
> *"Karl Popper"*

From the literature review associated with this research, the use of traditional cooking stoves in rural Sub-Saharan Africa has serious environmental, social, economic and health implications including harmful emissions of black carbon, an estimated four million premature deaths annually**,** local forest degradation due to unsustainable fuel collection and the loss of time spent while gathering fuel that could range from 1.5 to 5 hours as the distance travelled for collecting wood could involve several kilometres in rural areas. Consequently, alternative solutions such as eCook have the capability of bringing considerable health, development, and environmental benefits. However, when moving towards eCooking it was discovered that the energy systems in developing countries and their power needs were faced with several challenges (limited grid access, limited generation and the weak grid infrastructure) which obstruct the eCook transition. It was also seen throughout the literature review that there was the absence of a methodology able to assess the design readiness of power networks and future design requirement when accommodating the additional eCook. To fill this gap, this thesis aimed to provide proposals and the development of a methodology which will be an important functional tool for min-grid developers in planning and for designing eCook-based mini-grids in rural areas. The approach taken is to assess and understand the upcoming impacts of eCook demand on the mini-grid performance, to explore the potential solutions to minimise those impacts, to enable the widespread uptake of eCooks and finally to conduct techno-economic studies to bridge the affordability gap of eCooking and provide recommendations to identify the least cost, the best-fit cooking scenario when cooking with electricity as a cooking option in developing countries. Conducting these studies, give a better understanding of what a viable eCook mini-grid system design might look like as well as provide clear and comprehensive answers to the following questions:

- What are the technical network constraints limiting eCook deployment?
- Whether the existing network infrastructure is capable of supporting extra loads?

How ‘fit for purpose’ existing mini-grids to accommodate increasing eCook demand, or indeed what design considerations or interventions would be required to make them so? It should be noted that the overall results obtained throughout this thesis cannot be generalised as there is no standardised mini-grid. However, the proposed and the development methodologies can be used to assess the design readiness and speed up the eCook uptake.

1. From the analysis carried out on the mini-grid network modelled in OpenDSS/MATLAB, where the selected mini-grid topology is hub and spoke, the finding illustrated that the network voltage drop and VUF issues can be reasonably and affordably addressed by using cables of a larger CSA. The main issue prohibiting higher penetrations of eCook, centres on generation capacity limitation and the high COE. Therefore, the solution lies in either:
    - Reinforcing the mini-grid generation
    - Incorporating a smart DSM technique to minimise capacity upgrades and enable more HHs to cook with eCooks.
2. The proposed ‘smart’ EBMS in this thesis offers many advantages as it:
    - Maximises eCook demand deployment, and ensures that the network is within system constraints through actively monitoring the state of the grid and deciding on the eCook’s battery C-rate set-point required to address the network constraints
    - It enables a combination of slow and fast charging allowing a greater battery charge coverage across the network
    - Ensuring that eCook devices are ready for use in the evenings
    - It provides the best QoS, since it increases the number of eCook batteries recharged daily compared to a network without the ‘smart’ EBMS.

  - This approach could be used in conjunction with other flexible and non-flexible high-power appliances, to facilitate their uptake.

3. Communication technologies at mini-grid levels in rural areas have improved significantly. Smart meters are installed to provide consumers with information on their HH energy consumption while also providing the grid suppliers with information regarding consumer energy usage. Having an available infrastructure in place with communication facilities will facilitate the ‘smart’ EBMS integration within the system.
4. As seen in chapter 6, given that firewood is dominantly used for cooking in developing countries it is unlikely, at the present time, for a move toward eCook-supported batteries as the firewood is acquired with no financial cost. However, when the following main key factors are included; (1) accounting for the non-market cost of firewood, (2) ensuring a low mini-grid tariff that is within a range of the national grid tariff, (3) an optimal battery-operated eCook capacity sufficient to meet the required demand; in the techno-economic cost, modelling widens the opportunity for affordable eCook with respect to firewood usage.
5. For mini-grids with high tariff prices pro-poor actions should be encouraged to follow tariff schemes that help and make the connection and operational costs affordable to end-users, and/or focus on the investment costs of the system to support the poorer rural areas in accessing modern energy services. The national grid’s tariff scheme could be a suitable option, known as the graded tariff regime which is based on two tariff rates: a low tariff for the first kWh and a higher tariff for higher consumption.
6. To access eCook services it is essential for the mini-grid tariff rates to be coherent with the national level and to increase the lifeline tariff allowance sufficiently, to cook above the baseload energy demand while being affordable to all at the same time. Due to differing factors, tariff rates range considerably from country to country in Sub-Saharan Africa. For example, Zambia has a relatively attractive graded tariff scheme with a high tariff of \$0.09/kWh and a lifeline tariff of \$0.02/kWh for a monthly allowance of 200kWh. The same can be seen in Kenya in terms of the lifeline tariff allowance (\$0.17/kWh for maximum monthly consumption of 100kWh), although the high tariff is \$0.23/kWh. In the case of Tanzania, there is a necessity to increase the maximum monthly allowance limit from 75kWh to 100 kWh or even more, to enable 100% eCooking (as shown in

