Microgrid planning & design under uncertainty: A case study in Northern Angola

Prepared by:

Brian Kamanzi

KMNBRI001

Department of Electrical Engineering

University of Cape Town

Prepared for:

Dr D.T.O. Oyedokun

Department of Electrical Engineering

University of Cape Town

2019

Submitted to the Department of Electrical Engineering at the University of Cape Town in partial fulfilment of the academic requirements for a Master of Science degree in Electrical Engineering

University of Cape Town

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

University of Cape Town

Plagiarism Declaration

I know the meaning of plagiarism and declare that all the work done in this document, save for that which is properly acknowledged, is my own. This dissertation has been submitted to the Turnitin module (or equivalent similarity and originality checking software).

Signed by candidate

Brian Kamanzi

30 June 2019

Abstract

The national energy development plan for Angola, Angola Energia 2025, identifies the need to balance efforts to expand access to electricity in countries with low levels of industrialisation, across the urban and rural spheres. This need is coupled with the urgency of investing in environmentally sustainable technologies responding to local and international targets addressing the impacts of Climate Change. This dissertation seeks to assess the feasibility of an electricity micro-grid system (a) for uplifting the quality of life and development of two neighboring Angolan coastal villages, and (b) one that (I) depends entirely on *domestic renewable sources* of electricity generation; (ii)has a sustainable initial generating capacity of not less than 2MW and (iii) is flexible enough to undergo future expansion as needed over time.

The design of a proposed Microgrid solution for N'zeto and Tomboco villages located in Angola is developed through a thorough context study used in conjunction with remotely acquired contextual data and a variety of estimation and model techniques. Microgrids are defined as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity functioning with two modes of operation. The Microgrid design process requires a set of context specific empirical data ranging from load profiles of the site under survey to the availability of endogenous energy resources. The existence of *documented* public policy, the domestic availability of renewable resources in and around the study area, the present low population density in rural Angola, the low level of Angola's rural electrification , and the existence of financing mechanisms which the country can afford.

The load profile and contemplated electrical energy consumption in the study area along with an estimation of the availability, nature, diversity, and extent of the domestic renewable energy sources are developed as key inputs for design decisions related to component sizing. A comparative evaluation of their performance of two proposed candidate solutions, derived from the assessment of the available energy resources is used as a basis to select preferred candidate. The proposed solution is subjected a sensitivity analysis of key design variables. Aspects of the selected design, including concept of operations, reticulation and a discussion on the possible downstream benefits are elaborated in compliance with the technical and policy constraints of the proposed electrification scheme.

Acknowledgements

This dissertation has benefitted from diverse sources beside mine. First among them is my family. I would like, in this regard, to extend my special thanks to my father, Kamanzi-wa Binyavanga, for his general support as well as with the reading through the manuscript and providing feedback fairly promptly. He also assisted with making clearer some of the statistical sections of this study.

My mother, Sylvia Kamanzi, whose emotional and other crucial forms of support helped me get through difficult deadlines until the very end, equally deserves special mention.

To my supervisor, Dr David Oyedokun, I can hardly express my gratitude fully enough in this brief for the numerous consulting sessions he granted me whenever this was requested, as well as his consistent encouragement and prompt critical feedbacks.

Also, the discussions with and feedback from my department's Power Research Group from time to time often resulted in significant improvements to the study for which I am very grateful. The group comprises of staff and postgraduate students.

Lastly, but evidently not least, the examination copy of this dissertation was found during the examination phase to have some parts that needed amendment or correction. I am very grateful to the examiners for pointing them out as my subsequent attention to them has significantly improved the present dissertation.

Contents

Declaration i

Abstract ii

Acknowledgements iii

List of Figures vii

List of Tables viii

Microgrid planning & design under uncertainty: A case study in Northern Angola 1
Prepared by: 1
Department of Electrical Engineering 1
Prepared for: 1
Plagiarism Declaration i
Abstract ii
Acknowledgements iii
Contents iv
List of Figures vii
1. INTRODUCTION 11
1.1 MICROGRIDS SUITABITILITY IN ANGOLA 11
1.2. INTERNATIONAL EXAMPLES OF MICROGRID FINANCING 13
1.3. RESEARCH HYPOTHESIS 15
1.3.1. INTRODUCTION: 15
1.3.2. RESEARCH HYPOTHESIS: 15
2. LITERATURE REVIEW 17
2.1 DEFINITION OF MICROGRID 17
2.2 CLASSIFICATION 18
2.2.1 ON-GRID AND OFF-GRID MODES 18
2.3 SOURCES OF MICROGRID ENERGY 25
2.4 ENERGY STORAGE IN MICROGRIDS 26
2.4.1 STORAGE SYSTEMS 27
2.4.2 STORAGE TECHNOLOGIES 28
2.5 CONTROL SCHEMES 34
2.6 ADVANTAGES AND DISADVANTAGES 36
2.7 TECHNIQUES AND SOFTWARE TOOLS USED TO MODEL MICROGRIDS 37
2.7.1 TECHNIQUES 37
2.7.2 SOFTWARE 38
2.8 CHAPTER SUMMARY 42
On methods for microgrid modelling, the literature identifies six. They are genetic algorithm, linear programming, neural-network algorithm, numerical methods, particle swam optimisation, and stochastic modelling. The tools used to model are statistical data on various load profile-

components, and commercially available computer software. The chapter ends with two international examples microgrid financing. 43
3. CHARACTERISATION OF LOAD PROFILE MODELS 44
3.3. THE DENSITIES ASSUMED FOR THE RANDOM BEHAVIOUR OF POWER CONSUMPTION 45
3.3.1. THE NORMAL DISTRIBUTION 45
3.3.2. THE BETA DISTRIBUTION 46
3.4 LOAD PROFILE MODELS 47
3.4.1. MANDELLI MODEL 47
3.4.2. JARDINI et al MODEL 49
3.4.3. SIMILAR DAY CHARACTERISATION 50
3.5. OTHER USEFUL MEASURES OF LOAD PROFILE 50
3.6. SYNTHETIC DATA TO BE USED IN THE MMTPC 52
3.6.1. In the absence of historical data on electricity consumption characteristics from the study area, substitute information that will be used in the MMTPC for our study area is set out in Tables 3-2 and 3-3 to follow. 52
3.7. EXTENSION OF THE SIMILAR DAY MANDELLI MODELS 61
3.7.1. INTRODUCTION 61
3.7.2. BASIS FOR THE CHOICE OF SYNTHEIC DATA 62
3.7.3. EFFECT OF ANNUAL WEATHER SEASONS 65
3.8. EFFECT OF LONG-TERM POPULATION GROWTH 67
3.9. ALGORITHMS FOR FITTING SIMILAR DAY AND SEASON 68
3.9.1. FITTING SIMILAR DAY UNPARTITIONED & PARTITIONED 68
3.9.2. FITTING SEASON ADJUSTED MODELS 70
3.10 CHAPTER SUMMARY 71
4. RESOURCE & INFRASTUCTURE ASSESSMENT 74
4.1. INTRODUCTION 74
4.2. RESOURCE ENERGY MAP 75
4.2.1. SOLAR 75
4.2.2. WIND ENERGY 76
4.2.3. HYDRO POTENTIAL 77
4.2.4. BIOMASS 80
4.2 AVAILABILITY OF BIOMASS FROM AGRICULTURAL PRODUCTS IN THE STUDY AREA 82
4.3. CURRENT TECHNOLOGIES FOR BIOMASS ENERGY GENERATION 86
4.4. CURRENT STATE OF ELECTRICITY SUPPLY, ROADS, AIRPORT AND HARBOUR 90
4.4.1. ELECTRICAL INFRASTRUCTURE 90
4.4.2. ROADS, AIRPORT, AND HARBOUR 92
4.5 CHAPTER SUMMARY 92
5. MICROGRID DESIGN 93
5.1. INTRODUCTION 93
5.3. OPTION 1 MICROGRID 95
5.3.1. LOCATION 95
5.3.3. PERFORMANCE STATISTICAL ESTIMATES 97

5.4. OPTION 2 102
5.4.1. LOCATIONS OF CONTROL CENTRES 102
5.4.3. PERFORMANCE STATISTICS 104
CHAPTER 6 108
6. FINAL MICROGRID PROPOSAL 108
6.1. INTRODUCTION 108
6.2. GENERATION SITES 108
6.3. DETAILS OF POWER GENERATION 109
6.3.1. GENERAL 109
6.3.2. SOLAR POWER 110
6.3.3. HYDRO POWER 110
6.3.4. BIOFUEL POWER 111
6.4. DISTRIBUTION NETWORK 112
6.5. CONTROL OF THE SYSTEM 120
6.5.2. PRIMARY CONTROL 124
6.6 ENERGY EFFICIENCY 129
6.7 OVERALL MICROGRID OPERATION PLAN 130
6.8 SENSITIVITY ANALYSIS 131
6.9 OTHER COSTS NOT CONSIDERED THUS FAR 139
6.9.1.1. COST OF DISTRUBTION CABLES 139
6.9.2. TRANSPORTATION OF EQUIPMENT 140
6.9.3. ANNUAL OPERATION OF THE BIOFUEL PLANT 141
6.9.4. COST OF ELECTRICITY REVISITED: IMPROVEMENT ON HOMER ESTIMATION 143
7. CONCLUSION 146
8. REFERENCES 149

List of Figures

List of Illustrations

Figure 2-1 A diagram of a generalised Microgrid system (with main grid integration).....18
Figure 2-2 A diagram depicting a basic AC bus based Microgrid system 20
Figure 2-3 A diagram depicting a basic DC bus based Microgrid system 21
Figure 2-4 A diagram depicting an example of a hybrid ac/dc Microgrid system 22
Figure 2-5 An image depicting a lead acid battery taken from https://opentextbc.ca/chemistry/chapter/17-5-batteries-and-fuel-cells/ 28
Figure 2-6 An image depicting an example of a flywheel system taken from http://www.free-energy-info.co.uk/Chapt4.html 30
Figure 2-7 An image depicting the operating of a Compressed Air Energy Storage System taken from https://phys.org/news/2010-03-compressed-air-energy-storage-renewable.html 31
Figure 2-8 An image depicting the operation of a supercapacitor taken from https://www.slideshare.net/MuhammadHarithMohdFa/supercapacitors-as-an-energy-storage-device 32
Figure 2-9 An image depicting the operation use of a pumped storage system taken from https://www.energy-storage.news/news/energyaustralia-ponders-worlds-largest-seawater-pumped-hydro-energy-storage 33
Figure 2-10 A schematic of a generalised hierarchical control scheme for an array of AC Microgrid systems connected to a main grid supply.....35
Figure 3-1 Annual temperature for Shimoga, India taken from weatherspark (https://weatherspark.com/y/108156/Average-Weather-in-Shimoga-India) 62
Figure 3-2 Annual humidity for Shimoga, India taken from weatherspark (https://weatherspark.com/y/108156/Average-Weather-in-Shimoga-India.....63
Figure 3-3 Annual Temperature for Soroti, Uganda taken from weatherspark (https://weatherspark.com/y/97606/Average-Weather-in-Soroti-Uganda).....63
Figure 3-4 Annual humidity for Soriti, Uganda taken from weatherspark (https://weatherspark.com/y/97606/Average-Weather-in-Soroti-Uganda).....64
Figure 3-5 Annual temperature for N'zeto, Angola taken from weatherspark (https://weatherspark.com/y/71666/Average-Weather-in-Nzeto-Angola) 64
Figure 3-6 Annual humidity for N'zeto, Angola taken from weatherspark (https://weatherspark.com/y/71666/Average-Weather-in-Nzeto-Angola) 65
Figure 3-7 Graphs showing the population forecast for N'zeto and Tomboco from 2014 to 2025 under the assumptions.....68
Figure 3-8 A representation of the algorithm for fitting long term forecasting models (3.9.1.3).....69
Figure 3-9 The algorithm for fitting unpartitioned and partitioned season-adjusted Mandelli models 70
Figure 4-1 A visualisation of the Solar irradiation distribution in the region surrounding N'zeto and Tomboco – Global Horizontal Annual Data (kWh/m^2/ANO) 76
Figure 4-2 A visualisation of the Wind Speeds at an altitude of 80m in the region surrounding N'zeto and Tomboco – Wind Speed Data at 80m (m/s).....77

Figure 4-3 A visualisation of the Hydropower potential across the M'bridge river in Zaire, Angola – Hydroelectric Potential (MW) 77
Figure 4-4 A graph of the estimated annual flow rates of the M'bridge River for 2014 79
Figure 4-5 A visualisation of the Biomass potential across the region surrounding N'zeto and Tomboco – Biomass Potential (MW) 81
Figure 4-6 A visualisation of Above Ground Woody Biomass for the region surrounding N'zeto and Tomboco – Taken from the Conservation Biology Institute (https://databasin.org/datasets/30388e1fbd1b4ef899792894bb2cce0e) 82
Figure 4-7 A figure representing the yearly crop yield for N'zeto village (FAO Data – Angola Atlas) 83
Figure 4-8 A figure representing the yearly crop yield for Tomboco village (FAO Data – Angola Atlas) 84
Figure 4-9 A figure illustrating the annual agricultural (crop) behaviour for N'zeto (FAO data – Angola Atlas) 85
Figure 4-10 A figure illustrating the array of technologies in use to utilise waste biomass energy [52] 86
Figure 4-11 A figure illustrating the scheme of the BTA® Single-stage digestion reactor Source: BTA International GmbH [55] 88
Figure 4-12 A visualisation of the existing infrastructure (2017) in the region surrounding N'zeto and Tomboco – Electrical Transmission lines and Substations 91
Figure 4-13 A visualisation of the future prospected infrastructure (2025) in the region surrounding N'zeto and Tomboco – Electrical Transmission lines and Substations 91
Figure 5-1 A figure illustrating the topology of option 1 95
Figure 5-2 The basic features of Microgrid Option 1 96
Figure 5-3 A figure illustrating the topology of option 2 103
Figure 5-4 A figure depicting the topology proposed for the two Microgrid solution 104
Figure 6-1 A geographic location of the proposed power generation sources and hybrid distribution bus network 109
Figure 6-2 A diagram illustrating the hybrid nature of the distribution bus for the proposed microgrid 113
Figure 6-3 A figure illustrating the control scheme of the proposed hybrid Microgrid solution for the electrification of N'zeto & Tomboco area 121
Figure 6-4 A figure illustrating the layout and connection scheme for the Microgrid Management System for the proposed solution 122
Figure 6-5 A diagram illustrates the operation of the Voltage Source Inverter control and the relavenet signals used for tertiary, secondary and primary control of the distributed energy resources 123
Figure 6-6 A diagram illustrating signal inputs into cascaded block diagram description of the hierarchical control system for the single microgrid solution 124
Figure 6-8 A figure illustrating the operation of a Voltage droop characteristic function 127
Figure 6-7 A figure illustrating a Frequency droop characteristic function 127
Figure 6-9 Flowchart illustrating the Single Microgrid solution operation of use process 130
Figure 6-10 A graphical sensitivity analysis produced by HOMER software in the form of a plot of Scaled Average Cassava Biomass Collected against Scaled Average Solar Irradiation, demonstrating the impact of changes in these variables on the Estimated Cost of Electricity. 133

Figure 6-11 A graphical sensitivity analysis produced by HOMER software in the form of a plot of Scaled Average Flow of M'bridge River against Scaled Average Solar Irradiation, demonstrating the impact of changes in these variables on the Estimated Cost of Electricity. 134
Figure 6-12 A graphical sensitivity analysis produced by HOMER software in the form of a plot of Scaled Average Load Profile generated from a single source against Scaled Average Solar Irradiation, demonstrating the impact of changes these variables on the estimated Cost of Electricity. 135
Figure 6-13 A graphical sensitivity analysis produced by HOMER software in the form of a plot of Scaled Average Load Profile generated from a single source against Scaled Average Solar Irradiation, demonstrating the impact of variability of these factors on the Lead Acid Energy Storage capacity requirement. 136
Figure 6-14 A spider plot produced by HOMER software demonstrating the impact of the uncertainty in the Electrical Load, Amount of Cassava Biomass Collected , and M'bridge river Flow Rates on the projected cost of electricity. 137
Figure 6-15 A figure illustrating the proposed monthly collected Cassava for input into the industrial peeler 141
Figure 6-16 A chart depicting the estimated Number of Trips for collecting Cassava over a 50km radius 142
Figure 6-17 Estimated Monthly Transport Cost for Cassava transport to Biofuel Generator 143
Figure 7-1 A figure illustrating the geographical location of the proposed Microgrid solution including the collection zone for Cassava biomass collection 146

List of Tables

Table 1-1 A table illustrating the comparative rates of electrification in the ECCAS (data obtained from the World Energy Outlook Data Base) 11
Table 2-1 A table listing and describing advantages and disadvantages of each distribution bus category 23
Table 2-2 Advantages and disadvantages of Microgrid systems 36
Table 3-1 A table describing key measures of load used for load modelling 50
Table 3-2 A table approximating electricity usage data in N'zeto on an average day 53
Table 3-3 A table approximating electricity usage data in Tomboco on an average day 57
Table 3-4 A table of population statistics for N'zeto and Tomboco in 2014 (extracted from Tables 3-2 and 3-3) 67
Table 3-5 A table demonstrating, using the synthetic model data, the differences in the forecasted energy consumption between the Parametric Model & the Similar Day forecasts 71
Table 4-1 A table depicting the technical specifications of the COBA group M'bridge Hydroplant 78
Table 4-2 A table illustrating the characteristic properties of Cassava & Banana for use in Anaerobic digesters 89
Table 5-1 Load estimates under the assumptions of normally / beta distributed noise 97
Table 5-2 Load estimates under normally / beta distributed noise 104
Table 5-3 N'zeto's node annual power generation performance from DER A assuming noise is normally distributed 105
Table 6-1 A summary of the technical specifications of the proposed hybrid microgrid 110

Table 6-2 A table illustrating a selection of the technical specifications listed for the proposed distribution scheme 120
Table 6-3 A table providing confidence factors assigned to Solar Irradiation, M'bridge River-Flow Rate, and Biomass Yield from Cassava, and Electrical Load (N'zeto and Tomboco) 132
Table 6-4 A table illustrating the weighting and costing of distribution cables for the proposed microgrid solution 139
Table 6-5 A table listing the additional initial transport costs associated with installing the infrastructure of the Microgrid system 140
Table 6-6 A table of the additional costs relating to the Biomass Generator annual operation plan 143
Table 6-7 A table illustrating the revised Cost of Electricity taking into consideration transport costs to N'zeto, Angola and the proposed operation plan for the cassava peel based biofuel generator 145

CHAPTER 1

1. INTRODUCTION

1.1 MICROGRIDS SUITABITILITY IN ANGOLA

Angola has a vast landmass of approximately 1246700 square kilometres and a comparatively low population of around 24 million inhabitants. Furthermore, by 2014 the country was reported to have a low electrification rate of 33% nationwide and even with this, access to this basic resource was heavily skewed in favour of urban inhabitants.

Table 1-1 to follow compares urban and rural electrification rates of member countries of the African regional block known as Economic Community of African States (ECCAS) to which Angola also belongs[1].

Table 1-1 A table illustrating the comparative rates of electrification in the ECCAS (data obtained from the World Energy Outlook Data Base)

Name	National Electrification	Urban Electrification	Rural Electrification (RE)	Rank RE
Angola	*33%*	*69%*	*6%*	*7*
Burundi	*5%*	*28%*	*2%*	*8*
Cameroon	*62%*	*96%*	*23%*	*4*
Central African Republic	*3%*	*5%*	*1%*	*10*
Chad	*4%*	*13%*	*1%*	*9*
Congo	*42%*	*56%*	*16%*	*5*
Democratic Republic of Congo	*18%*	*42%*	*0%*	*11*
Equatorial Guinea	*66%*	*93%*	*48%*	*1*
Gabon	*89%*	*97%*	*38%*	*3*
Rwanda	*27%*	*72%*	*9%*	*6*
Sao Tome and Principe	*59%*	*70%*	*40%*	*2*

It is clear from the table that the country is below the majority of its peers yet, ironically, Angola's economy is the largest in the regional block by annual GDP which stood at $102 billion in that year.

Earlier in 2011, a plan titled *National Energy Security Strategy and Policy Report*, hereafter abbreviated as *NESSP Report*, had outlined a specific energy roadmap. The report was published by the country's *Ministry of Energy and Water*.

Briefly, the NESSP Report's broad strategy envisaged Angola rapidly (a) *expanding*; (b) *reforming*, (c) *diversifying*, and (d) *consolidating* the energy generation sources and distribution infrastructure. In the case of rural electrification, the plan emphasised, where feasible, the substitution of existing fossil fuel generated electricity, which at present is the more dominant feature, with that generated from renewable resources of hydro-power, natural gas, solar irradiation, and wind-power. This then opened possibilities for introducing localised electricity provision solutions for widely dispersed human settlements that in time could be *integrated* into the national grid as the country continued with the rebuilding and expansion of its energy infrastructure. In turn, this also opened further opportunities for regions far from the industrial cities, whose the immediate need for provision of local micro-grid electricity would be to service cold storage, lighting, and cooking to growing numbers of households and to public facilities such health institutions, schools, public administration, and so on, to evolve in time into servicing emerging rural-based industries, a prospect which ultimately could lead to integration with the national grid to facilitate excess energy demand to be drawn from the national grid.

Following the dismal picture that emerged from the publication of the World Energy Outlook Data of 2014, the Angola government took further steps that year by getting into an agreement with the ECCAS regional block that broadly sought to align with the United Nations call for "Sustainable Energy for All" or SE4ALL in short. Essentially the agreement committed the country to specific long term targets on three fronts, namely, the provision of *universal* electricity, the *doubling* of the renewable energy integration to the national grid and the promotion of *energy efficiency* in ways that positively impact on food security, health, gender-balanced economic benefits, and water provision, among others[2].

The ECCAS agreement was then backed by an additional ambitious national plan named "*The Angola 2025 Action Plan*" which sought to increase national electrification from 33% to 60% by 2025, where this 60% exceeded the 2030 targets set at the regional ECCAS.

In summary, Angola is endowed with (i) vast landmass, (ii) low population density, and (iii) a diverse wealth of renewable resources in the form of hydro-power, natural gas, solar irradiation, wind-power, and biomass from agricultural by-products, indeed the kind of endowments that precisely suit the development of localised micro-grid systems. It is therefore re-assuring from the aforementioned that the study undertaken through this dissertation not only suits Angola but also falls clearly within present rural electrification plans of the country.

1.2. INTERNATIONAL EXAMPLES OF MICROGRID FINANCING

Microgrid systems are increasingly becoming popular as options for rural electrification particularly in areas where grid expansion is prohibitively expensive or impractical. Studies conducted in Ghana, Nepal and India on the use of hybrid microgrid systems, namely, [3][4][5], all report that government financial support was involved to varying degrees.

Loka et al in a paper titled "A case study for micro-grid PV: lessons learned from a rural electrification project in India"[5] justify this support on well-known grounds that provision electricity to underdeveloped rural areas is largely a matter of provision of a public good to spur improvement of public and economic development, a twin-objective that is unlikely to attract pure private investment whose e cost recovery has little chance of success. However, a report titled "Literature Review: Rural Business Models in Asia" by Parthan [6] compiles a variety of mixed models currently in place in Asia involving various levels of public, private and civic society financing. In this partnership, governments build and maintain microgrids, private utility enterprises run them under profit-sharing agreements. Examples of this is the Sunlabob Hybrid Mini-grids in Laos [7] and India's OASYS South Asia Project for the development of decentralised Microgrid business models[8]. A schematic diagram to follow depicts a Parthan [6]'s summary of recent business models in use in Asia.