chapter 6). However, Uganda's graded tariff scheme could be a problem when switching to eCooking – it comprises of a high tariff of \$0.2/kWh and a lifeline tariff of \$0.06/kWh for a 15 kWh monthly allowance. Comparing these countries' tariff rates, clearly shows that a more structured pricing scheme is necessary to provide an optimal low tariff and a more generous allowance, sufficient to make the mini-grid projects commercially viable.

7. In addition, further subsidies and support grants are necessary to make mini-grid expansion in Sub-Saharan Africa more attractive to the developer. Other factors which could be considered in future studies to further reduce the COE [10] are:
    - More efficient appliances are used.
    - Integrating smart monitoring, management, and control devices into the system (such as using the 'smart' EBMS) to smooth out the daily peak and offers support for investment in system operation to reduce daily blackouts and restrictions on electricity consumption due to grid constraints.
    - Building standardised and integrated mini-grids capable of interconnection to the main grid when it arrives.
    - The cost of PVs, inverters and battery storage continues to fall sharply—Bloomberg New Energy Finance forecasts the COE of PV will decrease 66% by 2040 [134] and "The International Renewable Energy Agency" (IRENA), predicts the cost of lithium-ion batteries could decrease between 54–61% by 2030, reducing the total installed cost for lithium-ion batteries to as low as \$145/kWh [134].
    - Additional customers making productive use of energy connect to the mini-grid. BloombergNEF and Sustainable Energy for All [11] point out that the COE for mini-grids with daytime loads is less expensive than for mini-grids with only residential customers who consume electricity mostly in the evening. This is due to productive-use customers (such as agriculture and factories) with daytime demand aligning with the solar peak.
8. The firewood, as previously highlighted, collected in rural areas is a commodity without a market value, as the firewood is sourced from public forests and there are no monetary transactions involved. However, there are hidden non-market labour values and social carbon costs attached to this operation. Gender inequality implications must be considered also, as it is predominantly women and children

who collect this essential HH commodity and in doing so are prevented from receiving education, training, suffer from lost childhood and lack of social activities as well as endangering their physical health, such as back injuries caused by carrying heavy loads and respiratory illnesses caused by inhalation of toxic fumes when cooking indoors, leading to 4 million premature deaths annually.

9. These non-market labour activities must be factored into the price of the firewood and populations must be educated about the risks involved and shown the benefits of and advantages clean cooking and using electricity brings. It is necessary to develop an appropriate methodology and implement it as an important functional tool to estimate the non-market cost of cooking. This can be done by conducting surveys across the Sub-Saharan countries capturing a wider variety of data, including; evaluating the amount of time spent collecting firewood and, the wage paid to casual employees and a person of similar skills employed in the public or private sectors, together with the social cost of the carbon footprint. Analysing the data could compare the similarities and differences of the individual countries surveyed, predicting the optimal non-market value and evaluating whether it is appropriate to deploy eCooking in that particular country or consider another type of clean cooking. However, with a HH’s average monthly salary of $25-30, cooking with eCook batteries is still uneconomical and impractical.
10. The effects of climate change are experienced each year in Sub-Saharan Africa in the form of drought, flooding, and migration of people to survive these environmental impacts. Although, research, at present, again found to be very limited on how this impact the supply and price of wood, it is almost certain the consequences will inevitably lead to wood shortages and price increases. Once again putting a strain on low-income families through increased costs in cooking and heating, and additional collection times – quite apart from the environmental degradation and biodiversity loss caused.
11. Furthermore, regulations should be implemented by proposing to create plantations for firewood and impose controlled kilns for producing charcoal, reducing deforestation and unnecessary CO_2 emissions created from old or damaged private kilns. The operators would be required to obtain permits and pay tax revenues to the relevant governments. This additional income through carbon credit could then be invested, specifically in renewable energy projects, primarily in rural areas, to install solar PV panels, improve the country’s infrastructure or

subsidise the price of batteries or electricity. This can be regarded as a step towards making eCook on mini-grids viable and being adopted by other developing countries.