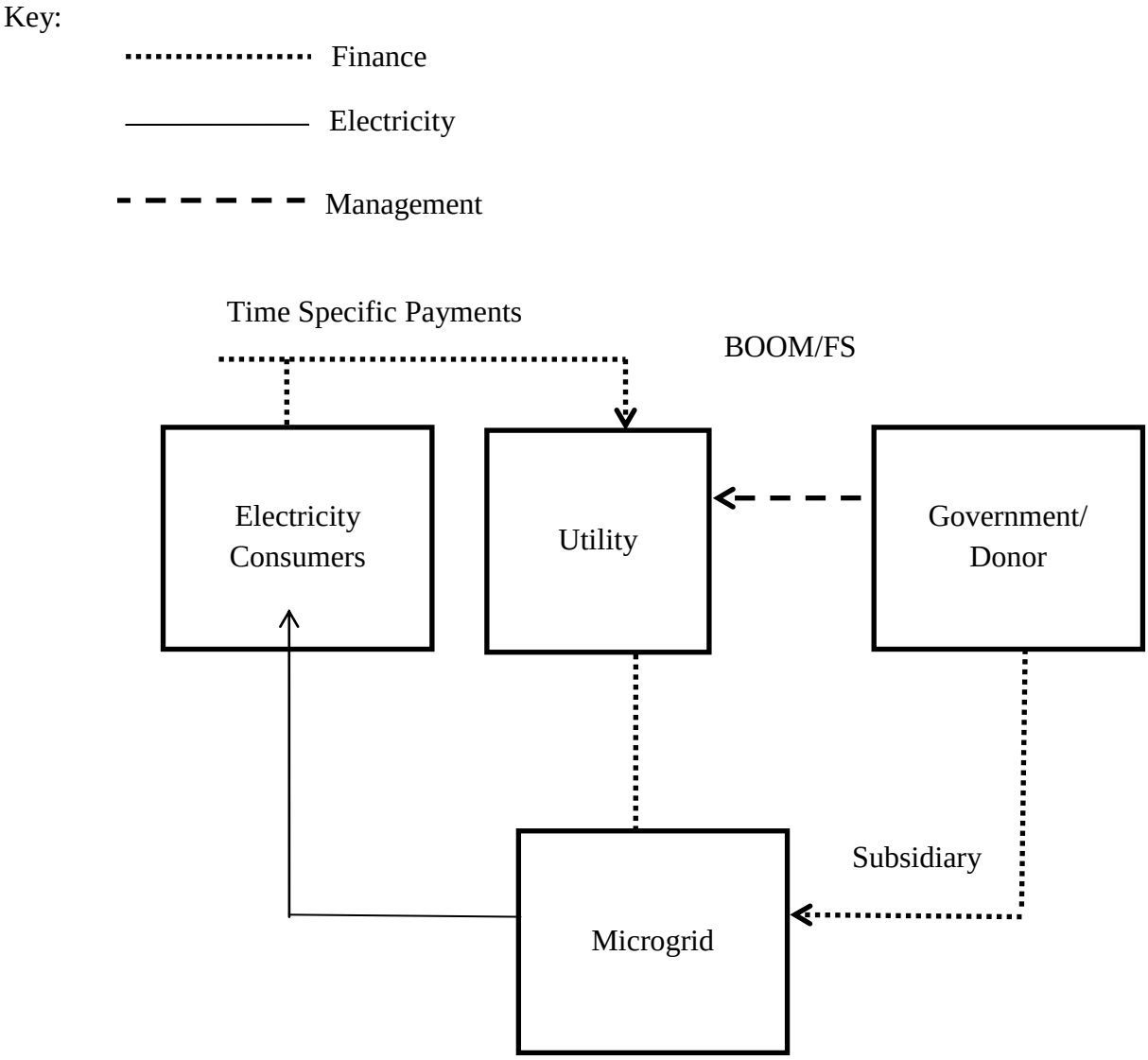

Figure 1-3 A figure of the high level operation of Microgrid business models operating in Asia. Source: Sustainable Energy Associates

A last international example of microgrid financing whose period of implementation actually coincides with that of "*The Angola 2025 Action Plan*" is described at the beginning of chapter 2 under an African Development Bank's project named "Transformative Partnership to Light up Africa by 2025"

1.3. RESEARCH HYPOTHESIS

1.3.1. INTRODUCTION:

Conventionally, research hypotheses comprise of two parts. One part is a *claim* that is 'testable' or 'confirmable' or 'verifiable' by means of reliable evidence and the other part is a *counter-claim* that is devoid of anything in the *claim part* but accounts for *all* other possibilities on the continuum *under consideration*. The traditional name and notation for the claim are *null* hypothesis and H_0 respectively, and the corresponding counterparts for the counter-claim are *alternative* hypothesis and H_a .Thus H_0 and H_a partition the universe of all possibilities *under consideration*. Since there is no hypothesis that is ever *finally* accepted or rejected in science, a *commonly* followed decision convention regarding conclusions of null hypotheses assessments is to 'not reject the claim' or to 'reject the claim'.

On the question of the *form* of null hypotheses take, convention allows diversity, depending largely on the *nature of the research topic*, or on the *field of study* in which the topic falls, or on the *activity that is central to the research*.

To illustrate the varied forms of research hypotheses and their testing or confirmation or verification, three examples are provided. First example: all hypothetical claims and counter-claims of statistical nature have to be in forms that are statistically testable using a relevant sample or a set of samples. For instance, that two *samples* are independent is a statistical (*non-parametric*) claim testable by some well-known nonparametric methods. Second example: some null hypotheses in the field of operations research are formulated using programming techniques such as linear or nonlinear programming, while their testing takes the form of determining associated *feasible* solutions, if they exist. Third example: in 'feasibility studies for projects', it is typical to first hypothesize the 'purpose and nature of a project desired' (the null hypothesis), followed by a more detailed study either to confirm/improve the feasibility of the hypothesized ideas or to confirm the infeasibility of the project. This dissertation follows the format of the third example.

1.3.2. RESEARCH HYPOTHESIS:

The null and alternative hypotheses of this dissertation are respectively,

H_0 : That a micro-grid system for the Angola villages of N'zeto and Tomboco with an annual electricity output of not less than 2 MW is *feasible,* based *exclusively* on *domestically* available renewable energy resources and possessing potential to sustain supply and distribution expansions over time.

H_1 : That H_0 does not hold.

i. *HOW ASSESSMENT OF H_0 IS ORGANISED*

An assessment that leads to the confirmation of H_0 proceeds in six chapters. The first chapter contributes to this assessment by identifying five prerequisite factors. They are (a) the existence of *documented* public policy as seen in section 1.3, (b) the domestic availability of renewable resources in and around the study area (chapters 4,5, and 6), (c) the present low population density in rural Angola, (d) the low level of Angola's rural electrification as seen in Table 1-1, and (d) the existence of financing mechanisms which the country can afford.

The second chapter reviews some key components of microgrid hardware as well as the approaches to modelling microgrid designs. Clearly, no procedure confirming or rejecting H_0 would be valid without reference to microgrid hardware and microgrid design models particularly those relating to electric power generation, its storage and consumption, to name a few.

The third chapter characterises the contemplated electrical energy consumption in the study area while the fourth assesses the availability, nature, diversity, and extent of the domestic renewable energy sources.

The fifth chapter first proposes two *candidate* microgrid options and then conducts a comparative evaluation of their performance from which a preferred candidate is chosen. The sixth chapter describes in detail the anatomy of the chosen option followed by the subjecting of key design variables of the chosen solution to a *sensitivity* analysis.

Chapter seven, the last, re-caps briefly the path followed to reach the chosen solution, followed by suggestions of constraints and obstacles which the implementation phase may face, should that phase be realised. The chapter ends with a summary of what this author regards as contributions of the study.

Lastly, each chapter begins with a summary of its key points. Thus the reader may wish to go through those summaries first, get a general feel of the details to come, before proceeding with the rest of the dissertation.

CHAPTER 2

2. LITERATURE REVIEW

A natural consequence of this world-wide citizen awareness of the right to access to electrical energy that has been witnessed in recent history, has been the emergence since mid1990's of *community power systems* that operate *at a smaller and more decentralised scale than the traditional large-scale national grids*, using locally available energy sources such as solar energy, wind energy, hydro energy and so on. Such set-up has been given a formal name of 'a *Microgrid System'*, and the purpose of this chapter is to review historical literature on seven key aspects relating to the microgrid study undertaken in this dissertation. These aspects are the microgrid classification (section 2.3), the sources of microgrid energy (section 2.4), energy storage (section 2.5), microgrid control (section 2.6), advantages and disadvantages of microgrids (section 2.7), techniques and tools used to model a microgrid design solution for the study area (section 2.8), and lastly, international examples of microgrid financing (section 2.9).

2.1 DEFINITION OF MICROGRID

In this dissertation the following technical definition due to United States Department of Energy [9] is adopted. According to the definition: **A microgrid system or simply a microgrid, is "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that connects and disconnects from such grid to enable it to operate in both grid-connected or "island" mode. Here and hereafter grid-connectedness means that a microgrid is connected to the main national grid and island mode means a stand-alone microgrid. In essence therefore, Microgrid systems are power systems whose primary role is to generate and distribute electricity locally, although often they are connected to national grids for purposes of exporting / importing excess / deficit power if need arises.**

2.2 CLASSIFICATION

Microgrids are presently classified in two ways. The first classification form is whether a microgrid is connected to a national grid (*on-grid* mode) or not (*off-grid* mode), and the second form is characterised by *the channel through which electrical energy is distributed to utilities*. Hereafter the *channel through which electrical energy is distributed to utilities* shall be replaced by the term '*distribution bus'*.

2.2.1 *ON-GRID AND OFF-GRID MODES*

Figure 2-1 to follow illustrates a microgrid that is integrated into a national grid. Hence its 'on-grid mode' classification name.

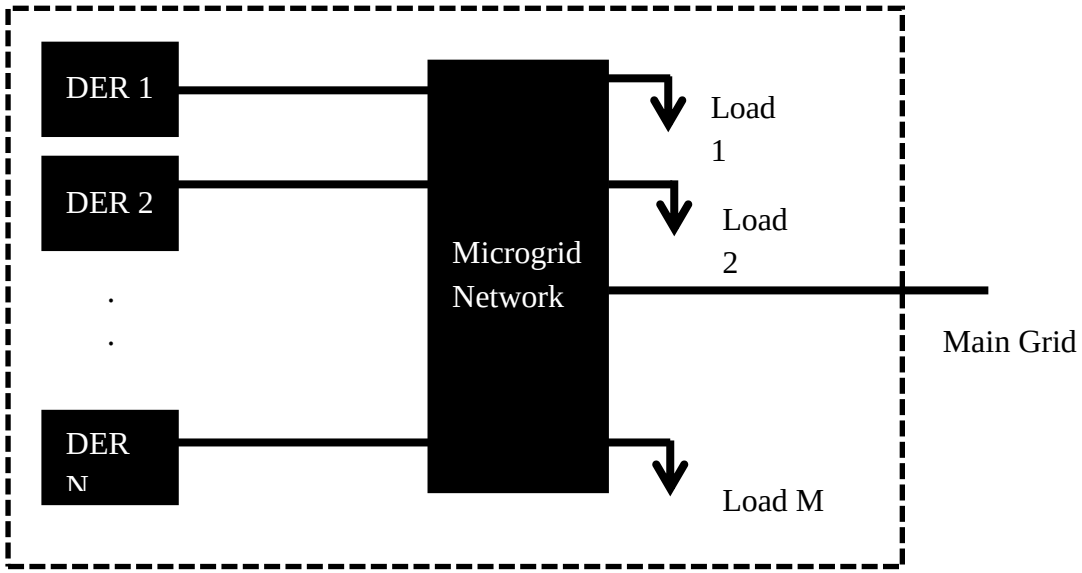

Figure 2-1 A diagram of a generalised Microgrid system (with main grid integration)

Key features of this class of microgrids include provision of storage devices for energy to compensate for unexpected spikes in power usage as well as devices that address the complex control requirement particularly those requiring the matching of the frequency of the power distributed by the microgrid and that of the national grid.

In the off-grid mode of microgrid systems (also known variously as '*isolated*' or '*islanded*' microgrids), the system is designed either as a stand-alone completely or it is connected to the main grid *but with a provision for a cut-off mechanism to be activated in the event of a fault or abnormal conditions.*

In the design of either on-grid or off-grid mode of microgrid, the following additional factors are taken into account:

a) Voltage control:

Under the on-grid type the voltage levels are determined by the main grid. In the case of the islanded mode, however, the operating voltages must be controlled both at the level of each of the local distributed energy-sources as well as at the microgrid- output which supplies the distribution bus.

b) Frequency control:

In the on-grid modes the frequency control of the microgrid requires the synchronisation of the supply from the Distributed Energy Resources to the main gird input. For the off-grid modes, the Microgrid frequency variations may cause damage on the demand side loads.

c) Demand Side Management: Balance needs to be maintained between the generation and consumption in the islanded mode in order to avoid possible grid collapse.

d) Energy Storage:

Energy reserves are planned for in design of microgrid systems through micro sources that can provide supplementary and/or stabilising power as needed.

i. ***ALTERNATING CURRENT BUS***

Microgrid systems that are classified by their distribution bus are divided into three categories: the alternating current (AC) bus, the direct current (DC) bus, and a hybrid system. [10][11].This is a distribution bus that supplies a utility or load with AC power as shown in Figure 2-2 to follow.

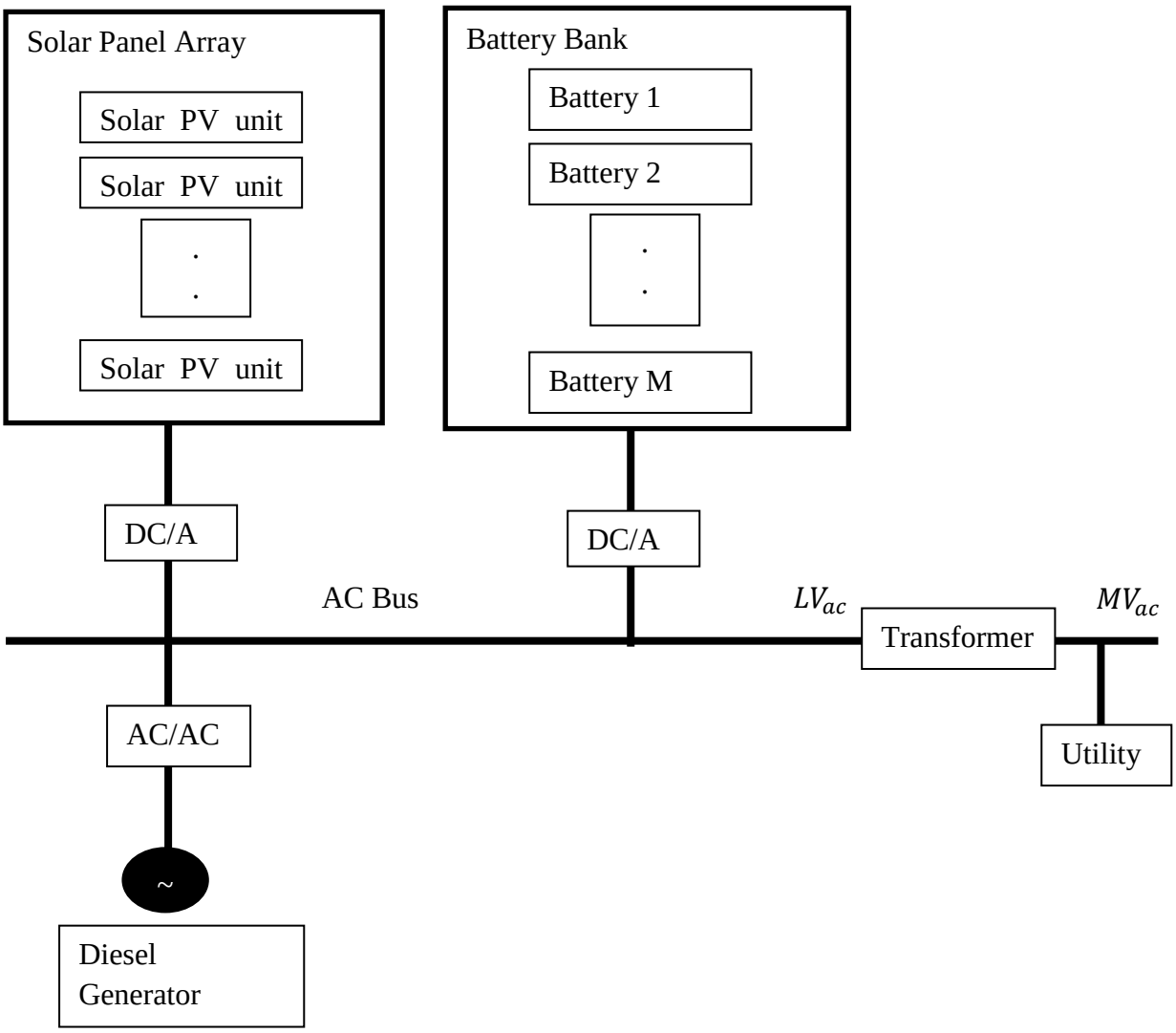

Figure 2-2 A diagram depicting a basic AC bus based Microgrid system

Figure 2-2 illustrates how an array of solar panels and battery banks connect to an AC distribution bus via an inverter, which in turn converts direct current into alternating current. Notice that the architecture of this category of a microgrid includes, among others, an AC generated source (in the form of a diesel generator) that feeds into a transformer which takes in a low ac voltage and steps it up to a medium ac voltage before supplying it to the utility.

ii. ***DIRECT- CURRENT BUS***

This is a distribution bus that supplies a utility or load with DC power, as shown in figure 2-3 to follow.

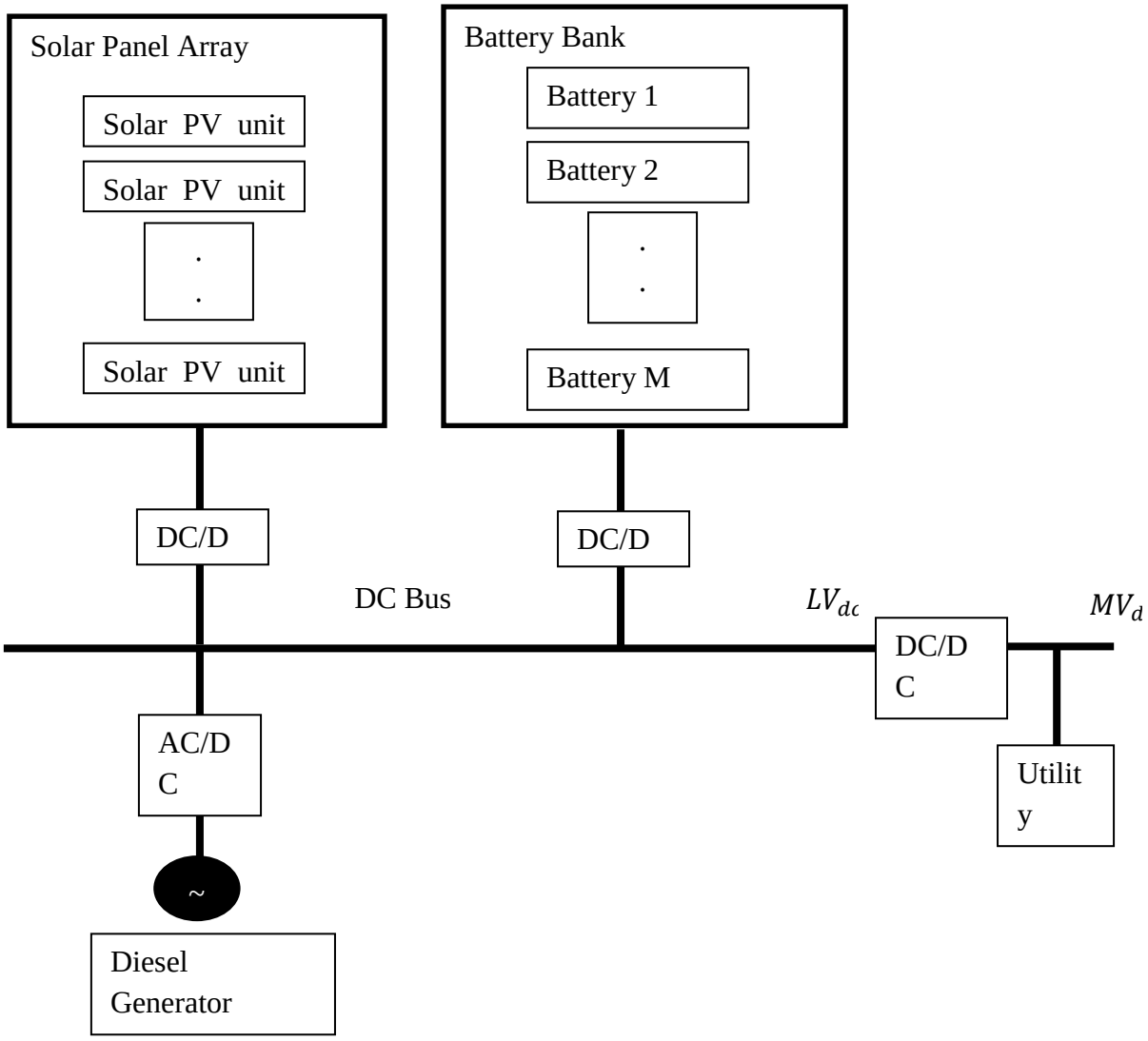

Figure 2-3 A diagram depicting a basic DC bus based Microgrid system

The diagram represents a simple DC bus Microgrid system that makes use of DC current distributed from a solar array and a battery bank, it also utilises a diesel generator which produces an AC voltage which is converted to a DC voltage by a converter. This DC voltage is then stepped up from a low dc voltage to medium dc voltage through a DC-DC converter before feeding the medium voltage to the utility.

iii. ***HYBRID BUS***

This category of a distribution bus configuration supplies a utility with both AC & DC power, as shown in figure 2-4 on the next page. The Micro-grid system in the diagram is considered a hybrid due to the presence of the two different classes of distribution buses AC and DC which are integrated into the system. This type of system typically makes use of a number of architectures that offer varying degrees of isolation and decoupling below the AC and DC supply paths[12].