7.1 Suggestions for Future Research Work

1. Concerning future research on the mini-grid level, it is important to highlight that mini-grid designs in developing countries are not standardised and not sufficiently developed to accommodate large power appliances, and for these reasons, future research needs to focus on and compare different mini-grid categories in terms of capacity and cable sizes to investigate network constraints and the maximum eCook penetration a system can accommodate with/without the ‘smart’ EBMS to determine the tipping point for this transition to be possible.
2. Due to the lack of accessible information surrounding mini-grids (location, quality, abundant energy sources, sizes, tariffs) to relevant sectors, there is a need to increase the understanding concerning mini-grid experiences and collect sufficient information and make it available in an open-access database. This would be an extremely useful tool when accessing existing mini-grids and planning future ones to accommodate new loads such as eCooks or other high-power appliances.
3. Furthermore, another important point to highlight is that cooking with electricity is still in an embryonic phase and there remains a lack of data concerning cooking load profiles and consumer behaviour. Most of the available data were collected over a short period making it difficult to predict the long-term effects or to extract meaningful information such as seasonal variations for the cooking data, gathered during COVID-19 may not give a true representation of information as this pandemic had an unprecedented effect on cooking practises and fuel usage. The pandemic dramatically changed people’s routines and their cooking decisions owing to a reduction in HH income and additional HH members being present during the day, price increases in staple food and fuel, travel restrictions and higher transportation costs. A combination of these factors significantly impacted the types and amount of food cooked, the person cooking, and the fuels used. Therefore, it is difficult to assess conclusively how the impact of seasonal variations influenced the cooking decision during this period. Hence, there is a

pressing need to collect and assess HHs eCook data to fill the current void at the social, economic and network levels.

4. Another area is to examine the advantages/disadvantages of a combination of energy resources in mini-grids and compare them with hybrid solar mini-grids to reduce energy costs. The advantages and benefits of introducing different technologies, increasing the share of renewables, and hence covering a variety of shifting load profiles during the day and reducing the cost of energy. Nevertheless, the following key factors must be considered when assessing the hybrid-multi source mini-grids:
    - The renewable resources and the technologies available in the region under study
    - The structural cost of the system
    - The quality of service
5. The danger when sizing the battery-operated eCook may be undersize/oversize the battery-operated eCook. The former could lead to the cooking demand not being met, while the latter could be detrimental to the system's cost. Scalable cooking with electricity is still in a rudimental stage and again as previously discovered in other areas of this research there remains a lack of cooking load profile data to analyse battery performance. This thesis has again identified an area for future research, battery-operated eCook trials on mini-grids need to be conducted to identify research gaps to select the necessary key requirements for the battery, calculate the optimal size with balanced performance, lifetime duration, and costs while keeping within the specified safety limit. The batteries must also be able to meet all the daily cooking demands and support all locations with variable levels of solar resources available. Also, eCook batteries offer a potential solution to clean cooking, from the environmental aspect, however, without a full life cycle assessment of this transition and compare case-by-case the cooking scenarios studied in this chapter, these environmental benefits will not become apparent.
6. Another subject for further research, not explored in this work, is to study the impact of increasing the load factor of the mini-grid with the cost of energy, as demand for cooking could increase and generate additional income for the developer and operator. At present errors are being made by developers in the

design and planning of mini-grids in developing countries. When constructing mini-grids they are sized and installed to satisfy today's economic situation, with only short-term planning in mind and without considering future economic activity. This theme, as discovered through the literature reviews was also found in most research to date, with the choices in technology and the generation sources being made for short-term least-cost scenarios. However, it is essential that long-term realistic planning is considered and put into place when constructing mini-grids, as inevitably future demand will increase dramatically, as new products such as eCooks are added to the mini-grid, while moving towards 100% load or other high-power appliances are introduced to HHs to improve living standards. Even though at present cooking 100% with electricity is not a viable proposition, however, there will, it is hoped, be a point in time when a 100% transition to meet the sustainable development goals will become mandatory. Therefore, without this foresight in future planning, severe burdens, coupled with the impossible task of fulfilling demand requirements and high additional upgrade costs will be incurred. The approach taken in this thesis was to consider long-term future planning, look beyond the short-term solutions and focus mainly on researching 100% eCook transition, along with the techno-economic barriers and proposing solutions to enable the sustainable and affordable future transition.

To conclude, similar obstacles were notable in the early days of EV and smart meter rollouts in developed countries as well as in the case of portable telephones and lighting in developing countries. The most discussed reasons behind the difficulty of the rollout of these technologies were technical, economic, political, cultural, social, and psychological; (high cost, vulnerability and poverty, problem of misattribution, lack of awareness, consumer resistance and ambivalence, and lack of product choice). However, a range of Governmental supports, tailored policies, and regulatory frameworks were supportive or deeply involved over the previous decades which also provided funding to suppliers and network companies to invest in these projects and innovative research. Therefore, the lessons learnt from previous technology rollouts can be applied to move towards eCooking.

With time, as with other technologies, the eCook market will increase due to customer awareness. Those who already engage in eCooks will act as educators to others informally, showing the advantages of this new technology, thus increasing the number of potential customers, throughout the market. As the demand for eCooks increases, this, in turn, will contribute to reducing the technical and generation cost and improving the technical performance. As in any new market, with growth, a wider range of eCooks will become available giving potential consumers more choice and purchasing power.

Furthermore, the real hope for developing countries to implement new projects and move forward at a quicker pace would be to encourage foreign investment. However, this is not a simple task, as unfortunately, in many developing countries projects are not well handled and corruption and bureaucracy are at the forefront. Hence, Governments would have to demonstrate and give assurance that overseas, financial involvement in any ventures would be secure and well-managed. Also, a dramatic investment in both public and private investments is needed to achieve on-the-ground results in clean cooking.

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9 APPENDICES

APPENDIX 1 DSM STRATEGIES AND TECHNOLOGIES

Table 9-1. DSM strategies and technologies (principle/advantages/disadvantages) [51].

Types of DSM	DSM measures	Its principle	Advantages	Disadvantages
DSM strategies	Efficient appliances and lights	Reduce the electricity consumption and peak demand by using more efficient appliances such as light bulbs	• Reduce the electricity bill • Enhance the quality of life • Reduction in the initial generation capacity of the mini-grid • Allow the mini-grid to serve more users	Long term result
	Commercial load scheduling	Load management action for commercial loads	• Allow companies to save energy and cost by minimising their demand consumption. • Protect the commercial equipment and processes from damage due to low voltages • The use of Time-of-use pricing	The commercial loads should be managed appropriately to provide adequate and affordable electricity to both residential and commercial customers
	Restricting residential use	Restricting households to certain types of residential appliances	• Limit peak load • Encourage electricity conservation	• Households could attempt to violate the agreement and use high power appliances • No mechanisms are put in place to reinforce it
	Price incentives.	Two schemes: • Capacity-base tariff: fixed charge based on the maximum allowable capacity	Capacity-base tariff: • Make billing easier • Limit the mini-grid power • Could be used in conjunction with	• Difficult to reinforce • Only applicable with a smart meter

		• Consumption-based tariff: based on the unit of energy consumption used	an energy-based tariff • Consumption-based tariff: encourage energy conservation for energy-limited mini-grids (solar and wind)	
	Community involvement, consumer education, and village committees.	Community involvement to allow for better durable achievement goals of the project and to ensure that the community complies fully with the DSM tools used	• Improve the management of the system • Improve user's satisfaction by explaining the importance of incorporating DSM • Can empower community members and project managers to manage and enforce decisions on tariff structure and load management • Cost and time savings	• Additional training requirement
DSM Technologies	Current limiters.	Restrict an upper limit on the current delivered to the household to protect the system from overloading. Different types are found in the market such as fuses, miniature circuit breakers (MCBs), positive temperature coefficient thermistors (PTCs) or electronic circuit breakers (ESMAP). Current limiters are commonly used with energy meters	• Cost savings • System protection from overloading by limiting the mini-grid power	Limiting the type and number of household appliances
	GridShare	Plays the role of a smart current limiter	• Reduces daily blackouts and	The cost of the pilot is

		to enable the utilisation of high-power appliances (rice cooker and water boiler)	enables households to use high-power appliances	unaffordable (cost under $100)
	Distributed Intelligent Load Controllers	Used to manage load and limit peak demand by prioritising load for curtailment as well as shifting the flexible loads to non-peak hours to use the access energy production	• Keeps the electricity consumption at its desired level • Enables high power appliances to be used • Less power outage with a reliable power supply	
	Conventional meter	A meter reader allows measuring the energy used and displays it to easily monitor the electricity consumption supplied from inconsistent generation and limited storage such as wind and solar. A billing scheme is used after the electricity is consumed	• Does not restrict any limitation on the power or energy consumption • Encourage energy conservation	• Can be misleading and inaccurate • Poorly managed billing practices can be controversial and lead to frustration for the customer as well as the billing authority • Lack of understanding of how electricity is used that can lead to higher bills
	Prepaid meter	The electricity is prepaid using regular payments either by a prepaid card or code which allows the consumer to control the bills	• Reduces account posting costs • More reliable power supply • Eliminate the need for meter readers • Guarantees payment	• The additional cost needed to install the prepaid meter
	Advanced metering systems with centralized communication	Advanced metering allows the utility the ability to monitor and control the generation and	• Creates the potential for DSM • Reduces the energy	• More expenses are added to the system's capital cost