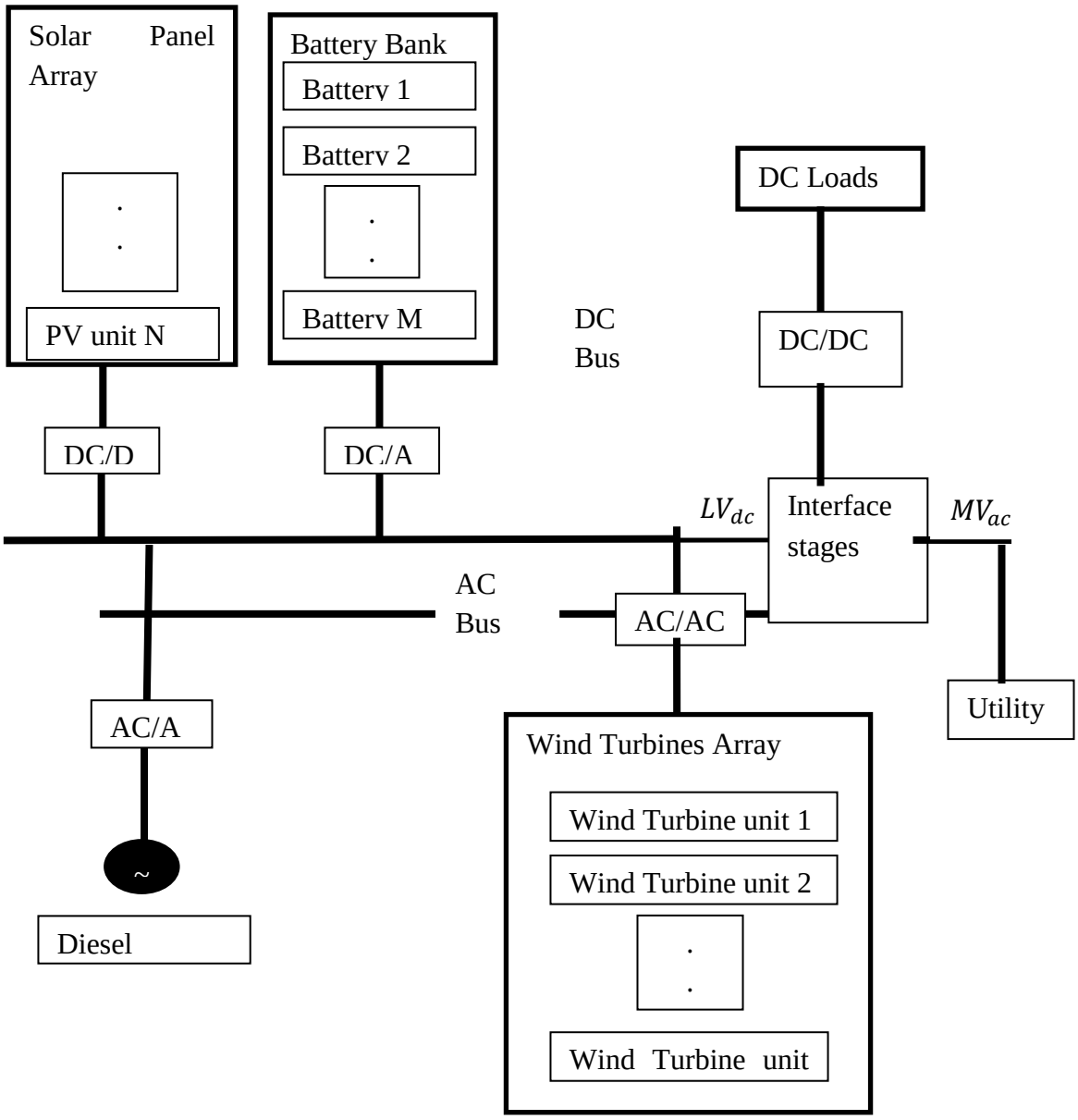

Figure 2-4 A diagram depicting an example of a hybrid ac/dc Microgrid system

iv. ***DISCUSSION***

All three classifications have advantages and disadvantages. In studies reported by [13][14] these advantages and disadvantages are summarised in a table to follow.

Table 2-1 A table listing and describing advantages and disadvantages of each distribution bus category

Distribution Bus	Advantages	Disadvantages
AC Microgrid systems	• Easier compatibility with loads in domestic contexts (consumer electronics without modification) • Simpler integration with national/state grid systems • Most commonly used	• Constant losses due to inverter which remains permanently on • Need to synchronise distributed generators to reduce the circulation of reactive power • Frequency monitoring required to ensure distributed power is marched (example 50hz/60Hz)
DC Microgrid systems	• Higher efficiency between DC loads and DC generating source due to the absence of the inverter • No reactive power compensation required in the purely DC system • No frequency monitoring of distributed power	• Power lines are more expensive to distribute using DC • More complex and expensive to integrate into national/state grid network • Protection systems are more expensive and complex • Loads used by system need to be compatible with DC supply (example household computers

		without modification generally require AC input)
Hybrid Microgrid systems	• Allow for simple integration with national/state grid • Provides an option to operate DC loads more efficiently while maintaining the overall benefit of the AC distribution network • Less commonly used, case studies not widely available • As the scale of the hybrid network increases the overall cost in comparison to solely AC and DC decreases due to the improved efficiencies	• More complex protection and fault detection devices and techniques required • The more interface stages are introduced into the system the lower the overall reliability of the system • More control complexity as the AC & DC components of the hybrid network both require their own control approaches

The AC Microgrid systems that involve the integration of diverse renewable energy sources potentially have widespread application in rural electrification programmes where power required is predominantly for household usage. In the case of the electrification of our two villages, preliminary information suggests that indeed it is the AC distribution bus that is required. Accordingly, this study must make a case that either confirms this preliminary choice or provide justification for the alternative of either hybrid or DC distribution options. Moreover, since DC Microgrids have advantages if industrial applications are brought into the picture, a case for possible future phasing in the Hybrid Microgrid system shall also be considered to cater for when the local economy begins to respond well to post-electrification.

2.3 SOURCES OF MICROGRID ENERGY

Since the advent of Microgrid systems, a number of different energy sources have been used in various configurations to meet the load requirement of a given microgrid. Table 2-2 summarises the popular distributed energy sources as reported in "Microgrid Technology and Engineering Application"[15].

Table 2-2 A table listing and describing the popular energy sources used in Microgrid system applications

Energy Source	Description	Features
Solar Radiation	Solar energy is utilised in Microgrid systems through the use of Photovoltaic devices which use the semi-conductive properties of engineered materials to use the photoelectric effect to convert solar radiation (from the sun) into electrical energy	● Photovoltaic produces electrical energy in Direct Current (DC) form ● Used widely in rural electrification projects ● Often supplemented by battery-based energy storage systems
Wind Speed	Wind energy is utilised by making use of the kinetic energy of wind through large aerofoil blades that drive a turbine converting the kinetic mechanical energy into electrical energy	● Produces electrical energy in Alternating Current (AC) form ● Used in isolated and grid integrated applications
Geothermal Energy	Geothermal energy attempts to make use of naturally occurring geothermal sources to, through interaction with a liquid such as water, produce steam that in turn drives a turbine generating electrical energy	● Produces electrical energy in AC form ● Less widely used
Biomass Energy	Biomass energy is utilised by	● Produce electrical

	burning, or making use of chemical processes, to convert a biomass into a gas form such that it can be fed into pressure systems such as boilers which in turn drive turbines which generate electrical energy	energy in AC form ● Have potential negative impacts on local environment and agro-industry
Hydro resources	Energy from hydro resources is primarily utilised for electrical energy through generators	● Produce electrical energy in AC form

2.4 ENERGY STORAGE IN MICROGRIDS

With the growing world-wide trend of using renewable energy sources to generate electricity has come the question of how to store excess energy when it is available for later use when generation is not feasible or not advisable. Indeed the importance of energy storage systems lies at the heart of the large scale viability of Microgrid systems, particularly for isolated mode applications. For example in the easily understood cases of solar and wind driven microgrids, some energy storage system would be required to power the interconnected loads where needed during night time, in the case of solar, and during low winds in the case of wind turbines. See[16][17].

Microgrid systems are often implemented in remote contexts delivering small amounts of power to a relatively low number of local residential consumers most often applicable in islanded operation in Developing world contexts [18]. Energy storage systems are installed to maintain system stability, ensure power quality and supplement the excess power off the base load during peak periods, where necessary. Major constraints on implementation include the costly nature of these systems as well as environmental concerns for battery bank based systems in particular[19]. Voltage and Frequency controllers designed to maintain system set points also make use of Energy storage systems to compensate for drops in system performance, storage systems must be selected to be compatible with the control scheme adopted for the Microgrid system [20] and able to absorb and send large amounts of real and reactive power from and to the network. Safety concerns and Energy Storage System reliability are a key consideration in the design phase as switching, safety circuitry and the

potential of overheating (for battery based systems) requires advanced power electronics systems[21].

2.4.1 *STORAGE SYSTEMS*

Historically there have been a number of ways that energy has been stored and more advances in this area are rapidly being achieved. From [12] it appears that energy storage systems are broadly differentiated into singular technology applications or hybrid energy storage systems:

a) A Single Technology Energy storage systems comprises of a configuration of energy storage in a Microgrid system where a single device or process is used to store electrical power to supplement the requirements of the utility. Figures 2-4 and 2-5 represent examples of the single technology method of providing energy storage in a Microgrid system with an energy storage system that makes use of only a battery bank.

b) In contrast, a Hybrid Energy Storage Systems comprises of a configuration that attempts to provide High Power and High Energy storage support for the utility by making use of two complementary storage devices.

The broad advantages and disadvantages of both are summarised from [22][23] in a table to follow:

Table 2-3 A table illustrating the advantages and disadvantages of Single-technology Energy Story System compared to a Hybrid Energy Storage system

	Advantages	Disadvantages
Single-technology Energy Storage System (ESS)	• Simple design and control required for operation • Lower cost to more adaptive alternatives	• Many fuel cells will large energy densities are slow to respond and are less able to rapid fluctuations in demand if needed • Have a lower reliability under extreme conditions
Hybrid Energy Storage Systems	• Makes use of two complementary storage devices to dually provide High Power and/High	• More complex design and control required for operation. • Comparatively expensive

	Density supply as is needed from the utility • Increase reliability of the system	to implement

2.4.2 *STORAGE TECHNOLOGIES*

On the energy storage technologies, literature sources [15][17] [24] report the following five kinds:

i. *BATTERY*

This technology consists of a vast array of different sub technologies. In general, however, the technology stores energy by charging electrodes during off peak periods that cause a chemical reaction within the battery system storing the electrical energy as chemical energy. Examples of such battery systems include lead-acid Battery, nickel-cadmium battery, lithium-ion battery, sodium sulphur battery, and vanadium redox flow battery systems. See an illustrative image to follow:

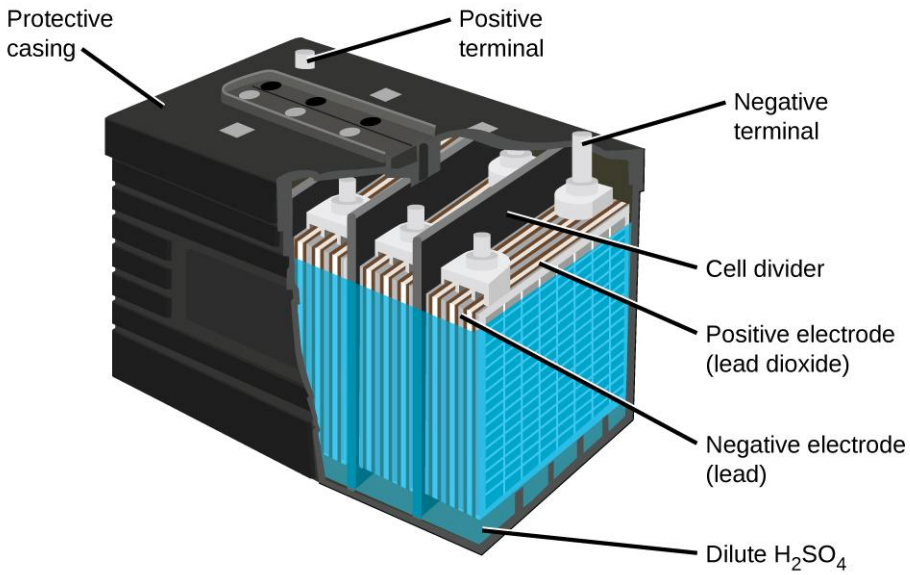

Figure 2-5 An image depicting a lead acid battery taken from https://opentextbc.ca/chemistry/chapter/17-5-batteries-and-fuel-cells/

As may be seen, batteries consist of stacked cells that make use of chemical reactions to convert electrical energy into chemical energy and chemical energy in electrical energy as needed. Within the battery itself the cells are connected combinations in series and parallel.

Batteries are dispatched in terms of their energy capacities, life span, depth of discharge, self-discharge and energy density.

Due to the capacity size and ability to connect the batteries in series and parallel configurations to form battery banks create the potential to develop large storage capacities, scales of up to 40MWh in the case of the lead acid battery have been seen in commercial operation.

Its key features are:

- Low cost systems
- Have low charge/discharge cycle lifespan
- Widely in use with renewable energy sources based system (particularly solar systems)
- Ranging performance in relation to ability to providing high energy density storage for short

  disruptions to systems with slower response profiles and a larger total capacity for reserve storage

ii. ***FLY WHEEL***

This technology makes use of mechanical energy stored in a rotating mass (flywheel) attached to an axle. During off peak periods the flywheel stores energy through the spinning of the axel connected to a device operating in motor mode. During peak periods the stored flywheel energy is connected to a device operating in generator format which produces electrical energy as the flywheel speed decreases.

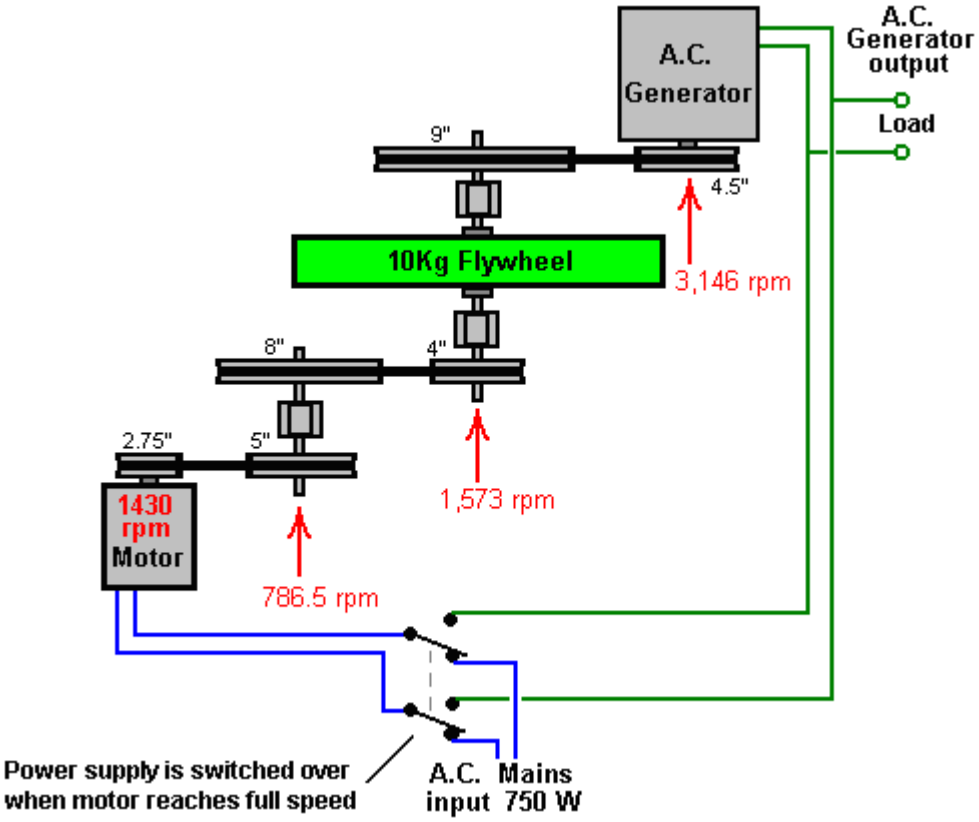

Figure 2-6 An image depicting an example of a flywheel system taken from http://www.free-energy-info.co.uk/Chapt4.html

If we note the Flywheel module diagram above we consider that when used for energy storage the electrical energy from the broader system is converted to electrical energy through the motor-flywheel system which stores the energy in the angular momentum of the rotating mass (flywheel). The flywheel is then used in motor mode when energy is required generating and AC output voltage from its terminals. An advantage lies with the Fly wheel's ability to change quickly between energy storage and generating modes. The Flywheel system is however highly sensitive to imbalance within the physical system hence it is often placed underground to ensure stability of the physical system as the inertia of the surrounding ground damps the vibrations of the Flywheel physical system. Large Flywheels are known to provide power for just over 2kWh.

Its key features are:

- Primarily used as an emergency backup device
- High speed switching between energy storage modes and generating mode
- Suitable for frequency control and short term storage

iii. ***COMPRESSED AIR /GAS***

Under this technology, excess energy produced during off peak periods is used to compress air/gas. During peak periods the compressed gas is released into a chamber and the force of the expansion powers a turbine which provides electrical energy.

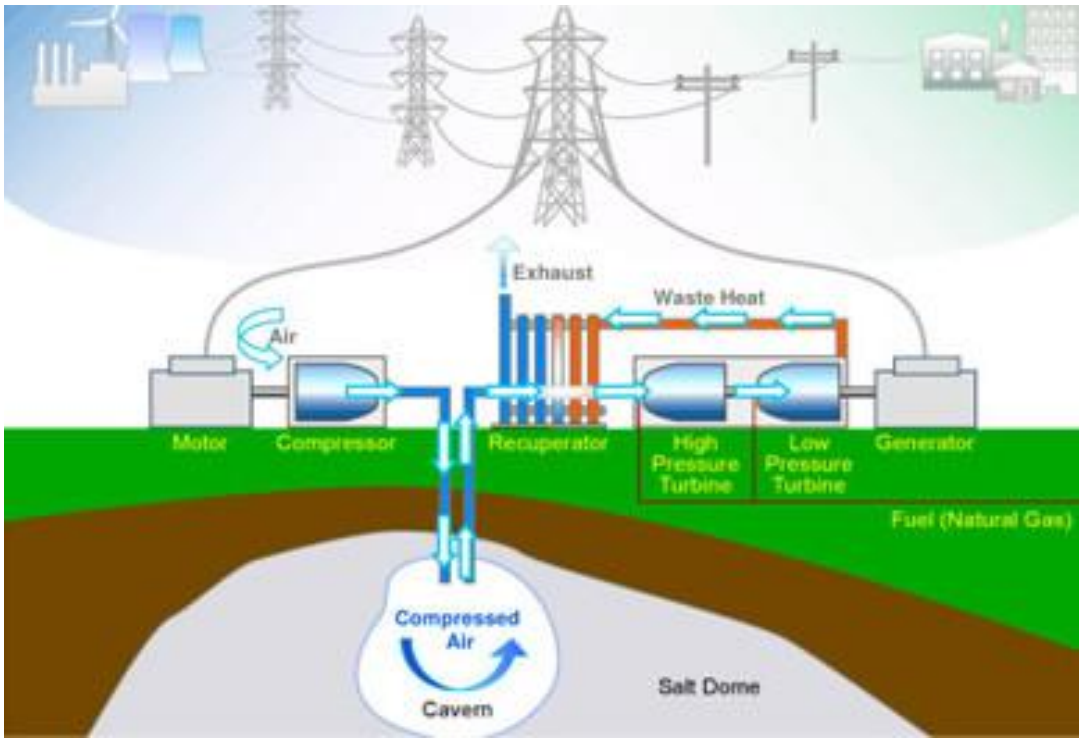

Figure 2-7 An image depicting the operating of a Compressed Air Energy Storage System taken from https://phys.org/news/2010-03-compressed-air-energy-storage-renewable.html

Compressed air systems consist primarily of the compressor and connected turbine shaft modules represented above. The system compresses air in the compressor the compressed air is then stored in a chamber, in the above case under ground, then in generation mode the compressed air is mixed with obtained Natural Gas which is then ignited in a combustion chamber which then powers the turbine generating electrical energy. Large scale application of Compressed Air Energy storage systems have been used in operation up to 180kWh.Its two key features are (a) Compressed air systems can start/respond immediately making suitable for use with voltage

regulation and frequency modulation and (b) CO_2 − free energy storage option

iv. ***SUPER-CAPACITOR***

This technology makes use of double layered super capacitor devices which store electrical energy between two polarised plates.

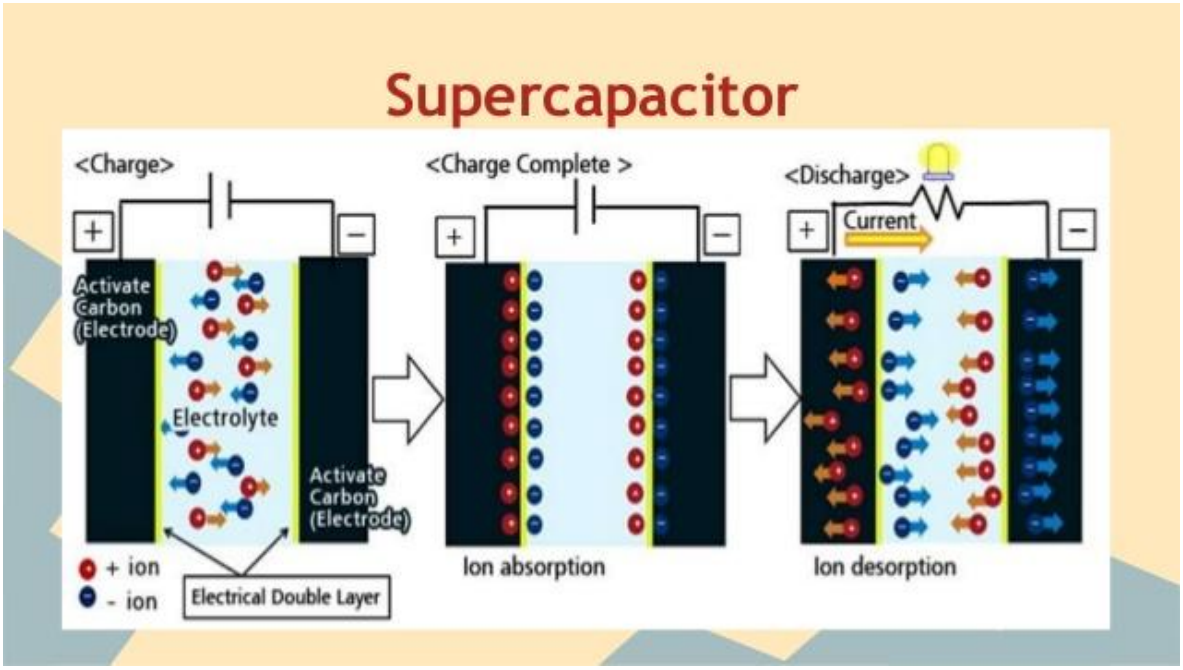

Figure 2-8 An image depicting the operation of a super capacitor taken from https://www.slideshare.net/MuhammadHarithMohdFa/supercapacitors-as-an-energy-storage-device

Capacitors more generally have been used, as energy storage devices, to improve power system stability. They consist of two metal places which are separated by air or a synthetic material with favourable properties which enhance the capacity of the electric field generated, when the plates are polarised by an external voltage, to hold charge. Super-capacitors and Ultra-capacitors are capacitors that have been optimally designed for use in energy storage systems.