		efficiently respond to current events. It uses a prepaid scheme	consumption and prevents overloading the system by integrating power limiters	• The estimated cost is around $100-$200

APPENDIX 2 A DETAILED FLOWCHART OF THE MINI-GRID`S CENTRAL CONTROLLER AND THE BATTERY-OPERATED ECOOK CHARGE CONTROLLER

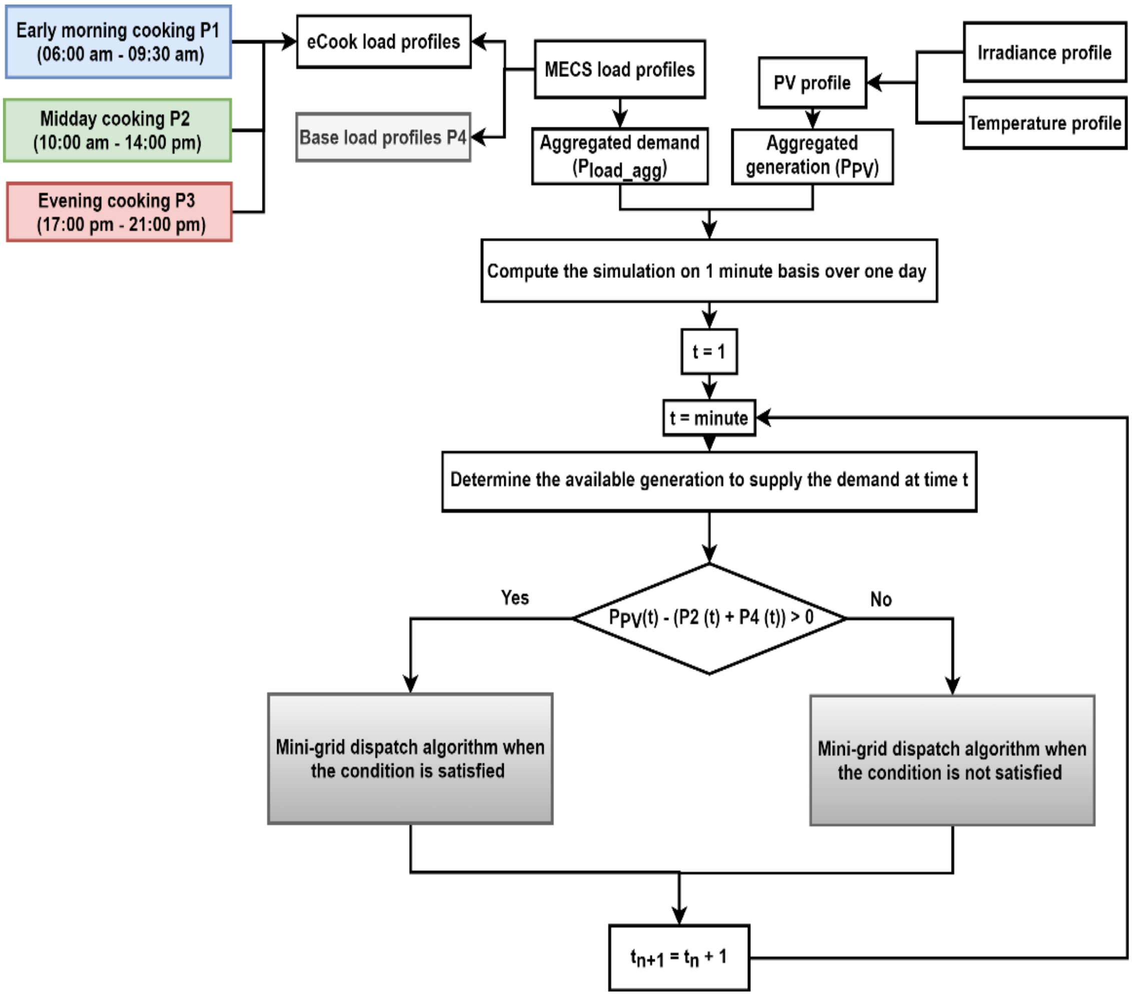

Figure 9-1. Mini-grid central controller and battery-operated eCook charge controller algorithm.