Its three key features are (a) High Energy Density, (b) Quick charge/Discharge – Suitable for short term storage application, and (c) very high number of charge/discharge cycles

v. ***PUMPED HYDRO STORAGE TECHNOLOGY***

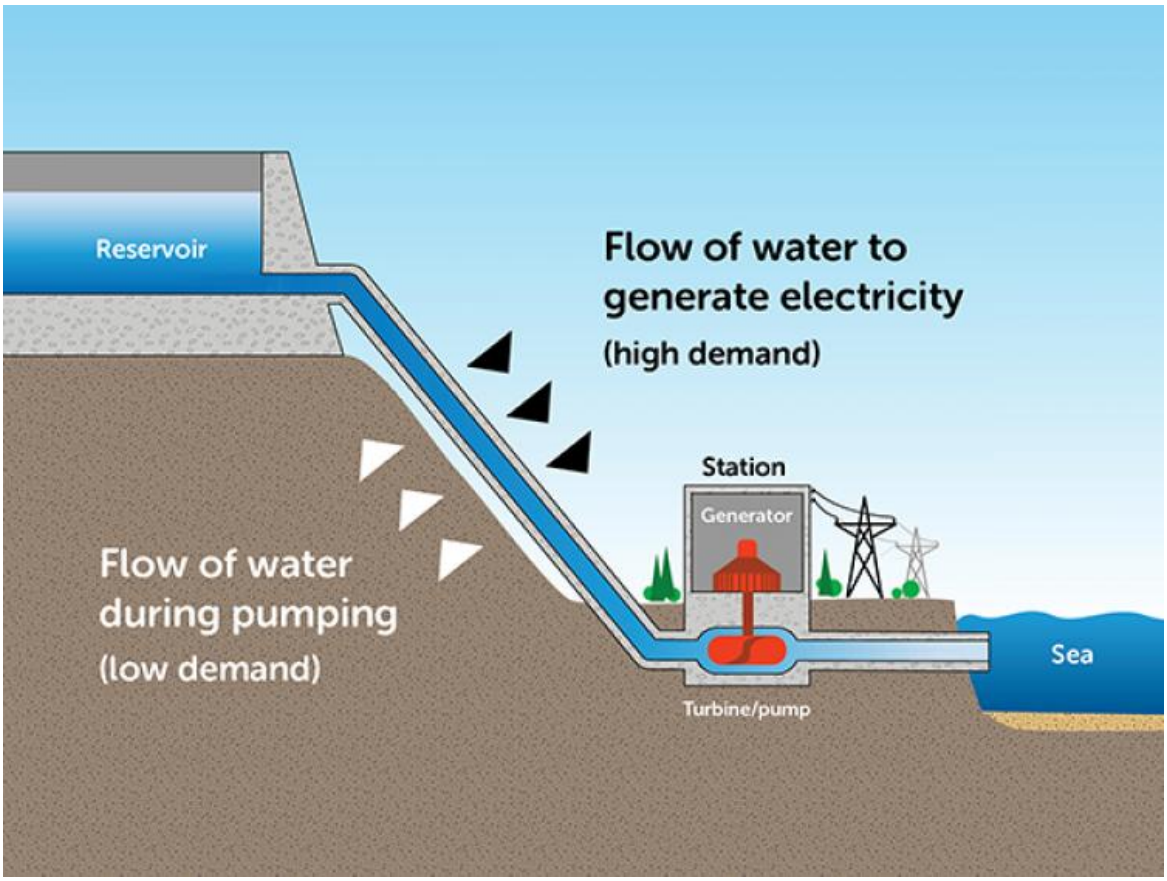

Figure 2-9 An image depicting the operation use of a pumped storage system taken from https://www.energy-storage.news/news/energyaustralia-ponders-worlds-largest-seawater-pumped-hydro-energy-storage

Pumped hydro storage technology in Figure 2-9 is physical storage systems that makes use of mechanical energy derived from the flow of water either up or downwards from an elevated area. The basic concept of operations dictates that during off peak consumption, when the distributed energy resources may be producing excess energy, the device operates in motor mode and an amount of water is pumped up an elevated area into a reservoir. During peak periods if energy supply support is required the device operates in generator mode and as water flows down from reservoir it powers a turbine which provides electrical energy.

As seen in the diagram above, crucial to the design of a pumped hydro energy storage system is the difference between the station and elevated height over the reservoir which ultimately determined the storage capacity. The advantage presented by this system lies in its ability to store large amounts of power, for example Japan's 2700MW Kannagawa pumped storage

system. Pumped storage systems can also be used to reduce or substitute the contribution of CO_2 emissions.

Its key features are:

- High Capital Cost
- Potential to store energy reserves from hours to days
- Suitable for voltage regulation and frequency modulation

2.5 CONTROL SCHEMES

The use of special schemes to control voltage, frequency, and power quality essentially involves resolving the often complex challenges around stability, protections, reliability and efficiency of a Microgrid that are implied by the different potential configurations of storage systems and technologies that we have just gone through. The control aspect is particularly challenging for isolated systems where variation between power demand and supply can be significant, for example if solar is the main energy source.

Control schemes traditionally used in Microgrids presently are either "centralised" or "decentralised". Decentralised controls involve local control of a distributed energy resource without reference to the state of other elements; include other sources, in the system. Centralised control, in contrast, involves a central controller that communicates with entire Microgrid network. This latter approach is potentially computationally expensive if multiple distributed energy sources drive the network[25].

In the [25] paper addressing "Trends in Microgrid Control" the authors propose a hierarchical layout of a control scheme that is a good compromise between the fully centralised and fully decentralised networks. This study will investigate the applicability of the hierarchical control scheme structure shown in Figure 2-10, adapted from the aforementioned paper, through the comparison of different design topologies which use the advantage of locally sourced endogenous energy resources and fully centralised local control to combat the common technical challenges of power quality, voltage regulation and frequency control in Medium Voltage Microgrid networks.

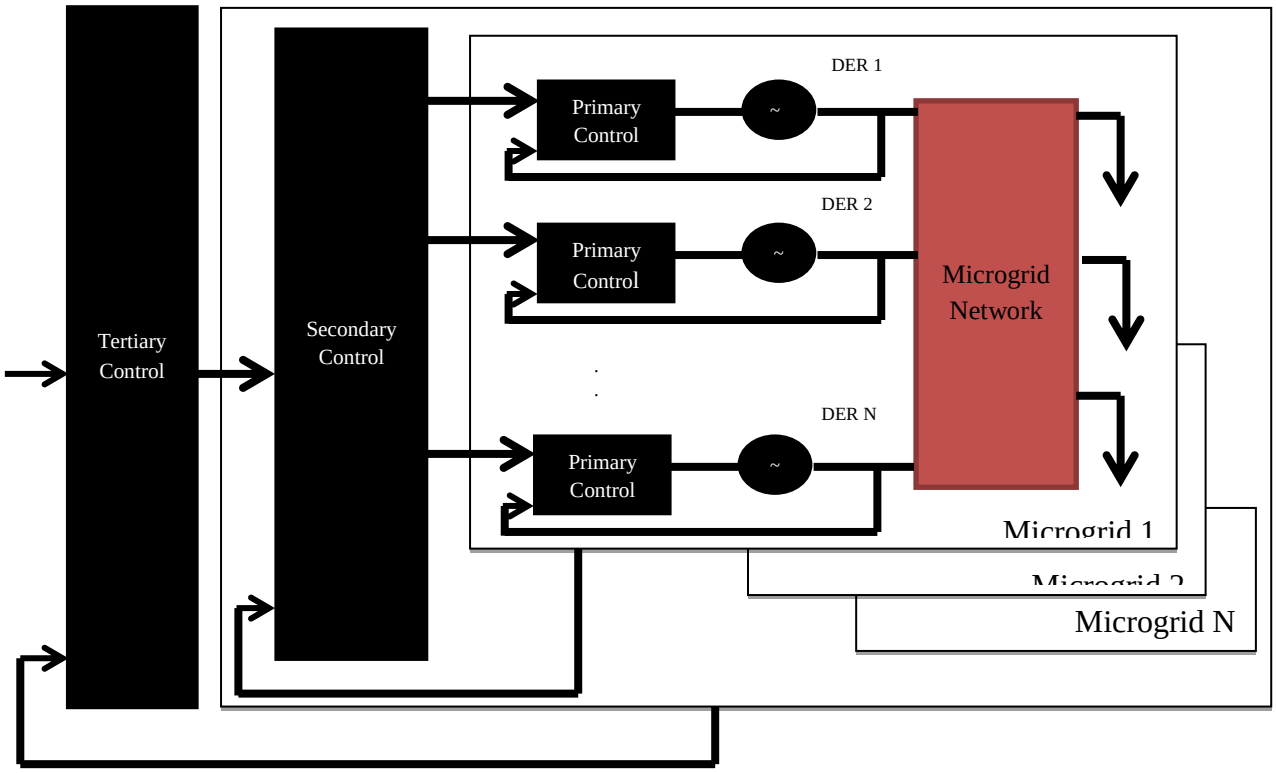

Figure 2-10 A schematic of a generalised hierarchical control scheme for an array of AC Microgrid systems connected to a main grid supply

This generalised hierarchical control scheme, as the authors describe it, in essence proposes a layered setup of interconnected controllers that perform control actions specific to the requirements and set points of that layer. At the tertiary layer the overall security, stability and economic characteristics of the system are controlled. The secondary control layer consists of what has been referred to in the literature as "Energy Management Systems" which forecast demand, the output of the distributed energy resources (DERs) and the state of the energy storage systems and perform the necessary control actions to compensate for faults and distortions in the system in order to maintain stable, constant supply voltages at a set frequency manage the system at that level. The primary control layer, which contains protection devices for the distributed energy resources, provides local control of each distributed energy resource performing control actions without knowledge of the state of other sources in the broader system [15].

To end this chapter, we look at the advantages and disadvantages of microgrids that have been reported and also comment on the question of applicability of microgrids to Angola

2.6 ADVANTAGES AND DISADVANTAGES

Microgrid systems in general have advantages and disadvantages, both of which will be taken into account in this study. Their summary which is extracted from [13][26] is provided in a table to follow.

Table 2-2 Advantages and disadvantages of Microgrid systems

Advantages:	Disadvantages:
Ability to design isolated or "islanded" systems that reliably deliver power to a load	Storage of electrical energy is required and is primarily resolved through battery technology which can be bulky in size and require maintenance both of which dramatically raise the cost of the system
Microgrids when connected to larger networks can supplement local power needs during peak hours of use in the broader system	Control schemes for the Microgrid system are more complicated to achieve as the smaller scale system are often more volatile
Ability to use low emission technologies to utilise energy sources to potentially reduce environmental impact	Microgrid systems require protection devices which can become costly
Reduce transmission losses by locating the generation source closer to the intended loads	Technical challenges exist with achieving synchronisation with the main grid
Reduce the excess energy produced by the system by providing solutions that closer match the expected energy needs of the intended loads	
When used in a grid integration connection, Microgrids can offer support to local loads during peak power demand periods relieving strain on the main grid	

When used in grid integration connection the Microgrid system can protect local loads from failures and outages in the main system improving the experience of the reliability of electrification provision from the perspective of the user	

2.7 TECHNIQUES AND SOFTWARE TOOLS USED TO MODEL MICROGRIDS

2.7.1 *TECHNIQUES*

A number of techniques for modelling a microgrid system are available. The subsections below provides a brief description of some of these suggested by [26][15] [27]

i. *Linear Programming*

Linear programming is a technique that describes the system constraints as functions and plots them in a plane as boundary conditions that contain possible solutions. A cost function for the overall system is then developed and the optimal solution(s) are calculated. Benefits to the method of Linear Programming include its ease of use and traceability. It is however considered expensive computationally particularly as the numbers of parameters increase.

ii. *Stochastic Modelling & Numerical Methods*

These methods use design constrains for performance of components and/or subsystems. First a robust stochastic model of the system under survey is developed and a set of design constraints on performance and are translated mathematically. This method, comparatively, is more difficult to understand and thereby harder to trace. It does have the benefit from being easier to code and implement from high level coding platforms such as MATLAB.

iii. *Neural Networks Algorithms*

This method employs a machine learning algorithm to determine the optimal parameters of a solution given a set of design constraints. The learning makes use of “training data” to produce meaningful values for the parameters of the defined system. Neural network algorithms require large amounts of training data for larger scale systems which can be a

barrier under extreme cases of uncertainty. It is also a method that proves to be expensive computationally.

iv. ***Genetic Algorithm, Particle Swarm Optimisation***

The Genetic Algorithm is an optimisation method that mimics the biological process of gene selection. It is an iterative method that parameterises the Microgrid into different categories, populates the sizing of the system randomly then through numerous processes of "selection" and "mutation" arrive at the optimal size through reference each stage to the optimisation constraints.

This algorithm can also be adapted to use a Particle Swarm Optimisation method, which uses a similar structure with the central difference being in the iterative procedure. This method, while covered widely in literature for complex problems, is regarded as increasing sharply in complexity with the rise in the number of parameters. Some bio mimicry methods are also difficult to represent in code.

2.7.2 *SOFTWARE*

The modelling of Microgrid systems including Distributed Energy Resources, Energy Storage Systems, Control schemes and Energy management can be conducted on many commercially available platforms some of which have the capacity to perform optimisation and sizing of components. Table 2-6 to follow briefly discusses some of the available software define tools for Microgrid system modelling [27]. In particular, the HOMER, SIMULINK, HYBRID2, Ret Screen, iHoga software tools , see [28][29][30][31][32][33] , are described in the sections to follow

i. ***HOMER***

Hybrid Optimization of Multiple Electric Renewable (HOMER) software package models components from a number of distributed energy sources, energy storage devices and configurations and provides a techno-economic projections. Some of the features of the HOMER system include its ease of use, expansive component libraries, wide use in literature and application in industry. It does however have inexact models of energy sources and other components, the design scheme is also rigid with marginal customisation options.

ii. ***SIMULINK***

Simulink is a graphical programming operating in the MATLAB simulation environment and is used for modelling, simulating and analysing multi-domain dynamic systems. The benefits of Simulink include its ease of use, modular design and notably the high level of customisation enabling inexact existing component models to be more suitably defined.

iii. ***HYBRID 2***

HYBRID2 is the second iteration of a simulation platform based on time series/probabilistic models of hybrid energy generation systems designed for long term performance and economic analysis. HYBRID2's platform, while rigid in its component definition capabilities offers input-error checking capabilities. It also has the capacity to simulate the operability of a system using up to 3 distribution buses as well as incorporating the capacity to consider shading over solar panels in its calculations, a feature well suited for urban, industrial contexts.

iv. ***RETscreen***

RETScreen is a software tool designed to assess the feasibility of energy efficient renewable energy technologies using climate and system component data. RETscreen's platform does not compute component sizing, nor does it consider the impact of temperature on solar PV systems. It is also very limited in its ability to input time series data.

v. ***iHoga***

Improved Hybrid Optimization by Genetic Algorithm (iHOGA) optimization software tool developed for systems a number of renewable energy technologies using Genetic algorithm it also has the capability to help asses and has purchase and selling energy options to the electrical grid. The iHoga system can only compute up to 10kW daily.

vi. ***Other commercially available packages***

There are a number of commercially available software packages such as the Hybrid Power System Simulation Model HYBRID 2, the General Algebraic Modelling system (GAMS) and the Simulation of Photovoltaic Energy Systems (SimPhoSys) among others, some of which focussing in on specific technologies.

In a 2014 paper titled “Review of software tools for hybrid renewable energy systems” Sinha et al [28] divides the software tools available for Microgrid design into four key categories. They are as follows:

- Pre-Feasibility tools: This set of tools generally comprises of capabilities to conduct rough sizing of the system under survey and subsequent financial estimation
- Sizing tools: This set of tools primarily provides capabilities to determine the optimal set of system components, based on input characteristics and a database of define components, including a description of the energy flows between components
- Simulation tools: Simulation tools are used to model behavioural dynamics of a system under investigation. This is achieved by characterising all the system components and using the software tool to observe, analyse and some cases optimise aspects of the system based the performance of the model in the software domain.
- Open Architecture tools: Software in this category are described as a research tool, a layer lower than Simulation tools. Open Architecture platforms allow users to modify model algorithms for individual components and their interactions within the system under investigation; this could involve different model representations for various types of battery storage, for example.

Since this study uses synthetic data (see meaning shortly), its scope with respect to the theory, planning, and design of a microgrid system based on renewable energy technology is limited to both rough system-sizing and rough financial cost estimation and will not involve in-depth investigation into the behavioural dynamics and performance of either the proposed or the preferred candidate systems or the final proposed system.

For this reason, in lieu of the descriptions given of the various software packages above, HOMER is chosen as most suitable out the alternatives given in the table. To operate the HOMER software package in this environment the following will be needed:

- Load Profile Models

  A model described in the next chapter will be used to forecast the expected loads for the energy consumption in the villages in question. The resolution of this model will need to in kW/h projected over a period of time (potentially several years) when fed into the HOMER system

- Necessary Time Series Input data:

  Distributed energy resource data such as hydro potential sources (rivers, streams, etc)and biomass sources will be statistically estimated in the absence of available physical survey data

- Relevant Component Data:

  Component data such as generator size, solar panel rating among other technical specifications will need to be specified for the candidate solutions to be produced by the HOMER algorithm

- Meteorological data:

  Since reliable solar radiation data and wind speed data for remote areas are difficult and expensive to obtain, this study will limit itself to making use of publicly available data sourced from the NASA archives.

2.8 CHAPTER SUMMARY

This chapter reviews historical literature on six aspects of microgrids, namely, the formal definition of a microgrid (section 2.2), their classification (section 2.4), a generic description of their key anatomical components(sections 2.5, 2.6, and 2.7), advantages and disadvantages of microgrids (section 2.8), the techniques and tools used in microgrid modelling (section 2.9), and lastly international examples of microgrid financing(section 2.10).

On the second aspect, the literature points out two criteria used to classify microgrids. They are: (a) whether a microgrid is connected to a central national grid or not and (b) by the channel (called *distribution bus*) through which electricity generated is distributed to utilities. Distribution buses are further classified on the basis of being either of the alternating-current kind or of the direct-current kind or a hybrid of the two.

On the anatomical components, the literature classifies them into three categories, namely, electricity generation *sources* (section 2.5), electricity *storage* (section 2.6), and voltage/frequency/ power quality *control* schemes (section 2.7).

Electricity generation is reported as mainly through solar, wind power, geothermal sources, biomass, and tidal ocean waves.

On storage, first a distinction is made between storage *systems* and storage *technologies*. Of the two systems in use, one is based on single-technology and the other is a hybrid of two complementary storage devices that makes use of that system to dually provide high-power and high-density electricity supply.

Regarding control schemes, the literature distinguishes three forms: ‘’completely centralised’’, ‘’completely decentralised’’, and a compromise between the two.

On advantages and disadvantages of microgrids, these are conveniently presented in a tabular form.

On methods for microgrid modelling, the literature identifies six. They are genetic algorithm, linear programming, neural-network algorithm, numerical methods, particle swam optimisation, and stochastic modelling. The tools used to model are statistical data on various load profile-components, and commercially available computer software. The chapter ends with two international examples microgrid financing.

CHAPTER 3

3. CHARACTERISATION OF LOAD PROFILE MODELS

3.1. INTRODUCTION

Designing a microgrid system for the study area requires knowledge of the load profile that the system is expected to satisfy. Accordingly, having just presented a generic description of the key anatomical components of a microgrid system in the last chapter, the natural next task is to address the question of how much power-consumption is contemplated in specific periods of time, since this in turn largely determines how much the power-sources in the system to be designed would need to generate *over those time periods*. The time periods in this study area 24 hours that make up a day and the 12 months that comprise a year.

However, central to the umbrella question just stated are three important power consumption determining factors, namely:

(a) the study-area's power user-classes (sub-classified further by income-classes where feasible);
(b) the period of the day and;
(c) the season of the year.

The purpose of this chapter is to characterise the daily and annual load profiles contemplated for the study area, using a " Mandelli model", see shortly, and taking into consideration these factors.

3.2. ASSUMPTIONS

Underpinning the load profile characterisation that we seek are five assumptions. They are:

(a) the assumption that for a variety of reasons (which we omit to spell out in detail for reason of space), power consumption is a random variable whose distribution is either normal or the standard beta (next section);
(b) the assumption that synthetic power consumption data in Tables 3-2 and 3-3 of section 3.6 represent a reasonable substitute for the study-area's unavailable counterpart data for reasons to be given shortly;
(c) the assumption that the power consumption model of S. Mandelli [34] in section 3.3 appropriately applies to this study;
(d) the assumption that our multiplicative way of incorporating the impact of a season's weather on power consumption in section 3.7.3 invokes a reasonable and commonly-used modelling practice in such circumstances (see justification in that section), and lastly;
(e) the assumption that the climatic conditions of Shimoga in India and Soroti in Uganda, as depicted by the weather charts in Figures 3-1 to 3-6 in section 3.6 are
(f) sufficiently similar to those of our study area.

3.3. THE DENSITIES ASSUMED FOR THE RANDOM BEHAVIOUR OF POWER CONSUMPTION

The peak load demand on a given electricity generating system at an instant in time, hereafter denoted by $X(t)$, varies randomly for a variety of reasons. It turns out from the literature that two probability distributions have historically been used to model the statistical behaviour of $X(t)$. They are the *normal* and *beta* densities.

3.3.1. THE NORMAL DISTRIBUTION

The earliest two sources to report the use of the normal distribution in load demand modelling are Hamilton's 1944 "The summation of load curves" [35] and Rusck's work titled "in "The simultaneous demand in distribution network supplying domestic consumers" [36]. Subsequent writers on the topic until early 1990's followed suit. The normal distribution has the form:

$$f(x(t)) = \frac{1}{\sqrt{2\pi\sigma^2(t)}} \exp -\frac{1}{2}\left(\frac{x(t)-\mu(t)}{\sigma(t)}\right)^2 \qquad \text{for } |x(t)| < \infty \text{ ,}$$

$|\mu(t)| < \infty$, and $\sigma(t) > 0$ (3.3.1)

where $\mu(t)$ and $\sigma(t)$ denote the *mean* and *standard deviation* of $X(t)$, respectively.

A major reason why the normality assumption is justifiable, if initially at least, is that each observed load measurement represents, among others, a result of effects of many factors which affect the true but unknowable value and which vary at random. In so far as these random effects have a degree of mutual independence, their sum would tend to comply with central limit theorem as the number of factors become large.

3.3.2. THE BETA DISTRIBUTION

In their relatively recent 1991 work, Herman et al [56] point out that while the normality assumption is valid for large groups of customers, feeders typically supply fewer than 30 customers. In the latter case they proposed the use of the beta family of densities to accommodate skewed that is associated with those small samples. From Johnson and Kotz [37] the family of beta distributions comprises of all distributions of the form:

$$f(w) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \frac{w^{\alpha-1}(b-w)^{\beta-1}}{b^{\alpha+\beta-1}} \qquad \text{for } 0 < w < b$$

(3.3.2.1a)

$$= \quad 0 \qquad \text{otherwise}$$

(3.3.2.1b)

where α, β are parameters of the distribution.

Two useful special cases are, firstly, when $a = 0$ leading to:

$$f(y) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \frac{(y-a)^{\alpha-1}(b-y)^{\beta-1}}{(b-a)^{\alpha+\beta-1}} \qquad \text{for } a < y < b \text{ and } \alpha, \beta > 0$$

(3.3.2.2a)

$$= \quad 0 \qquad \text{elsewhere}$$

(3.3.2.2b)

while the second arises from transformation

$$X = \frac{(y-a)}{(b-a)}$$

(3.3.2.3)

whereupon one obtains the standard beta form:

$$f(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \frac{x^{\alpha-1}(1-x)^{\beta-1}}{} \qquad \text{for } 0<x<1$$

(3.3.2.4a)

$$= \quad 0 \qquad \text{elsewhere}$$

(3.3.2.4b)

Lastly, useful point to note is that since (3.3.2.3) is a one-to-one transformation, one working under (3.3.2.4) with range $0<x<1$ is free to convert, by reverse transformation, to working with (3.3.2.2) which has a flexible range $a<y<b$.

3.4 LOAD PROFILE MODELS

3.4.1. MANDELLI MODEL

Central to the modelling of the daily load profile adopted in this chapter are two approaches: one introduced by Mandelli [34] in a doctoral thesis titled “Strategies for access to energy in developing countries: methods and models for off-grid power systems design”, and another proposed by Jardini et. al [38] in their paper titled “Determination of the Typical Daily Load Curve for Residential Area based on Field Measurements”.

Under the Mandelli [34] approach, the Daily Total Power Consumption in watt-hours (*Wh*) either at a point in time or in an interval of time *t*, hereafter denoted by *MDTPC(t)*, is governed by the product sum rule:

$$MDTPC(t) = \sum_{j}^{User\ Class} N_{ij} * (\sum_{i}^{No.of\ Appliances} n_j * PR(t)_{ij} * h_{ij})\ [Wh]$$

(3.4.1.1)

where at or during *t*:

MDTPC(t) is daily total power consumption under Mandelli model;

$N(t)_{ij}$ is the number of users of the ith appliance in the jth user-class ;

$n(t)_j$ is the number of appliances used by the jth a user-class;

$PR(t)_{ij}$ is the power rating of the ith appliance used by the jth a user-class;

h_{ij} is the duration of the usage of the ith appliance item by the ith user-class (measured in hours).