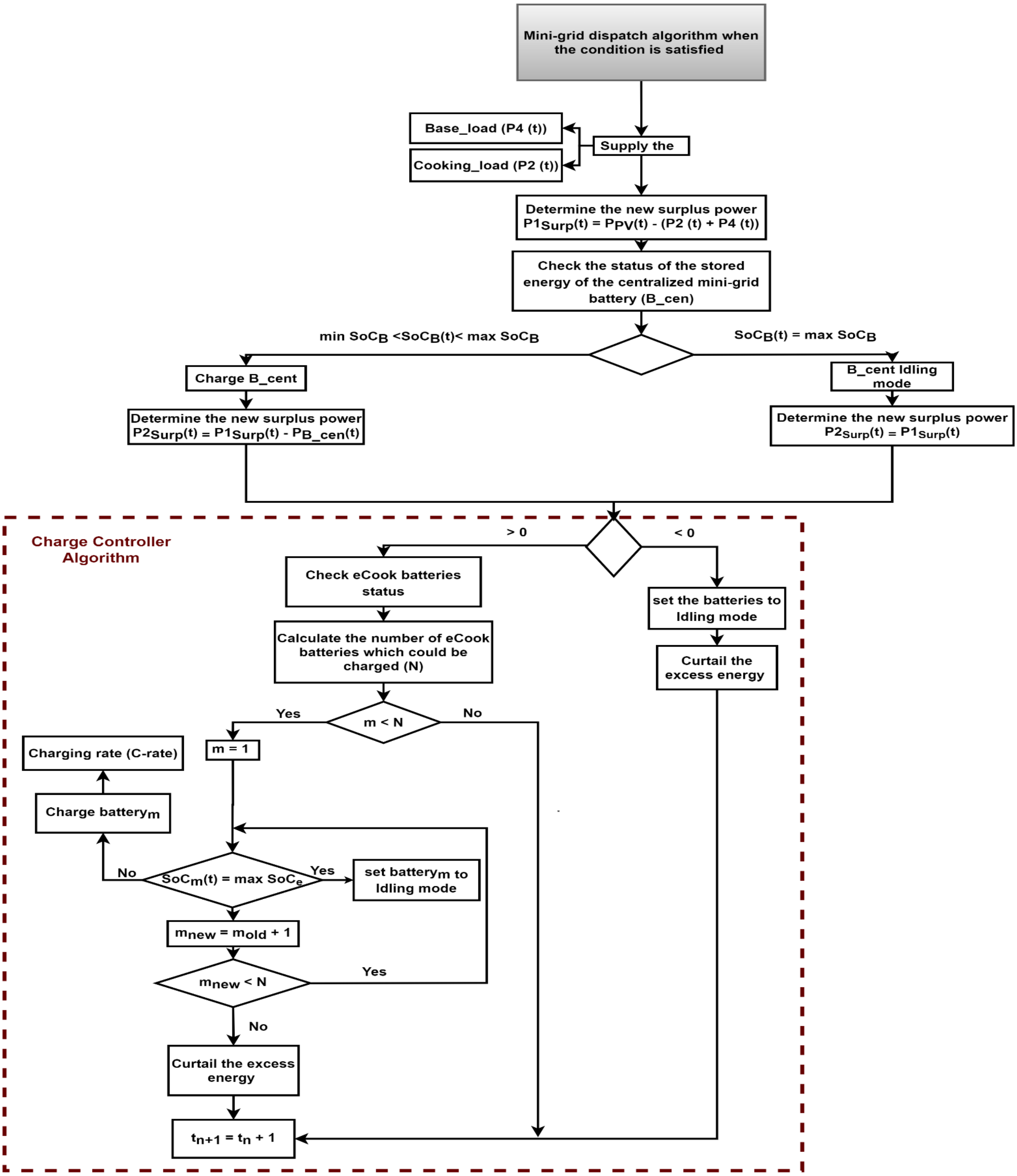

Figure 9-2. The logical flow of the mini-grid's central controller and battery charge controller when the condition is satisfied in Figure 9-1.

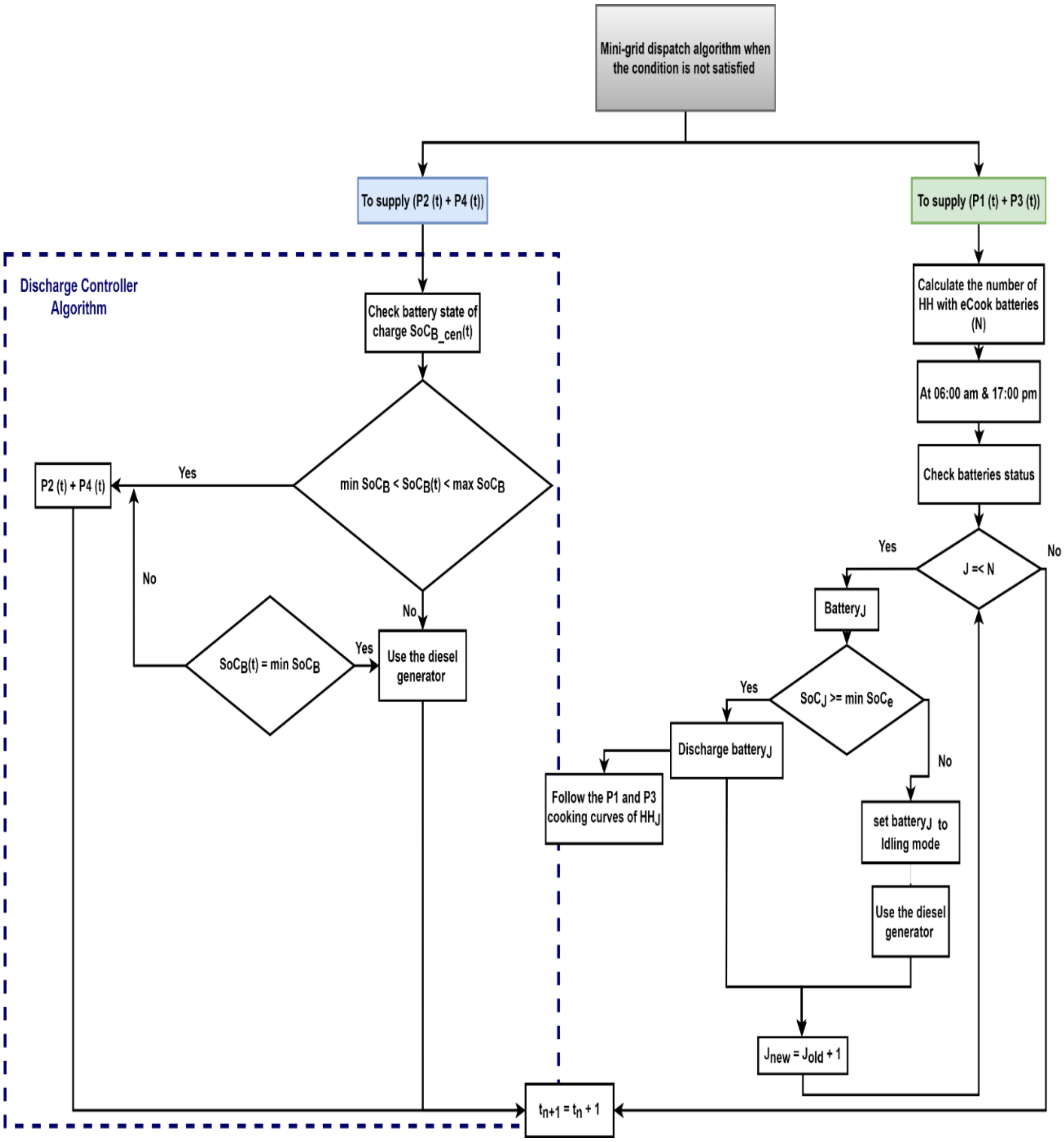

Figure 9-3. The logical flow of the mini-grid's central controller and battery charge controller when the condition is not satisfied in Figure 9-1.

APPENDIX 3 THE REVIEWER'S COMMENTS AND RESPONSES FOR EACH OF THE PAPERS PUBLISHED

During the reviewing process of [79], [114] and [126] valuable observations, comments and feedback were given by the reviewers for each of the published papers that contribute to the novelty of this thesis. Each of these comments was addressed as follows.