The values of $h_{ij}'s$ will be obtained from the columns of Tables 3-2 and 3-3 headed by 'h-start'(the time at which an appliance is switched on' and 'h-end' (the time it is switched off').

The user-classes that are adopted in this study are three: residential households (sub-classified further by 'high income' and 'low income' categories), small-scale private enterprises, and state services (admin offices, police station, clinics, schools and public light). However, while no industrial user-class is excluded from the power consumption at this point, an assessment of future development of a sugar mill near N'zeto for bio ethanol production and a saw mill in Tomboco is considered in later chapters.

Now let *MHPC(t)* denote the hourly counterpart of *MDTPC(t)* and let the duration applicable to $N(t)_{ij}$, $n(t)_j$, and $PR(t)_{ij}$ be an hour, then (3.4.1.1) decomposes as follows:

$$DTPC(t) = \sum_{1}^{24} MHPC(t)$$

(3.4.1.2)

Another decomposition that will be used later is

$$DTPC(t)_{partitioned}(t) = \begin{cases} \sum_{00:00hrs}^{06:00hrs} HTPC(t) & \text{for } 0 \le t \le 6 \\ \sum_{06:00hrs}^{12:00hrs} HTPC(t) & \text{for } 6 \le t \le 12 \\ \sum_{12:00hrs}^{18:00hrs} HTPC(t) & \text{for } 12 \le t \le 18 \\ \sum_{18:00hrs}^{24:00hrs} HTPC(t) & \text{for } 18 \le t \le 24 \end{cases}$$

(3.4.1.3)

where model (3.4.1.3) partitions a day's load profile into "Early Morning", "Morning", "Afternoon", and "Evening" segments.

Because of the primary roles they will play later, models (3.4.1.1) and (3.4.1.2) shall henceforth be referred to variously as 'the Mandelli models for Daily Total and Hourly Power-consumption respectively or 'the MMDTPC/MMHTPC' or just ' the Mandelli models', while (3.4.1.3) will be referred to as the "Partitioned Mandelli Model". The models shall further be characterised "short-term", meaning that they apply to hourly or daily, or one-year power consumption periods. For long-term consumption, see section 3.10.

3.4.2. JARDINI et al MODEL

Jardini et al [38] have proposed a method that is based on the standardisation of the hourly power consumption *HPC(t)* :

$Z(t)=\{HPC(t)-\mu\}/\sigma$

(3.4.2.1)

where are μ and σ are the mean and standard deviation of *HPC(t)* respectively. Then rewriting these transformation one obtains

$HPC(t) = \mu + \sigma Z(t)$

(3.4.2.2)

which henceforth will be called variously as "Jardini et al [38] model" or " parametric model". According to this model, α is the probability that *HPC(t)* will not exceed $\mu + \sigma z_{\alpha}(t)$, where 100α is a positive integer and $z_{\alpha}(t)$ is the 100α-th percentile of the probability density of *HPC(t).*

3.4.3. SIMILAR DAY CHARACTERISATION

Note that the effect of weather on power consumption is not accommodated by the models above. This is addressed in section 3.7. Because the models above would apply only in conditions where every day of a given year is similar in power consumption as another day throughout the year, they will also later be referred to as "Similar Day models" to distinguish them from those that incorporate the impact of weather.

3.5. OTHER USEFUL MEASURES OF LOAD PROFILE

Another category of load profile measures appear in[39] and will play a variety roles in chapters 5 and 6. They are summarised in the table to follow.

Table 3-1 A table describing key measures of load used for load modelling

Symbolic Abbreviation	Measure of Load	Determining Rule	Use of Measure
LF	''Load factor of a system in a given area over a given time period'' is average load of a system in the area over the period relative to the system's peak (maximum) load over the same period. The higher the load factor is, the smoother the load profile is, and the more efficient the infrastructure is being utilized. The highest possible load factor over the given	$f_L = \frac{Average\ Load}{Maximum\ load}$	The load factor is a representation of the "smoothness" of the load profile. The forecasted peak can also be calculated using the load forecast and the average forecasted load profile. This information can be used to specify the sizing and

	period is unity, which indicates a flat load profile.		ratings of infrastructural items.
DF	‘’Diversity factor of an area in a system in a given time period’ is the aggregate load (i.e. sum of peak loads of all the components in a system) relative to peak of the entire system in the area during the time period. The higher the diversity factor, the more diverse the individual loads are in terms of peaking time. If the individual loads peak at the same time, the diversity factor is 1.	$f_D = \frac{Aggregated\ load}{Maximum\ load}$	Useful in the planning of infrastructure (see also to follow)
CF	‘’Coincidence factor of an area in a system over a given time period’’ is the reciprocal of the diversity factor in the area during the time period. The highest possible	$f_c = \frac{1}{f_D}$	The coincidence and diversity factors are useful in the planning of infrastructure by providing information about

	coincidence factor is 1, when all of the individual components are peaking at the same time.		the forecasted peaks various feeders in the system.

All the numerators and denominators in the above table equations refer to the same given area and same given time period.

3.6. SYNTHETIC DATA TO BE USED IN THE MMTPC

3.6.1. In the absence of historical data on electricity consumption characteristics from the study area, substitute information that will be used in the MMTPC for our study area is set out in Tables 3-2 and 3-3 to follow.

Table 3-2 A table approximating electricity usage data in N'zeto on an average day

							Early Morning		Morning		Afternoon		Evening	
N'zeto	**45000 individual residents**	**N_ij**	**Appliance list**	**n_ij**	**Power Rating (W)**	**h**	**h-start**	**h-end**	**h-start**	**h-end**	**h-start**	**h-end**	**h-start**	**h-end**
Residential	Household 1	**6750**	CFL Lighting	4	20	6			6	8	-	-	18	22
			Phone Charger	2	5	4			6	8	12	14	20	22
			Radio	1	10	6			6	8	9	12	17	22
			Security light	1	20	12	0	6			-	-	18	24
			Cooling Fan	1	30	6			-	-	12	14	18	20
	Household 2	**750**	CFL Lighting	4	20	6			6	8	-	-	18	21
			Phone Charger	2	5	4			6	8	-	-	20	22
			Radio	1	10	6			6	8	9	12	17	22
			Cooling Fan	2	30	6			-	-	12	14	18	20
			TV	1	100	5			6	8	12	14	18	22
			Security	1	20	12	0	6			-	-	18	24

			light											
			Geyser	1	660	4			6	8	-	-	18	20
			Refrigerator	1	300	24	0	6	6	8	9	16	17	24
Enterprises	Hotel Perola do N'zeto	1	CFL Lighting	20	20	6			6	8	-	-	18	21
			Phone Charger	10	5	3			6	8	-	-	18	20
			Radio	5	10	6			6	8	9	10	17	21
			Cooling Fan	5	30	-			-	-	10	16	-	-
			Security light	1	20	12	0	6			-	-	18	24
			TV	5	100	4			6	8	-	-	18	22
			Geyser	2	660	4			6	8	-	-	18	20
			Refrigerator	2	300	24	0	6	6	8	9	16	17	24
	Convenience store	2	Cooling Fan	2	30	8			-	8	9	16	17	-
			CFL Lighting	4	20	8			-	8	9	16	17	-
			Security light	1	20		0	6			-	-	18	24
			Refrigerator	2	300	24	0	6	6	8	9	16	17	24
	Hair	5	Cooling Fan	2	30	8			6	8	9	16	17	-

	#Dresser/Barber		Hair dryer	1	1000	4			-	-	11	15	-	-
			Hair clipper	2	10	4			-	-	11	15		
			Security light	1	20	12	0	6			-	-	18	26
			CFL Lighting	4	20	8			6	8	9	16	17	-
	Market Place	1	CFL Lighting	8	20	8			6	8	9	16	17	-
			Cooling Fan	2	30	6			-	-	9	16	-	-
			Refrigerator (big)	1	500	24	0	6	6	8	9	16	17	24
			Radio	2	10	8			-	-	10	16	-	-
State services	state admin offices (State admin offices)	2	CFL Lighting	20	20	8			-	-	9	16	17	-
			Cooling Fan	10	30	6			-	-	9	16	-	-
			Refrigerator	1	300	24	0	6	6	8	9	16	17	24
			Security light	1	20	12	0	6			12	24		
			Personal Computer	10	400	8			-	-	9	16	17	-
			Radio	2	10	8			-	-	9	16	17	-

	Primary & Secondary School	2	CFL Lighting	30	20	8			-	-	9	16	17	-
			Security light	2	20	12	0	6			-	-	18	24
			Cooling Fan	20	30	6			-	-	9	16	-	-
			Personal Computer	5	400	8			-	-	9	16	17	-
	Community Health Care Clinic	1	Refrigerator	2	500	24	0	6	6	8	9	16	17	24
			Personal Computer	5	300	8			-	-	9	16	17	-
			Cooling Fan	10	30	6			-	-	9	16	17	-
			Medical Equipment	2	1000	4			-	-	11	15	-	-
			Security light	1	20	12	0	6	-		-	-	18	24
			CFL Lighting	20	20	8			-	8	9	16	17	-
	Police Station	1	Cooling Fan	4	30	6			-	-	9	16	-	-
			Personal Computer	2	400	8			-	-	9	16	17	-
			CFL	10	20	8			-	8	9	16	17	-

			Lighting											
			Security light	1	20	12	0	6			-	-	18	24
			Refrigerator	2	300	24	0	6	6	8	9	16	17	24
	Street Lights	1	Street lamps	100	50	24	0	6	6	8	9	16	17	24

Table 3-3 A table approximating electricity usage data in Tomboco on an average day

							Early Morning		**Morning**		**Afternoon**		**Evening**	
Tomboco	**40000 individual residents**	**N_ij**	**Appliance list**	**n_ij**	**Power Rating (W)**	**h**	**h-start**	**h-end**	**h-start**	**h-end**	**h-start**	**h-end**	**h-start**	**h-end**
Residential	Household 1	**6000**	CFL Lighting	4	20	6			6	8	-	-	18	22
			Phone Charger	2	5	4			6	8	12	14	20	22
			Radio	1	10	6			6	8	9	12	17	22
			Security light	1	20	12	0	6			-	-	18	24
			Cooling Fan	1	30	6			-	-	12	14	18	20
	Household 2	**667**	CFL Lighting	4	20	6			6	8	-	-	18	21
			Phone Charger	2	5	4			6	8	-	-	20	22
			Radio	1	10	6			6	8	9	12	17	22

			Cooling Fan	2	30	6			-	-	12	14	18	20
			TV	1	100	5			6	8	12	14	18	22
			Security light	1	20	12	0	6			-	-	18	24
			Geyser	1	660	4			6	8	-	-	18	20
			Refrigerator	1	300	24	0	6	6	8	9	16	17	24
	Convenience store	2	Cooling Fan	2	30	8			-	8	9	16	17	-
			CFL Lighting	4	20	8			-	8	9	16	17	-
			Security light	1	20		0	6			-	-	18	24
			Refrigerator	2	300	24	0	6	6	8	9	16	17	24
	Hair Dresser/Barber	5	Cooling Fan	2	30	8			-	8	9	16	17	-
			Hair dryer	1	1000	4			-	-	11	15	-	-
			Hair clipper	2	10	4			-	-	11	15		
			Security light	1	20	12	0	6			-	-	18	26
			CFL Lighting	4	20	8			-	8	9	16	17	-
	Market Place	1	CFL Lighting	8	20	8			-	8	9	16	17	-
			Cooling Fan	2	30	6			-	-	9	16	-	-
			Refrigerator (big)	1	500	24			0	8	9	16	17	24
			Radio	2	10	8			-	-	10	16	-	-
State services	state admin offices (State	2	CFL Lighting	20	20	8			-	-	9	16	17	-
			Cooling Fan	10	30	6			-	-	9	16	-	-

	admin offices)		Refrigerator	1	300	24	0	6	6	8	9	16	17	24
			Security light	1	20									
			Personal Computer	10	400	8			-	-	9	16	17	-
			Radio	2	10	8			-	-	9	16	17	-
	Primary & Secondary School	2	CFL Lighting	30	20	8			-	-	9	16	17	-
			Security light	2	20	12	0	6			-	-	18	24
			Cooling Fan	20	30	6			-	-	9	16	-	-
			Personal Computer	5	400	8			-	-	9	16	17	-
	Community Health Care Clinic	1	Refrigerator	2	500	24	0	6	6	8	9	16	17	24
			Personal Computer	5	300	8			-	-	9	16	17	-
			Cooling Fan	10	30	6			-	-	9	16	17	-
			Medical Equipment	2	1000	4			-	-	11	15	-	-
			Security light	1	20	12			-	6	-	-	18	24
			CFL Lighting	20	20	8			-	8	9	16	17	-
	Police Station	1	Cooling Fan	4	30	6			-	-	9	16	-	-
			Personal Computer	2	400	8			-	-	9	16	17	-

			CFL Lighting	10	20	8			-	8	9	16	17	-
			Security light	1	20	12	0	6			-	-	18	24
			Refrigerator	2	300	24	0	6	6	8	9	16	17	24
	Street Lights	1	Street lamps	100	50	24	0	6	6	8	9	16	17	24

The tables are constructed from three sources: two are studies conducted in India and Uganda and the third is the ‘’Angola Municipal Map’’ compiled by the Food and Agricultural Organisation of the United Nations[40].

The India study, “Modelling of integrated renewable energy system for electrification of a remote area in India” by S. Rajanna et. al [41], was conducted as part of a design for a renewables-based rural electrification design. It performed a load assessment on four villages in India by means of a survey and in this task the study divided the electrical loads into categories reflecting “Domestic”, “Community”, and “Commercial” & “Small Industrial” load classes as well as appliance classes, with corresponding power ratings, and seasonal hourly operation period.

The Uganda study, ‘’Effect of load profile uncertainty on the optimum sizing of off-grid PV Systems for rural electrification” by Stefano Mandelli et. al [42], investigates the impact of uncertainty in load profiles on solar-PV isolated Microgrid systems in Soroti region, north-east of Uganda.

To distinguish the substitute information contained in the above tables from the unavailable authentic counterpart, the former has been assigned the name ‘synthetic data’.

3.7. EXTENSION OF THE SIMILAR DAY MANDELLI MODELS

3.7.1. INTRODUCTION

Clearly, beside user-classes, the time period of a day, the annual seasonal temperatures, and the annual seasonal humidity levels are additional factors that cannot be ignored when modelling the contemplated DTPC by the three user-classes above.

In contemplation of the first factor, a 24-hour day was partitioned into four equal subinterval of ‘Early Morning’ (00:00 hrs to 6:00hrs), ‘Morning’ (06:00 hrs to 12:00 hrs), ‘Afternoon’ (18:00 hrs to 6:00 hrs), and ‘Evening’ (18:00 hrs to 24:00 hrs) in section 3.4.1.

On the second and third factors, seasonal temperatures and humidity levels are utilised in this chapter in three ways. Firstly, we use them to highlight the remarkable similarities of the climatic conditions prevailing in past case-studies of Soroti in Uganda and Shimoga in India on the one

hand, and our study area on the other hand (see next section). The second way uses that similarity to justify our adoption of the power consumption statistics from those case-studies as our synthetic substitute for the un-available study area power consumption counterpart. The third way is dealt with in section 3.7.2 where a composite factor that represents the impact of weather on power consumption is modelled.

3.7.2. BASIS FOR THE CHOICE OF SYNTHEIC DATA

As evidence of our claim of similarity of the climatic conditions between Shimoga, Soroti, and our study area, six charts are provided to follow comparing typical monthly temperature and humidity levels in the twin case-study areas of the S. Rajanna et. al [41] paper and the Stefano Mandelli et. al [42] on the one hand, and N'zeto on the other hand (the restriction in the latter case to Nzeto only is based on the Tomboco's proximity to N'zeto).

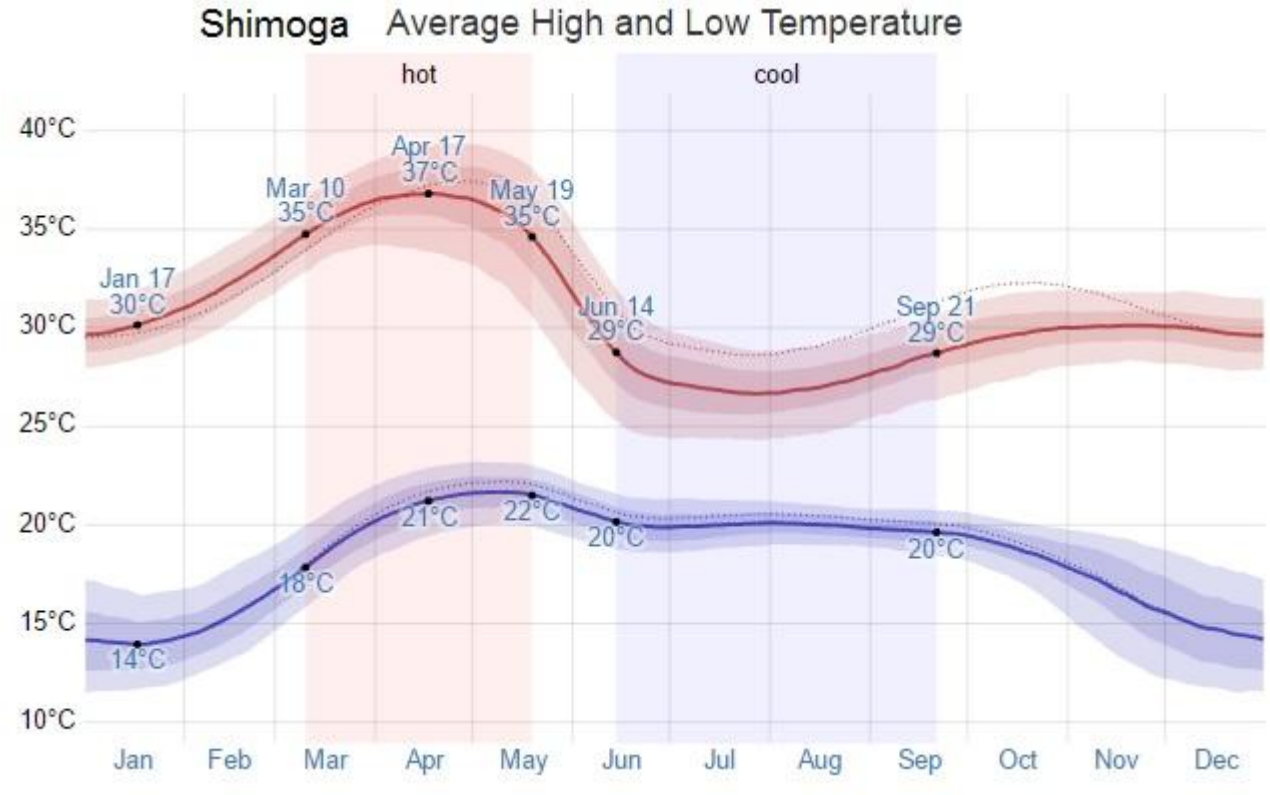

Figure 3-1 Annual temperature for Shimoga, India taken from weatherspark (https://weatherspark.com/y/108156/Average-Weather-in-Shimoga-India)

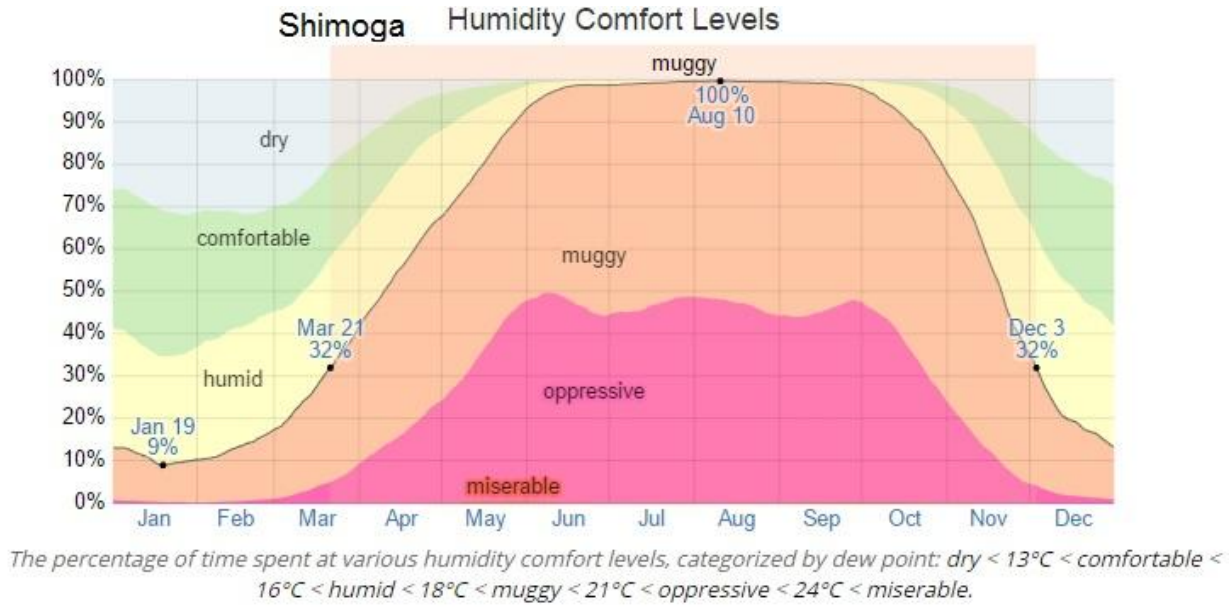

Figure 3-2 Annual humidity for Shimoga, India taken from weatherspark (https://weatherspark.com/y/108156/Average-Weather-in-Shimoga-India

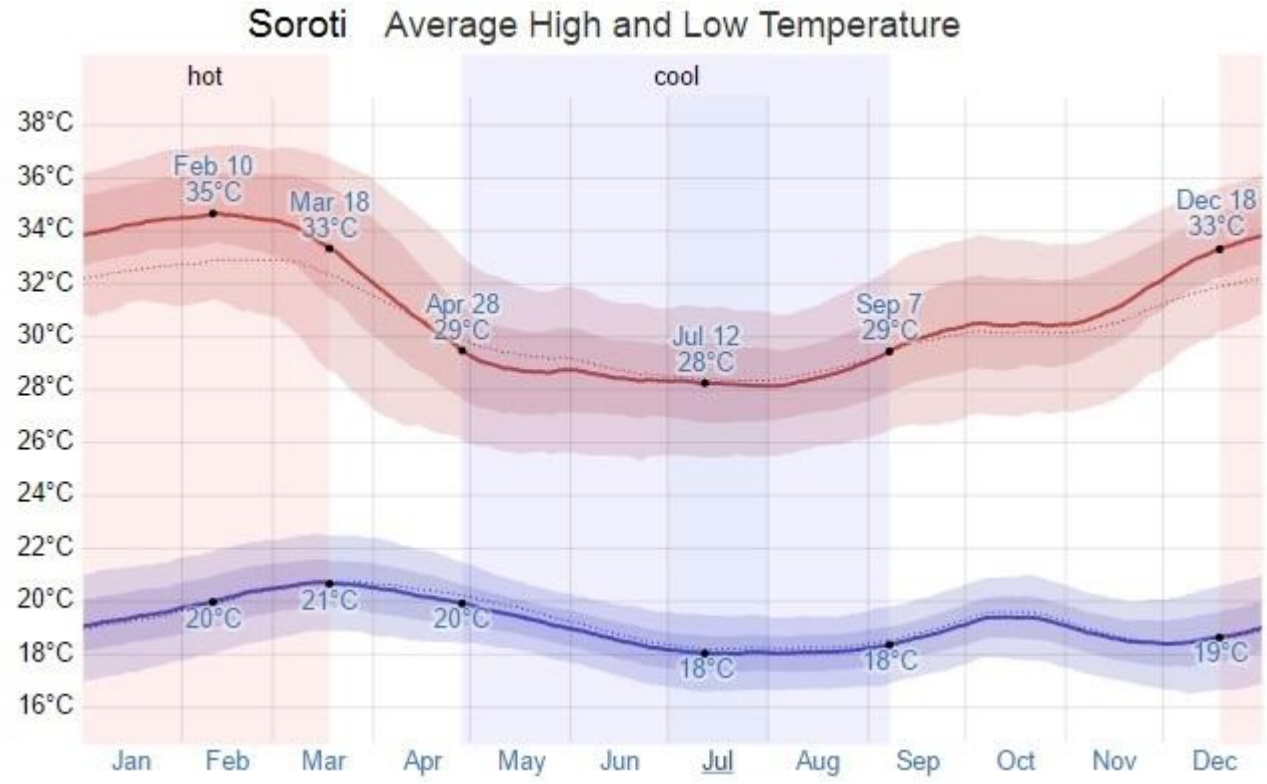

Figure 3-3 Annual Temperature for Soroti, Uganda taken from weatherspark (https://weatherspark.com/y/97606/Average-Weather-in-Soroti-Uganda)

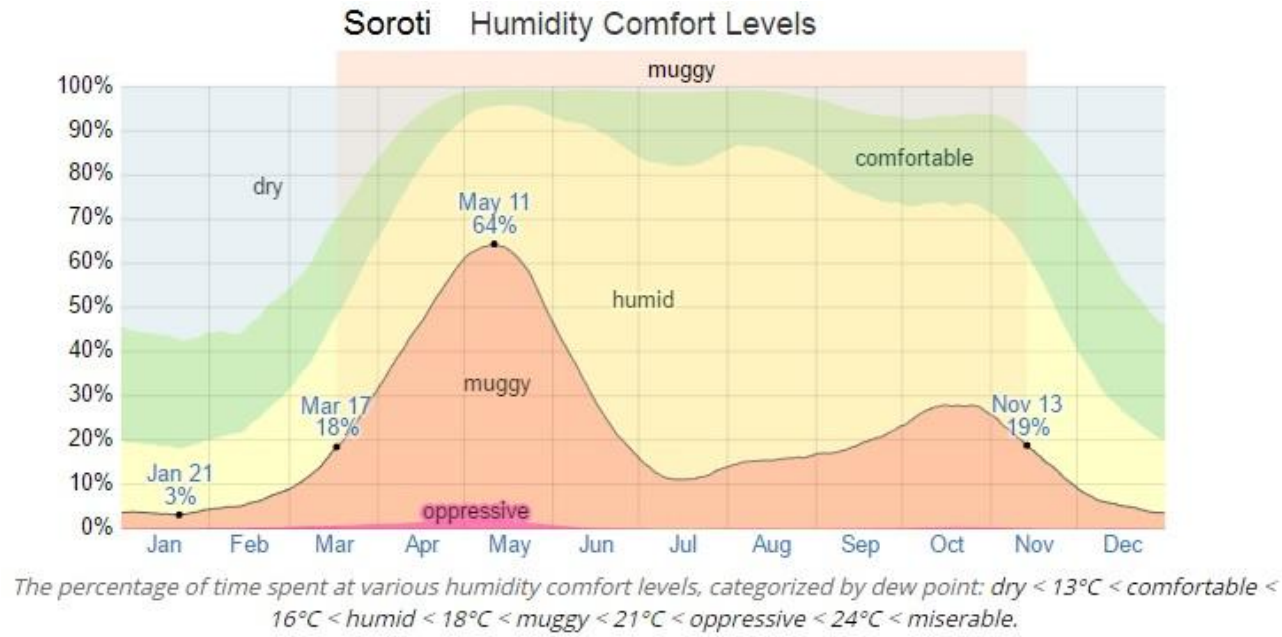

Figure 3-4 Annual humidity for Soriti, Uganda taken from weatherspark (https://weatherspark.com/y/97606/Average-Weather-in-Soroti-Uganda)

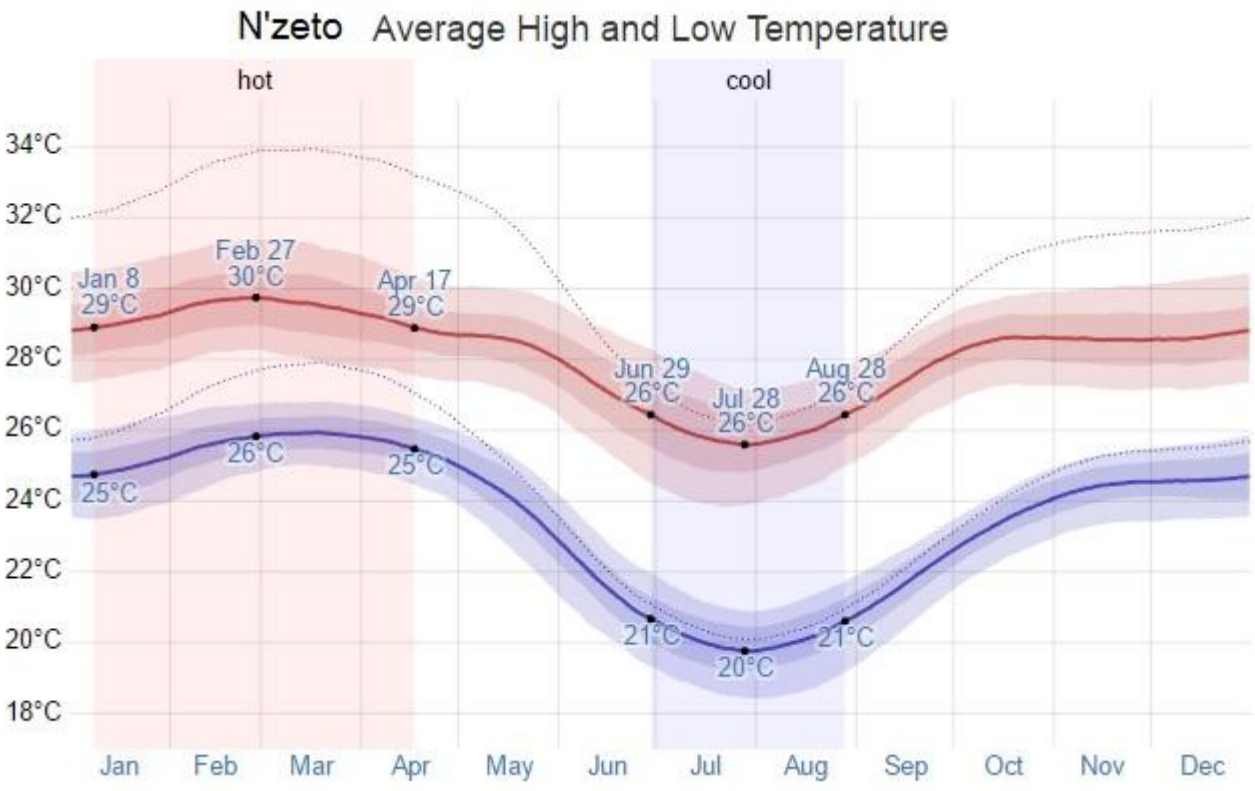

Figure 3-5 Annual temperature for N'zeto, Angola taken from weatherspark (https://weatherspark.com/y/71666/Average-Weather-in-Nzeto-Angola)

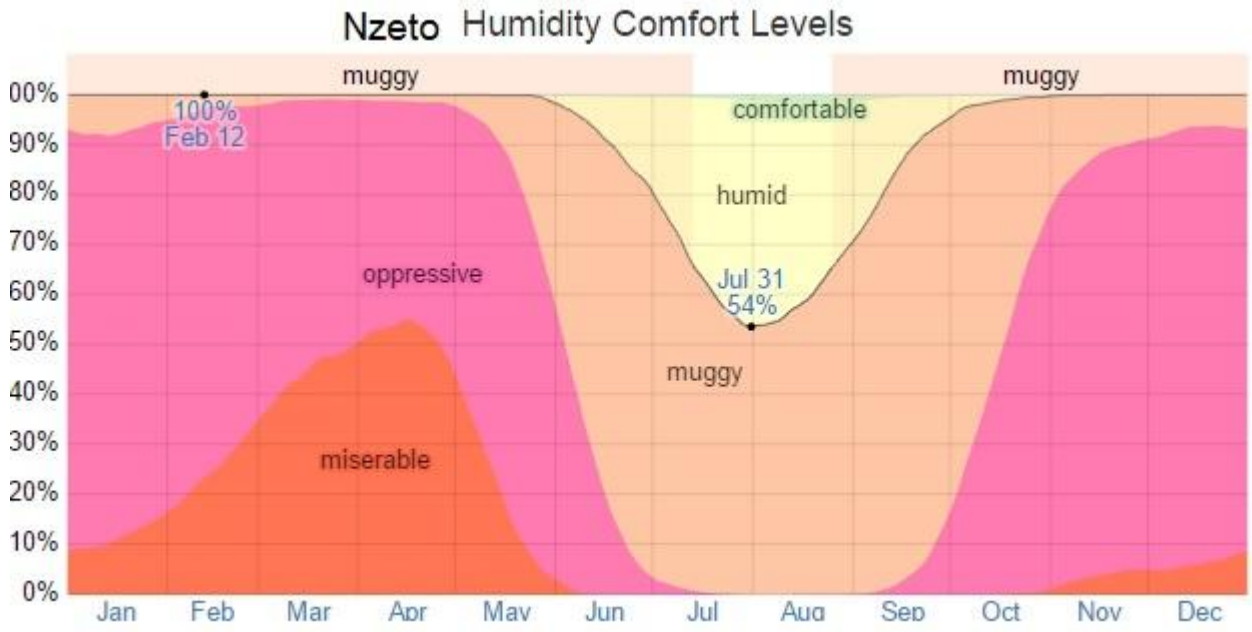

Figure 3-6 Annual humidity for N'zeto, Angola taken from weatherspark (https://weatherspark.com/y/71666/Average-Weather-in-Nzeto-Angola)

From charts, the remarkable closeness of the climate statistics of Shimonga, Soroti, and N'zeto is self-evident.

3.7.3. EFFECT OF ANNUAL WEATHER SEASONS

In this section an extension of the short term Similar Day Mandelli models of section 3.4. is made by incorporating the impact of seasonal weather in a given year on the short term load profiles contemplated for the study area.

We start with a rule of thumb that in hot and humid seasons, more power consumption would be demanded to 'cool' homes, work-place environments, and so on, the higher the temperatures and the greater the degrees of discomfort when humidity levels increase. To formulate the composite effect of temperature and humidity, let:

$T(t)$ be the temperature at a time-point t on a given day;

$T_{average}$ be the monthly average temperature per day;

$H(t)$ be the level of humidity at a time-point t on a given day;

$H_{average}$ be the monthly average obtained from historical data, while;

$a(t)$ be a function as defined, namely,

$$a_{Temperature}(t) = \frac{T(t)}{T_{average}}$$

(3.7.3.1)

$$a_{Humidity}(t) = \frac{H(t)}{H_{average}}$$

(3.7.3.2)

Then, following a multiplicative practice used commonly in statistical regression analysis as well as in analysis of variance to model interaction of explanatory variables, a multiplicative relationship:

$$a_{seasonal\ effect}(t) = a_{Temperature}(t) * a_{Humidity}(t)$$

(3.7.3.3)

or more explicitly

$$a_{seasonal\ effect}(t) = \frac{T(t)}{T_{average}} * \frac{H(t)}{H_{average}}$$

(3.7.3.4)

is proposed as a composite model for the interaction between humidity and temperature. We further propose to transfer this approach to the modelling of the 'interaction of weather and the Mandelli Similar Day power consumption models of section 3.4' so that, say,

$$SA - MDTPC(t) = \alpha_{seasonal\ effect}(t) * (\sum_1^{24} MHPC(t)$$

(3.7.3.5)

would be the a Season-Adjusted MMDTPC (SA-MMDTPC) of Similar Day model (3.4.1.2). In other words, a SA-MMDTPC is the original 'version (3.4.1.2) MMDTPC' adjusted for the composite effect of temperature and humidity in the manner of (3.7.3.5). The other versions, namely, (3.4.1.1) and (3.4.1.3) as well as the parametric model are similarly adjustable.

Lastly, to emphasise the role of weather, the original Mandelli models and those of this section shall be distinguished by calling the latter "Season-adjusted Mandelli and Jardini et al Models".

3.8. EFFECT OF LONG-TERM POPULATION GROWTH

Power consumption, particularly by the residential user class, is naturally further influenced by population growth over a time period L, say (measured in years). A simple model that is chosen for this growth a simple exponential function

$$P(L) = P_o e^{-rL}$$

(3.8.1)

Where, P_o is the population size at the start of L and *r* is the annual growth rate.

Choosing L to be the years 2014-2025 for reasons indicated in chapter one, and assuming for simplicity that the population would double by 2025 (due to factors that include migration into our study area triggered by its electrification as well as improved services such as health care and schooling that accompany such electrification), one has the following:

Table 3-4 A table of population statistics for N'zeto and Tomboco in 2014 (extracted from Tables 3-2 and 3-3)

	Population	Number of Households
N'zeto	45000	7500
Tomboco	40000	6667

Then for N'zeto: $P_0 = 45000;\ \ P(12) = 90000;$ and hence $r = \ 5{,}78\%$

and for Tomboco $P_0 = 40000;\ P(12) = 80000;$ so that also $r = 5{,}78\%$

(a) Figure 3-7 Graphs showing the population forecast for N'zeto and Tomboco from 2014 to 2025 under the assumptions

indicated.

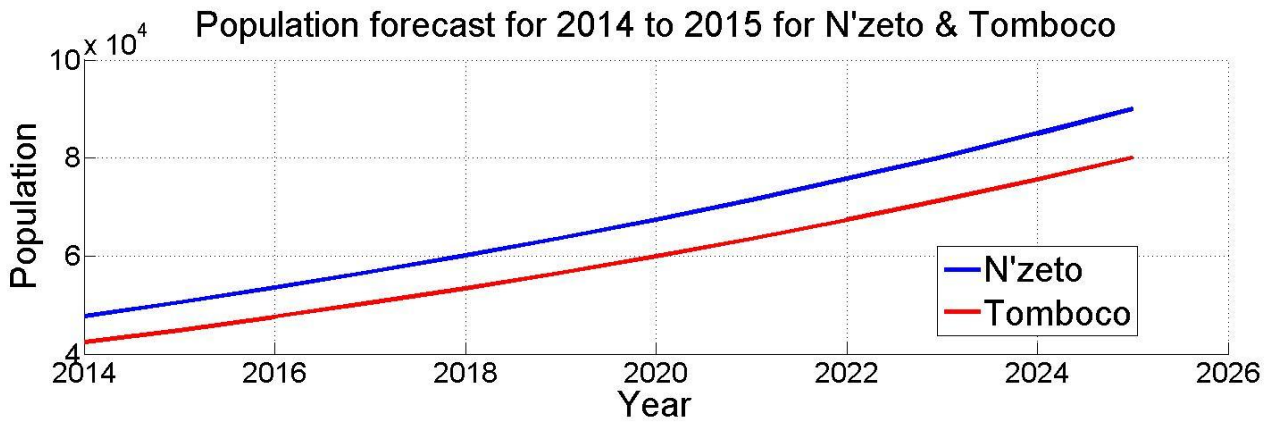

Figure 3-7 Graphs showing the population forecast for N'zeto and Tomboco from 2014 to 2025 under the assumptions

These population growth forecasts for N'zeto and Tomboco would then be fed into our $\varphi_{hourly\ model}(t)'s$.

3.9. ALGORITHMS FOR FITTING SIMILAR DAY AND SEASON ADJUSTED MODELS

Algorithms are presented in this section that are used to fit the Similar Day Mandelli models as well as their season-adjusted counterparts. The fitted models are then used in section 3.12 to display the study area's synthetic load profile curves, whose peaks will play an important role in the design of the load capacity of the ultimate microgrid solution.

3.9.1. FITTING SIMILAR DAY UNPARTITIONED & PARTITIONED MANDELLI MODELS

Unpartitioned and partitioned Similar Day Mandelli models with either a normally- or beta-distributed noise will be fitted using a least squares procedure that is implemented on MATLAB (source code is available upon request). That is to say, MATLAB functions NORMFIT & BETAFIT use of the method of least squares to determine the parameters of each respective distribution. The following are the steps;

- Step 1: Extract the relevant model data from Tables 3-2 and 3-3 ;
- Step 2: distribution and the parameters are estimated using a least squares algorithm
- Step 3: Forecast population size
- Forecast future power consumption for a given year

Below is the summary of the algorithm will be implemented in the MATLAB simulations to generate a load forecast for N'zeto and Tomboco for a twelve -year period 2014 to 2025.

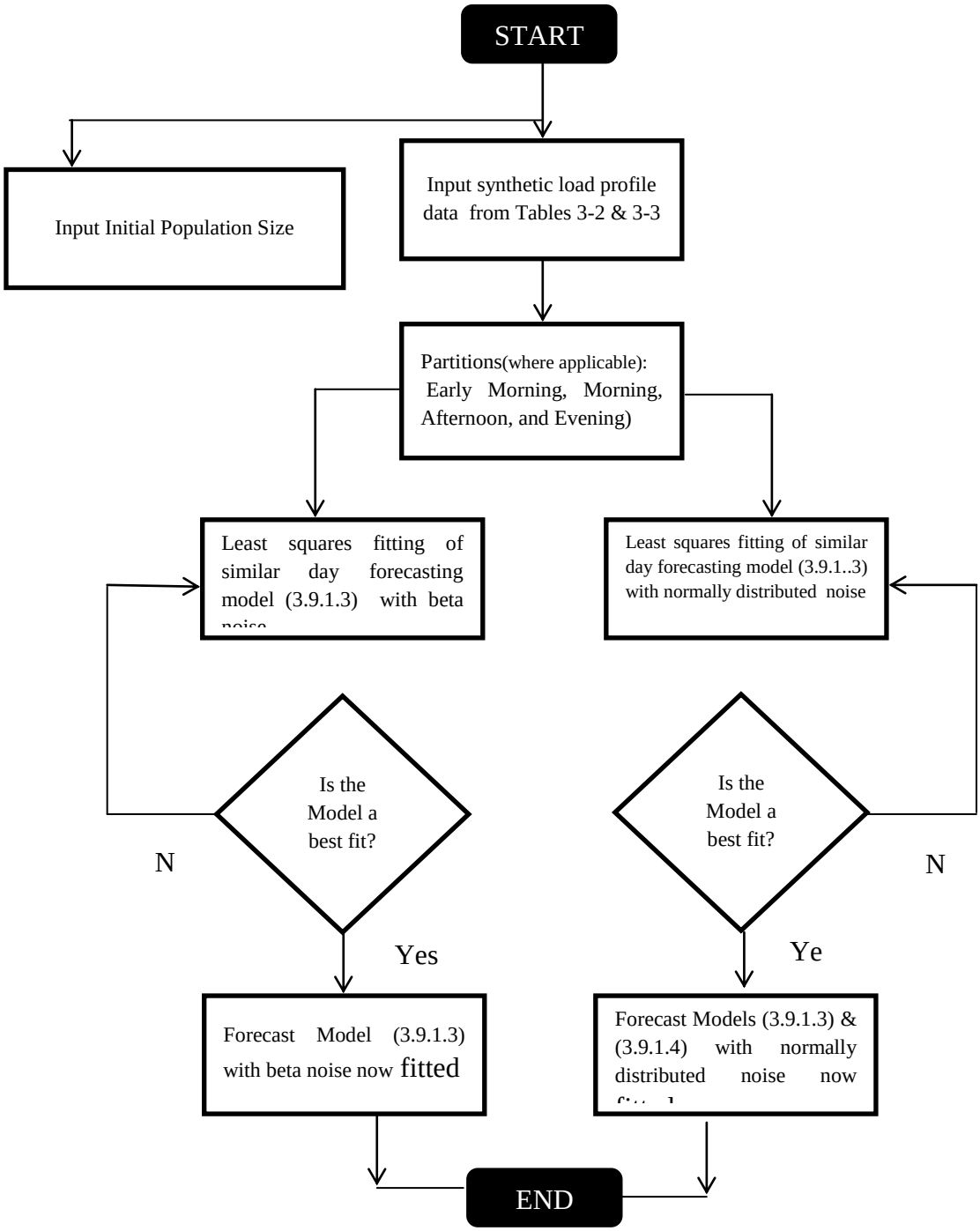

Figure 3-8 A representation of the algorithm for fitting long term forecasting models (3.9.1.3)

Note: Source code is available upon request

3.9.2. FITTING SEASON ADJUSTED MODELS

The diagram to follow is a summary algorithm for fitting the season-adjusted counterparts of the Similar Day model.

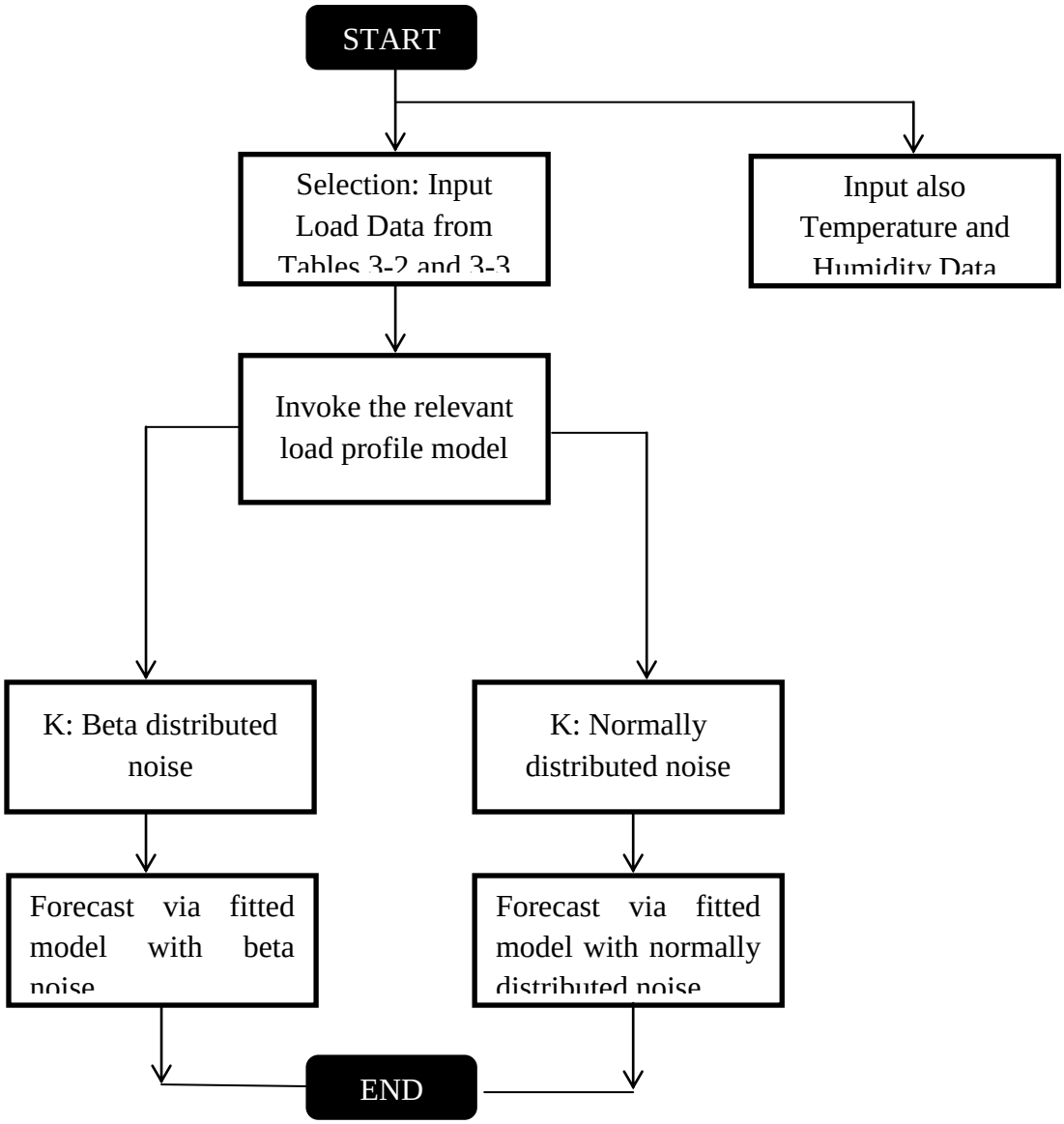

Figure 3-9 The algorithm for fitting unpartitioned and partitioned season-adjusted Mandelli models

Note: Source code is available upon request

3.10 CHAPTER SUMMARY

This chapter, focussing on the synthetic characterisation of load profiles and energy consumption, made use of remotely acquired public data most significantly from GIS data collected via municipal surveys from the Food and Agriculture Organisation of the United Nations. This information assisted in the development of synthetic load tables demonstrated in tables 3-1 and 3-2 using component data and behavioural patterns from similar contexts in Uganda and India and context specific information about N'zeto and Tomboco to generate test data to be used in absence of available historical data of actual energy consumption.