- Since the electrical network Figure 3-6 has a dendritic structure it is not surprising that the voltage drop is largest at the end of the lines. Had it not been useful to consider a loop wiring system to stabilise the voltage? Indeed, it would increase the installation costs but would stabilise the system for further extension and hence reduce the costs in future.
- The authors acknowledge that loop wiring systems (mesh networks) have many advantages however, this research, it did not consider this type of network topology as the aim was to conduct the necessary studies on a mini-grid topology representative of the ones installed in Sub-Saharan Africa which are hub-and-spoke (also known as a "radial" topology). The mini-grid was developed as a composite of those designed and installed by practitioners and based on mini-grid design methods available in the literature (in terms of topology and other network characteristics "included; the cable sizes, lengths, bus connection, resistance and reactance"), this has been explained in detail in chapter 3 particularly section 3.1.2. Hence, the objective was to investigate 'how fit for purpose' a radial topology and existing mini-grid networks to accommodate increasing eCook demand without any rearrangements. However, a loop wiring system will be an interesting feature to include in our future research work.
- Furthermore, the "cost of energy" section seems to be not well-thought-out in chapter 4 (section 4.1) since it does not consider the price fluctuation of diesel, however, the probability of markup is high in future, life-time of PV and batteries and general maintenance costs of the different parts, e.g. diesel generator and PV, are quite different. This is not considered in the simulation, but a significant aspect of sustainability.
- The cost analysis considered the most recent diesel price which was recorded by the World Bank corresponding to that one of 2016. We acknowledge that

the fuel price fluctuates substantially, and this question was considered and researched before the simulation was carried out. Throughout the research, it was discovered that there is insufficient data available in literature representing this issue as it is difficult to accurately forecast events in World fuel prices. Also, another factor, is that all countries are unique in the methods used for domestic fuel pricing such as the rate of excise duty charged, or any subsidies given. These could be subject to rapid change due to an economic crisis.

- In addition to this, in the simulation, a 6% inflation rate and a 10% discount rate (which are standard figures for business planning) were used. Also, the following parameters were considered:
    - The initial capital cost, the replacement cost and the life cycle of each of the mini-grid components.
    - The annual fixed operation and maintenance (O&M) cost accounted for 2% of distribution capital expenditures (CAPEX).
    - The project's lifetime is assumed to be 20 years.
- It has been stated that the daily average consumption for cooking is 1.6kWh and based on this, the size of battery-operated eCook is stated 6kWh in chapter 5 (section5.3.1). It is suggested to elaborate on this. Also, if 6 kWh is for one battery-operated eCook then total demand increases to 47*6 = 282 kWh, kindly verify.
- The equation used to calculate the size of the battery-operated eCook can be found in [123] as well as the steps taken to calculate the battery size of the 1.6 kWh daily average energy consumption used, as well as considering other important factors to improve the battery's performance through its mid-life design. These values are highly sensitive to the DoD, C-rate, and temperature. They are the calendar life ageing, and the cycle life, also, in the case of a hot climate, where the average temperature is around 33°C, the cycle life of lithium-ion reduces to 20% of its rating under ambient temperature due to internal reactions. Hence, it is important to limit the DoD to 80% or less to prevent harm to the eCook batteries, prolong their life and minimise charging losses. For these reasons in this paper, the minimum and maximum SoC are set at 20% and 80% respectively [124]. The round-trip

efficiency of the battery and the bidirectional converter efficiency were also considered in the calculations. Also, even though the battery size is 6 kW, the daily charging energy needed can vary depending on the SoC, since the batteries could be partially charged whilst waiting in the queue.

- Different countries may have very different situations in chapter 6. It would be better if the authors could show and discuss the data of scenarios based on different countries.
- Cooking with electricity is still in a rudimental stage and as we found in conducting the literature review there remains a research gap in this area in terms of the data concerning consumer behaviour, and little information is available on the amount of energy is needed to cook a meal in different countries how in particular, how much electricity, how it varies across cultures, the energy mix and cost. Unfortunately, the gathering of data was halted due to the Global Pandemic. That is why the analysis include a wide range of parameters and assumptions, and a wider generalisation of the results is discussed to understand the upcoming trends of eCooking with different energy mixes. However, it still only explores a subset of the possibilities. The studies and analysis presented in this paper highlight the most relevant data collected from cooking diary studies which tracked the energy use. However, as we gather enough data, the plan is that our future work will consider analysing and studying scenarios based on different countries which will be an extension to this paper.

الحمد والشكر يا الله على كل شيء

أتوكل عليك

” لَا تَقْنَطُوا مِنْ رَحْمَةِ اللَّهِ”

"...وَاعْبُدْ رَبَّكَ حَتَّىٰ يَأْتِيَكَ الْيَقِينُ"
(سورة الحجر - الآية 99)

"وَآتَاكُم مِّن كُلِّ مَا سَأَلْتُمُوهُ ۚ..."
(سورة إبراهيم - الآية 34)