Sections 3.5.5 and 3.5.6 then went on to describe two broad methods for forecasting the load profile in N'zeto and Tomboco taking into consideration various statistical assumptions. Thereafter in sections 3.5.8 and 3.5.9 programmatic forecasting algorithms were proposed and implemented in a MATLAB software environment with results illustrated in 3.6.2 and 3.6.3.

Table 3-5 A table demonstrating, using the synthetic model data, the differences in the forecasted energy consumption between the Parametric Model & the Similar Day forecasts

	Period	Total Energy Consumed Over Period (kWh)		Peak(kW)	
		Normal Dist.	Beta Dist.	Normal Dist.	Beta Dist.
N'zeto (Parametric)	1 January 2014 (Single day)	**1.7776e+004**	**1.9475e+004**		
	June 2014 (Full Month)	**5.6028e+005**	**5.4251e+005**		
	2014 (Full Year)	**6.8490e+006**	**6.7238e+006**	**2.3767e+003**	**3.0543e+003**
Tomboco (Parametric)	1 January 2014 (Single day)	**1.6701e+004**	**1.6093e+004**		
	June 2014 (Full Month)	**4.8659e+005**	**4.7075e+005**		
	2014 (Full Year)	**5.9610e+006**	**5.7123e+006**	**1.9319e+003**	**2.3146e+003**
N'zeto (Similar Day)	1 January 2014 (Single day)	**2.0098e+004**	**1.8658e+004**		
	June 2014 (Full	**5.5715e+005**	**5.0101e+005**		

	Month)				
	2014 (Full Year)	**6.5899e+006**	**6.0673e+006**	**2.8581e+003**	**2.3323e+003**
Tomboco (Similar Day)	1 January 2014 (Single day)	**1.7001e+004**	**1.7003e+004**		
	June 2014 (Full Month)	**4.9328e+005**	**4.7563e+005**		
	2014 (Full Year)	**6.1991e+006**	**5.7993e+006**	**2.5435e+003**	**2.2140e+003**

Table 3-4 summaries aspects of the Similar Day and Parametric Windowing Approach model performance by focussing on the total energy consumed and the peak power over various periods for case. Each time series out for the forecasts generated from each model will be used as an input into the HOMER.

As discussed in Jardini et. al [**64**] among the many factors of interest in assessing and validating Load Models include the total energy used during a period and the estimated peak power over the period under investigation. From table 3-4 it is evident that between the proposed modelling approaches & distribution choices there exists variability is it relates to those factors, using this information this study will investigate and comment on the impact of this variability in the selection of Microgrid design solutions.

Furthermore, in PhD dissertation titled “Load research and load estimation in electricity distribution” by Ansii Seppälä [**69**] a historical account is provided for the development of load survey studies in Europe. Initially as early as the 1950s load surveys took place with the use of automatic and/or manual devices which recorded power readings at nodes within the system on printed paper. Later towards in 1970s and 1980s recordings were able to be stored on magnetic tape lowering the cost of comprehensive load studies [**70**]. Post-1980s till today has seen an exponential increase in computing power with a equally dramatic drop in cost opening up the possibilities for more expansive statistically based modelling approaches for load curve estimation.

The research conducted in Chapter 3, through scientific enquiry and application of engineering design methodology, suggest that while the modern era have opened up new possibilities for more complex and comprehensive load modelling the theory available in this research area does not adequately engage with some of the, potentially unique, challenges to this work posed within the context of the “developing” world. In this case, for Angola, in the wake of decaying infrastructure

due to civil war, and with the realities of a state struggling to extend basic services need to be taken into consideration as part of robust technical and policy planning as they relate to electrification.

Following from this assessment the process and development of the “Similar day” and Parametric models for the daily load profiles for N’zeto and Tomboco using meteorological, geographical, socio-economic and demographic data are crucial to surfacing important aspects of the proposed electrisation developed through this dissertation. Microgrid optimisation programmes such as HOMER and PVsyst offer functions that generate standard load curves that can be adjusted by peak and basic seasonal modelling.

Chapter 6, which goes on to define the proposed Microgrid solution includes a sensitivity analysis which takes into consideration load profile uncertainty.

4. RESOURCE & INFRASTUCTURE ASSESSMENT

4.1. INTRODUCTION

In section 2.5 of chapter two, we saw that a number of different energy sources are used in various configurations to meet the load requirement of a given micro-grid system and Table 2-2 there provided a summary of the popular distributed energy sources, together with some of their key characteristics as reported in "Microgrid Technology and Engineering Application"[15].

The purpose of this chapter is (a) to assess which of those sources are available in or within the proximity of the study area; (b) to make a specific choice from (a) for a focus of this study and (c) to assess the state of current physical infrastructure in the study area, since we consider (a) and (c) to be among the most the critical *determinants* of both (i) the *feasibility* of the electrification proposal of this study *in the short –to- medium term* and (ii) its *ultimate overall impact* and *sustainability in the long-term*.

The chapter proceeds as follows. Section 4.2 describes the geographic availability of Solar, Wind, Hydro and Biomass resources in the regions of Angola/Democratic Republic of Congo which surround the study area, as well as related government policy positions on their exploitation (where such policy positions already exist). Section 4.3 describes the technologies that are currently available for converting biomass into electrical energy while section 4.4, the last, describes briefly the current state of electricity supply, roads, airport, and harbour. Last preliminary: the various data forms appearing (or used) in this chapter have been obtained from the following sources:

. Angola 2025 Action Plan; published in (2014) World Energy Outlook[43];

. National Energy Security Strategy and Policy: Government Strategic Policy Overview Report 2011; published by the Ministry of Energy and Water of Republic of Angola [44];

. Angola Energia 2025: Government Public Report 2015; published by the Ministry of Energy and Water of Republic of Angola [45]

. GIS viewer from Angola Energia 2025: Government Public Report 2015 ;

. Special Reports, [46][47][48][49], and;

. Food and Agriculture Organisation of the United Nations Municipal Atlas[40]

4.2. RESOURCE ENERGY MAP

This section maps the availability of Solar, Wind, Hydro and Biomass resources in the geographical regions of Angola/Democratic Republic of Congo which surround study area, as well as provides related comments on these sources.

4.2.1. SOLAR

Due to its geographical location, Angola overall has high solar irradiation levels across the entire country that make it well suited for the development of photovoltaic systems in its rural parts. The photovoltaic cells themselves are generally relatively light weight which will become a significant design consideration for the proposed Microgrids. Indeed the National Energy Security Strategy and Policy (NESSP) Overview Report 2011 highlights this potential in relation to rural electrification. In addition, two examples of this potential are given in the Energia 2025 Report. One is the existence of solar systems in Central Angola which has produced solar electricity at a cost as low as $0.15/kwh, compared to a reported cost of $0.20/kwh electricity produced by diesel-driven generators. Another is the development of a 2MW, 100% solar, plant in Rivungo which, from the viewpoint of our study, falls within the range of the envisaged power requirements for each of N'zeto and Tomboco.

The image to follow is produced by the "Map Angola 2025" GIS viewer and demonstrates the average solar irradiation patterns projected.

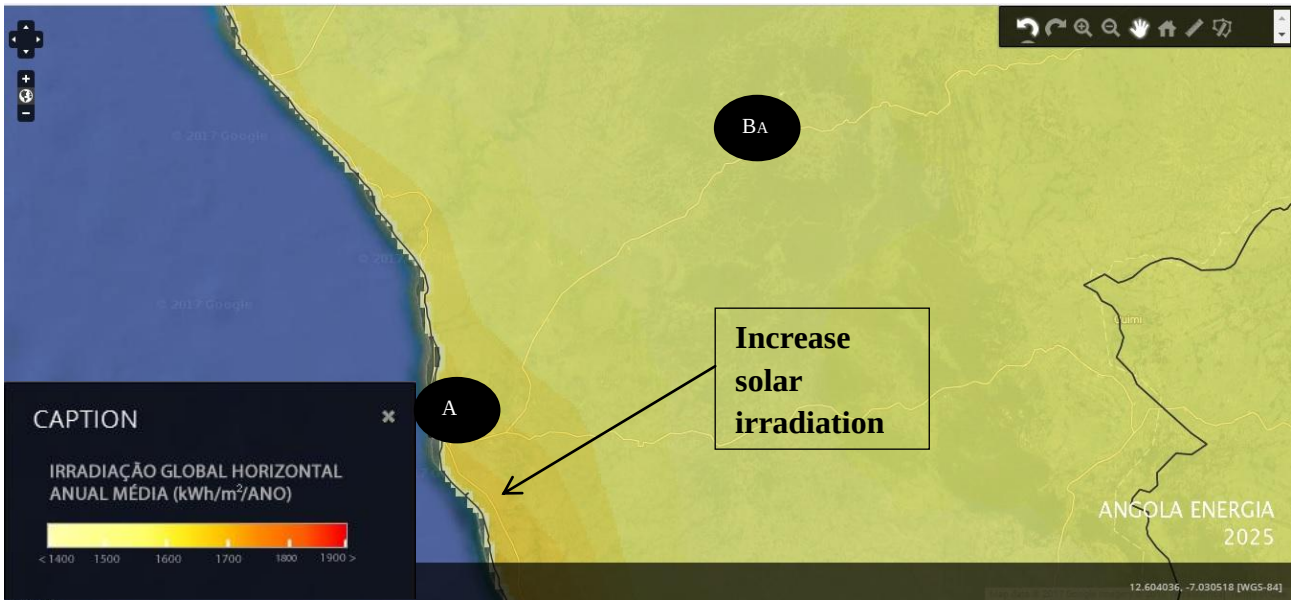

Figure 4-1 A visualisation of the Solar irradiation distribution in the region surrounding N'zeto and Tomboco – Global Horizontal Annual Data (kWh/m^2/ANO)

In this map and those that follow, areas A & B respectively represent the locations of N'zeto and Tomboco. Furthermore, the arrow in Figure 4-1 shown moving inwards toward the coast South of N'zeto emphasises the direction of increased solar irradiation levels.

4.2.2. WIND ENERGY

In contrast to solar irradiation, wind energy resources in Angola are distributed sparsely across the country and generally are associated with higher altitudes. Areas of high potential are concentrated in south east of the country as Figure 4-2 shows. In particular, the small area highlighted in the map and located between Tomboco and M'banza Kongo, the provincial capital, is projected to have relatively high wind speeds of around 6m/s.

a

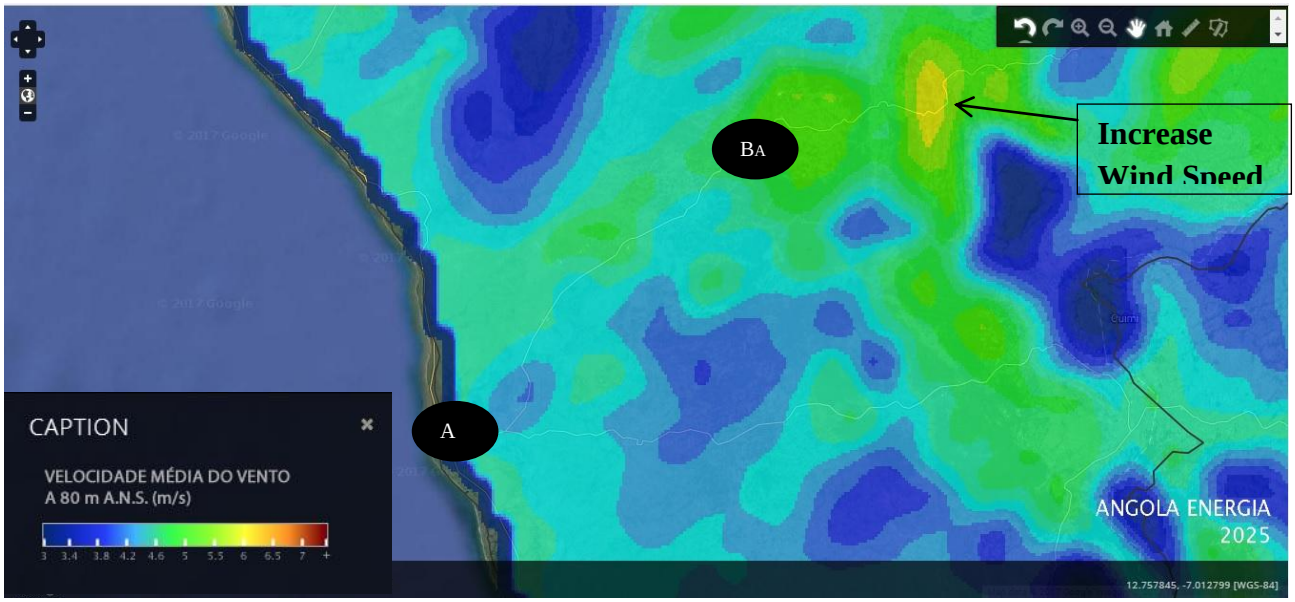

Figure 4-2 A visualisation of the Wind Speeds at an altitude of 80m in the region surrounding N'zeto and Tomboco – Wind Speed Data at 80m (m/s)

4.2.3. HYDRO POTENTIAL

4.2.3.1. GENERAL

The NESSP Overview Report 2011 highlights the rich hydro potential across Angola with numerous river basins located across the country as may be seen in Figure 4-3 to follow.

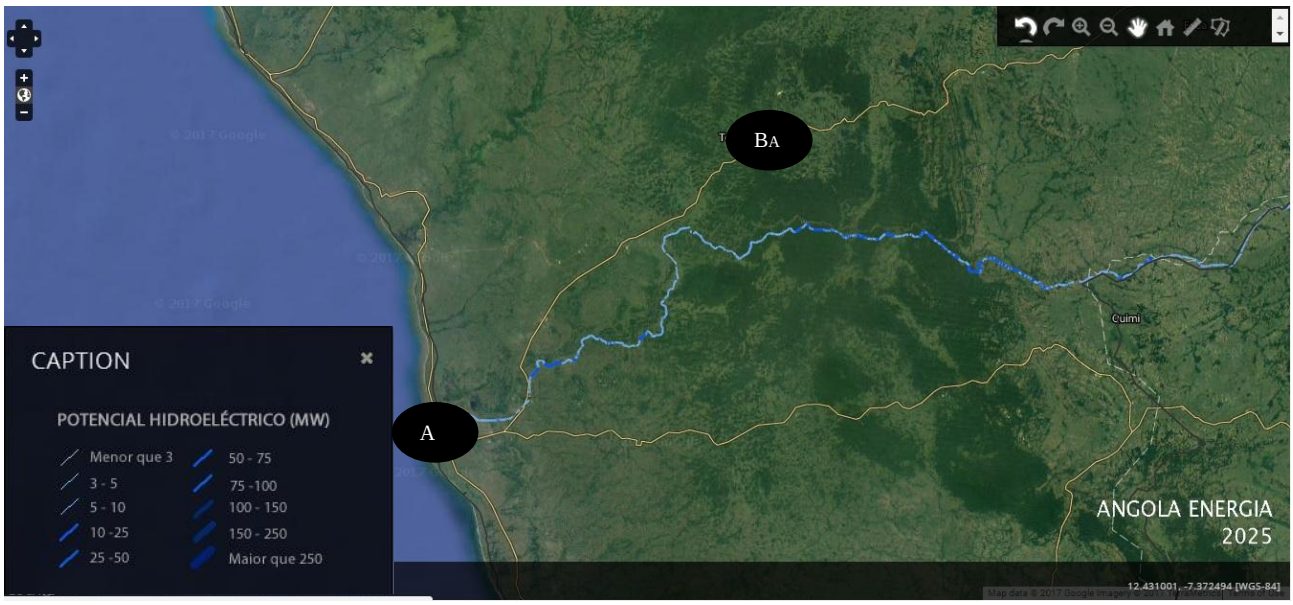

Figure 4-3 A visualisation of the Hydropower potential across the M'bridge river in Zaire, Angola – Hydroelectric Potential (MW)

In the above map, the hydro-electrical resource identified by the Angola Energia GIS viewer is known variously as the M'bridge and Mebridge River. A hydropower plant based on the exploitation of this river was planned to supply the provincial capital, M'banza Kongo. An article published by the International Water Power and Dam construction titled "Focus on Angola", and a feasibility study report titled "Cambambe Hydropower Development – Power Strengthening" published in 2011 by an engineering company called COBA Group are the only available sources we have found containing technical details relating to the projected specifications of the M'bridge hydro plant. The table to follow represents the key information for the proposed plant:

Table 4-1 A table depicting the technical specifications of the COBA group M'bridge Hydroplant

Description	Specification
Power Rating	(3 x 2,275MW) 6,825MW
Maximum flow – M'bridge River	2.4 m^3/s
Distribution infrastructure	Substation 60kV
Production Potential	23.8GWh/year
Cost of Energy Production	US$0.096/kWh
Instalment costs	US$4,755/kW

Furthermore, and more generally, the Angola Energia 2025 Report did identify two main categories of hydropower plants needed by the country for development purposes, namely, the *micro*-hydro plants having generation capacity of up to 10 MW and the *medium sized* hydro plants with capacity of over 250 MW. The Report favoured the location of the former category in rural applications.

In summary then, there exists hydro power potential for consideration for the microgrid application in the in the vicinity of the N'zeto-Tomboco and there also exists a precedent for research on this potential.

4.2.3.2. ESTIMATES OF ANNUAL FLOW RATES OF M'BRIDGE RIVER

In order to assess the feasibility of using the M'bridge river as a *micro*-hydro source, monthly flow rate data are needed but apparently not available. Studies such as "Modelling of river flow rate as a function of rainfall and temperature using response surface methodology based on

historical time series" by S. Kostić et. al [50] contain ways of modelling the impact of rainfall and temperature variability on river flow using system identification. Such an approach would only be possible at this stage if one has flow rate input data from M'bridge and unfortunately that information is not available. A simple alternative is the model :

$$A\hat{F}R = \frac{1}{\alpha_{temperature}(t)} MFR$$

(4.2.3.1)

where $A\hat{F}R$ denotes estimated annual flow rate in m^3/s, $a_{Temperature}(t)$ is defined by equation (3.7.3.1), and MFR is the maximum flow rate. According to this simplified model , the higher the weather temperature *T(t)* relative to the average temperature $T_{average}$, the lower the maximum river flow.

When executed using MATLAB, the following graph is the result:

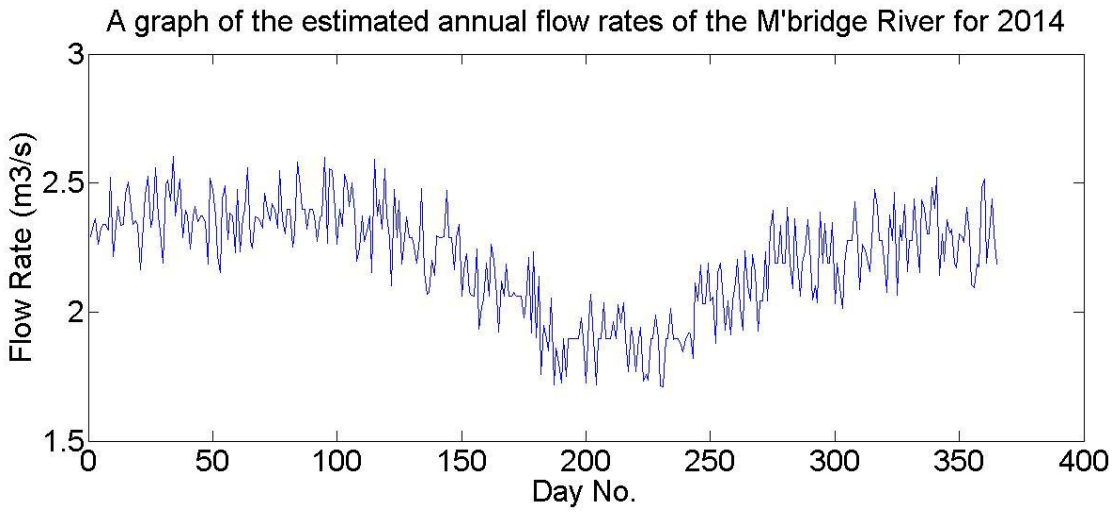

Figure 4-4 A graph of the estimated annual flow rates of the M'bridge River for 2014

Figure 4-4 depicts the annual flow rate calculated hourly, for integration as input into HOMER, but graphically represented above as daily flow rates estimated through MATLAB software implementation of equation 4.2.3.1.

4.2.4. BIOMASS

4.2.4.1. INTRODUCTION

The term "Biomass", according to http:// Isa.Colorado.edu /essence/texts/biomass.html, refers to any organic matter that can be used as an energy source. The citation classifies the biomass used today into four types. They are:

(a) Wood and agricultural products;
(b) Solid waste;
(c) Landfill gas and;
(d) Alcohol fuels.

In Angola, broadly speaking, the NESSP Overview Report 2011 supports use of biomass raw materials from local agriculture industries, where these exist. In an article titled "North from Luanda" issued in a GAUFF engineering publication titled "Universo" the agro-economy between N'zeto and Tomboco is described as being based on cassava, groundnuts, maize, beans, bananas, sweet potatoes, citrus fruits and pineapples [51]. In another report titled "Report on the Agro-angola fair and a field trip to the Malanje region" [46] the following agro-industrial activity was listed as follows: Projecto de Desenvolvimento Agro-industrial do N'Zeto (near N'Zeto, Zaire province), comprising of 2,600 hectares of land, produces grains, concentrated feed, eggs (2.5 mln /yr) and has a cassava processing plant .

Furthermore, the Angola Energia 2025 Report [45] mentions a future development of a sugar mill near N'zeto which if realised may also serve as an additional biomass resource for the contemplated microgrid configuration. To follow is the Angola Energia 2025 Map Viewer biomass potential which indicates higher biomass energy densities closest to N'zeto and even more so in the area surrounding Tomboco village.

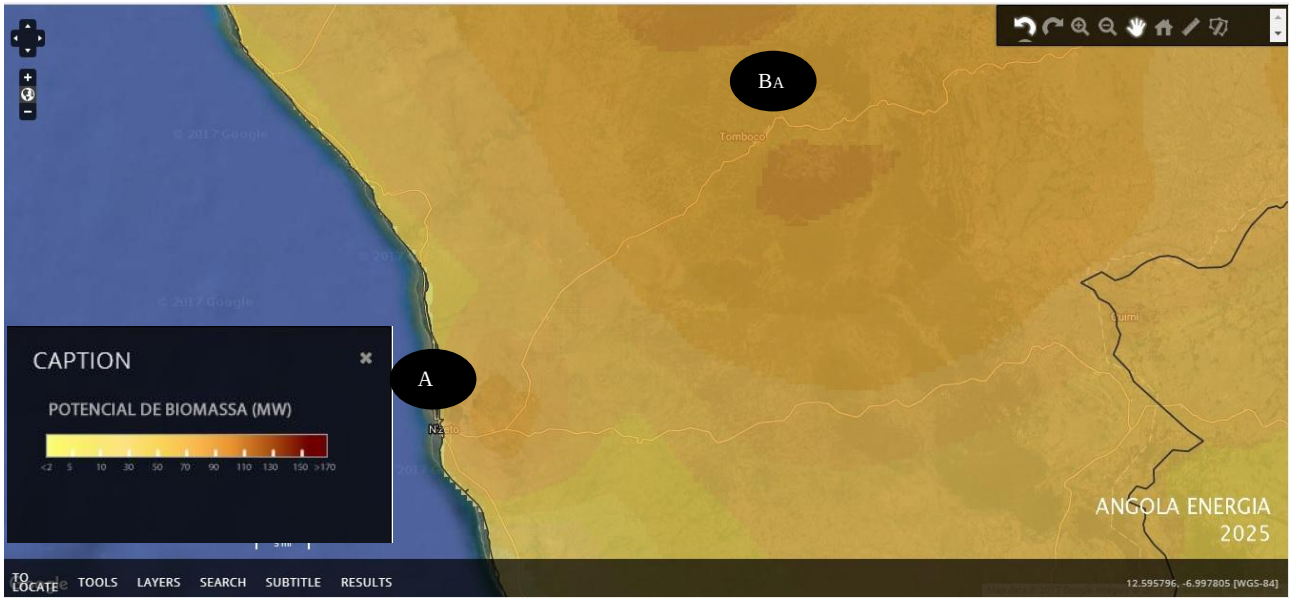

Figure 4-5 A visualisation of the Biomass potential across the region surrounding N'zeto and Tomboco – Biomass Potential (MW)

Figure 4-5 was obtained from the Angola Energia GIS viewer makes use of a biomass density function over Angola to plot bounded regions of estimated available biomass resources. This graphical representation, while useful for identifying areas where biomass resources should be strongly considered, does not take into consideration which resources specifically are available in each particular and in which quantities. Therefore further investigation making use of context specific information from the FAO UN Angola municipal atlas of 2006 will be used to determine resource details.

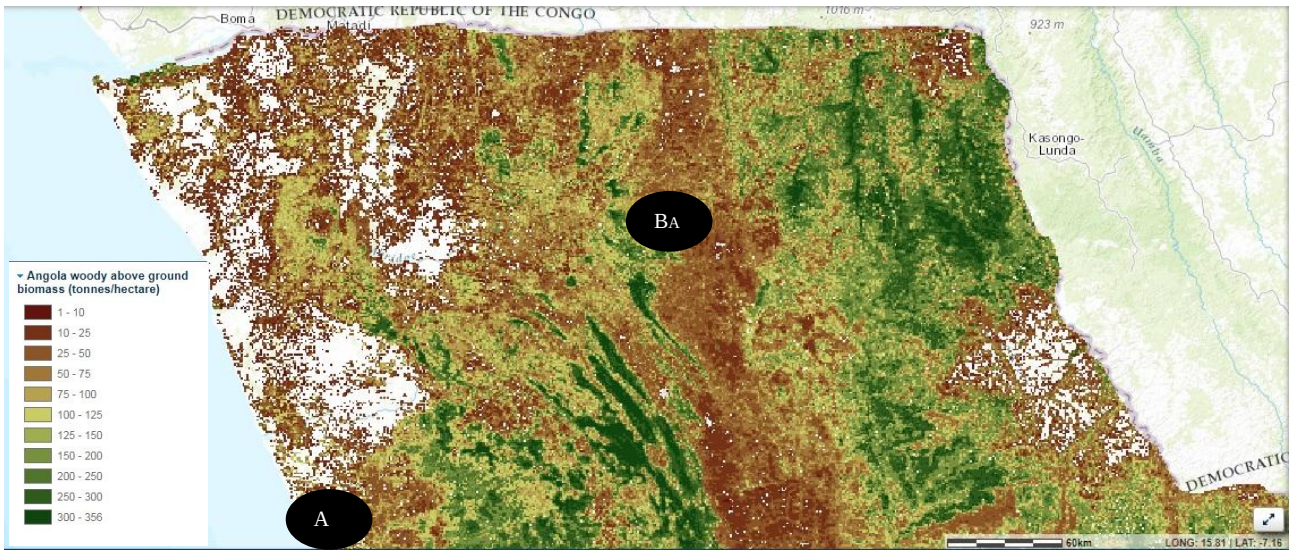

Figure 4-6 A visualisation of Above Ground Woody Biomass for the region surrounding N'zeto and Tomboco – Taken from the Conservation Biology Institute (https://databasin.org/datasets/30388e1fbd1b4ef899792894bb2cce0e)

The above ground woody biomass density represents the forest/plant biomass residue that can be utilised as a fuel. From Figure 4-4, the area around Tomboco with high biomass appears likely to relate to forest/plant residue given the data visualised in Figure 4-5.

For this study, the biomass produced from agricultural activity and not from the forest/plant residue is the preferred candidate energy source.

4.2 AVAILABILITY OF BIOMASS FROM AGRICULTURAL PRODUCTS IN THE STUDY AREA

To assess the viability of biomass-based energy sources for the contemplated microgrid system, one needs to assess two aspects of *availability* of those sources: the availability of *suitable* raw materials and the and quantification of the *regularity of their availability annually*.

i. *AVAILABILITY OF SUITABLE BIOMASS RESOURCES*

A survey was conducted between 2004 and 2006 jointly by the Ministry of Agriculture and Rural development (MINADER) and Government of the Kingdom of Sweden in an effort to develop a GIS platform titled "Angola Municipal Atlas" for the purposes of strengthening planning and decision making at that level. The two graphics in Figures 4-7 and 4-8 have been constructed from annual total crop tonnages drawn from that Municipal Atlas. Unfortunately no breakdown of these totals of any form is provided by the atlas.

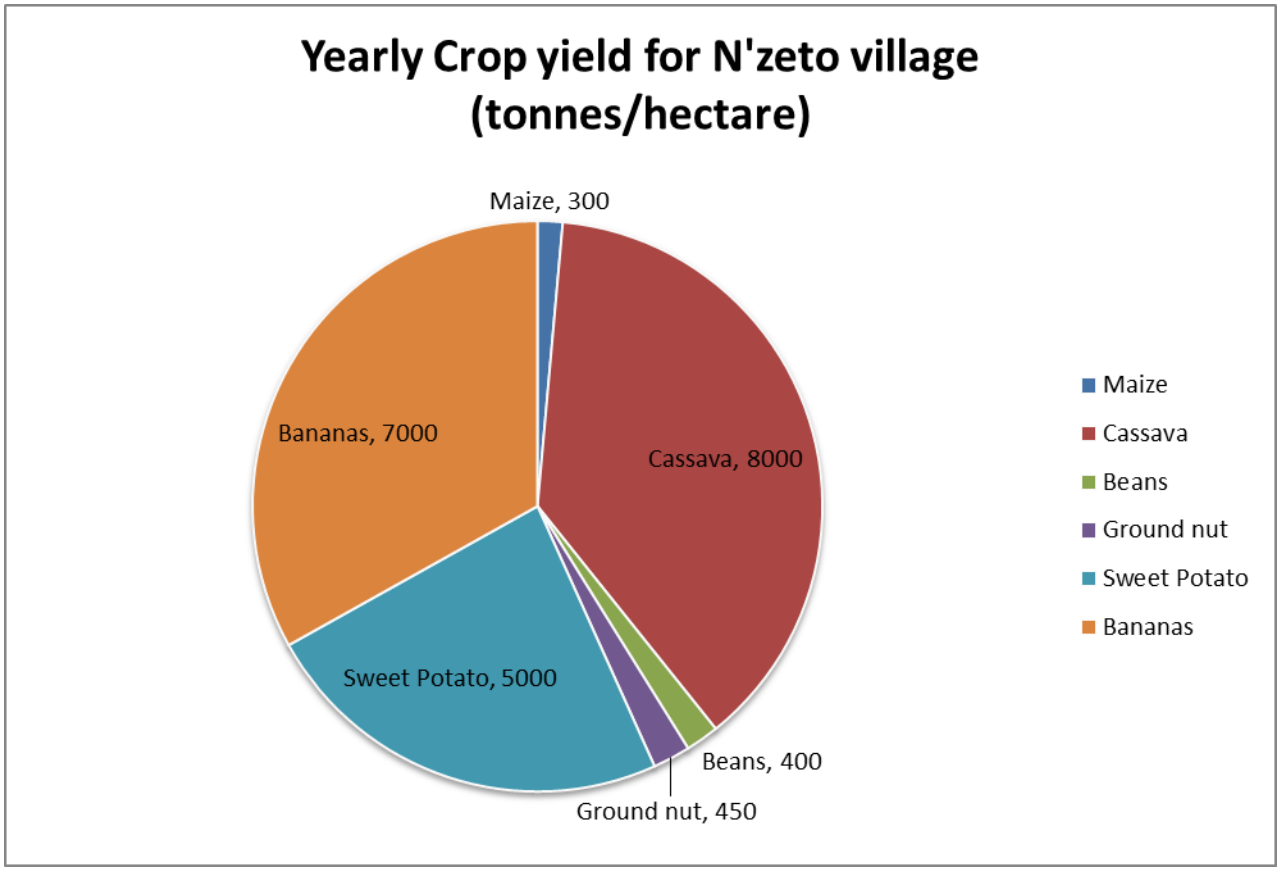

Figure 4-7 A figure representing the yearly crop yield for N'zeto village (FAO Data – Angola Atlas)

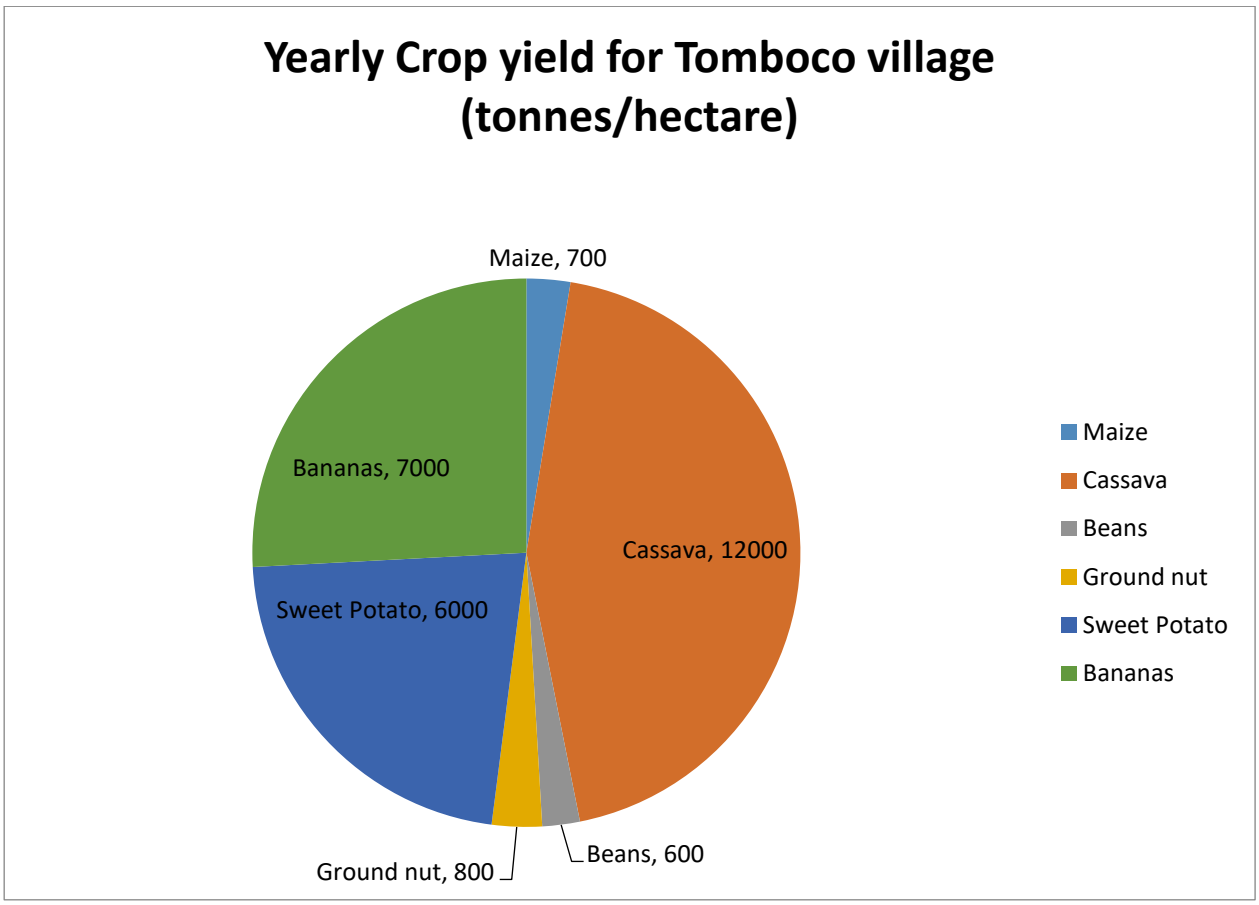

Figure 4-8 A figure representing the yearly crop yield for Tomboco village (FAO Data – Angola Atlas)

From the pie charts one finds that annual production tonnages of Cassava, Banana and Sweet Potatoes in both the N'zeto and Tomboco villages are significant. Indeed 1998 special report by the Food and Agriculture Organisation of the United Nations (FAO) and the World Food Programme (WFP) titled "Crop and Food Supply Assessment Mission to Angola" also had identified cassava in particular as key crop in the Northern region of Angola and that the average small holding size for irrigated crops is purported to be 2 hectors[49]. This small holding size will be used as the basis for estimation of biomass potential in this study.

Further data provided by the atlas which are relevant are those displayed in Figures 4-9 to follow.

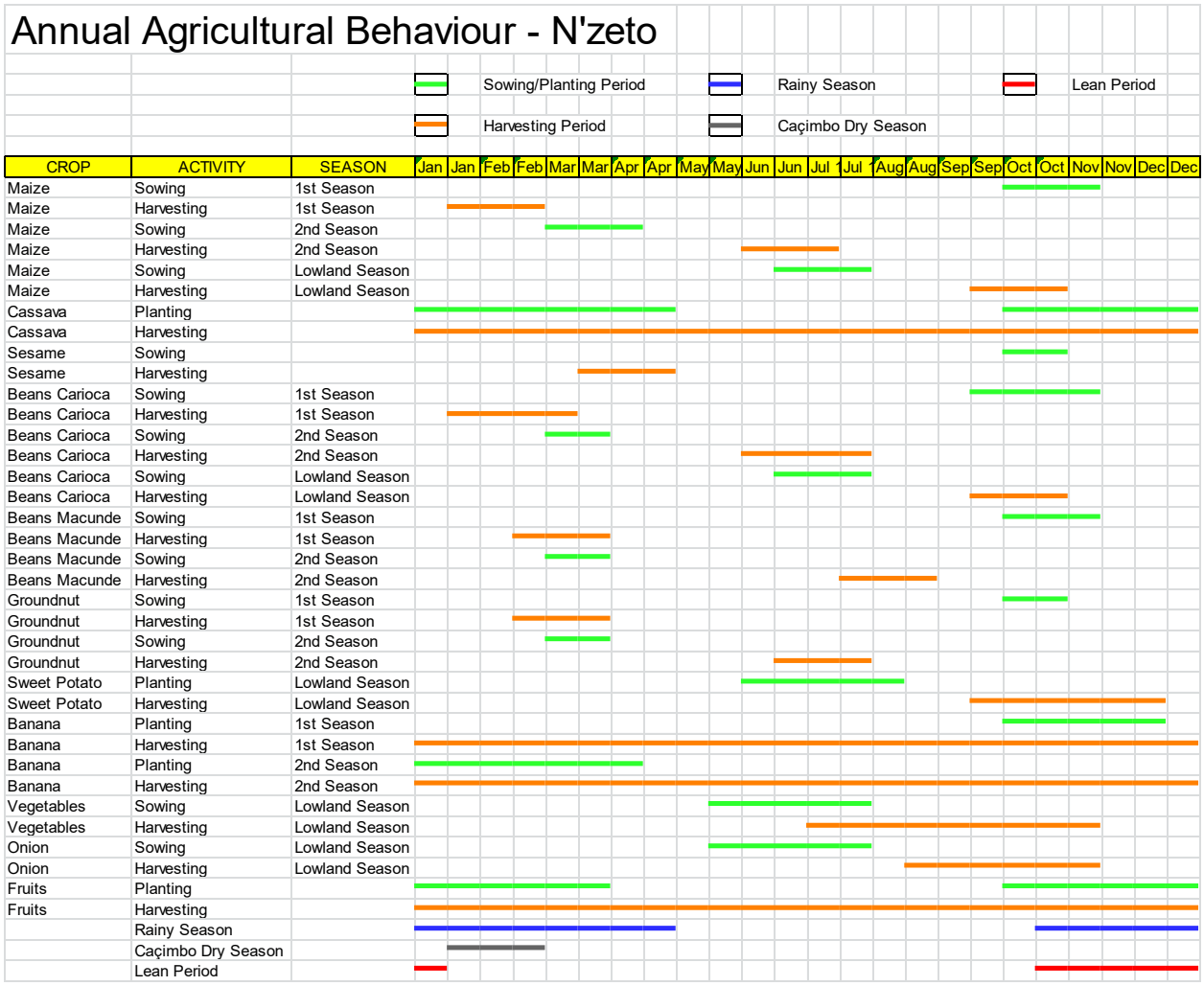

Figure 4-9 A figure illustrating the annual agricultural (crop) behaviour for N'zeto (FAO data – Angola Atlas)

ii. *REGULARITY OF AVAILABILITY ANNUALLY*

Since un-interrupted availability of raw materials is a requirement for electricity generation, one sees from Figures 4-9and 4-10 that out of the potential raw materials for biomass listed there, only Bananas and Cassava are harvested throughout the year and therefore only they are the viable choice of raw materials that we make for this study. Now, let MBA be monthly biomass availability, $AMBP$ be average monthly banana production, and $AMCP$ be average monthly cassava production. Then from Figures 4-7 and 4-8 one has that

$$MBA = \begin{cases} AMBP & in\ the\ case\ of\ \ banana\ biomass \\ AMCP & in\ the\ case\ \ of\ cassava\ biomass \end{cases} \quad (4.2.4.1)$$

4.3. CURRENT TECHNOLOGIES FOR BIOMASS ENERGY GENERATION

The diagram to follow which is sourced directly from the paper titled "The crucial role of Waste-to-Energy technologies in enhanced landfill mining: a technology review" by Bosmans et. al. [52] illustrates a review of bio fuel utilisation technologies which will inform our final proposal for the N'zeto & Tomboco microgrid.

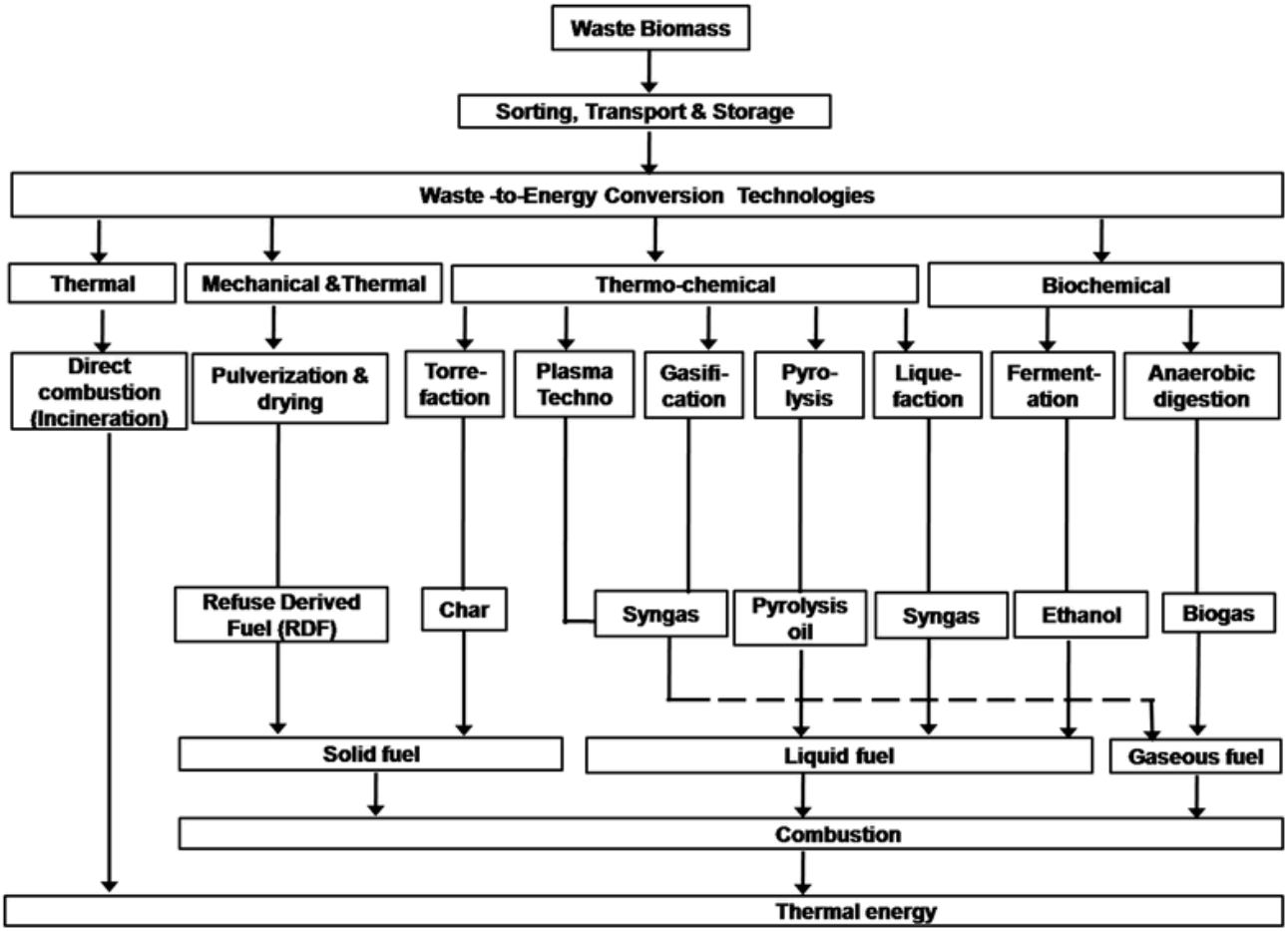

Figure 4-10 A figure illustrating the array of technologies in use to utilise waste biomass energy [52]

The first three technologies from left to right all involve burning, and in some cases incineration, involving the release of carbon fumes as a by-product of the biomass waste to thermal energy conversion process.

The last, namely, biochemical processes is identified in literature [53][54] as the preferred eco-friendly alternative to those first three, where decomposition of biomass waste is performed by a complex microbial ecosystem producing a by-product comprising of carbon-dioxide and methane, which is referred to as "biogas". This process is described as "Anaerobic digestion" and has the advantage of being suitable for small scale applications with its compact design however it requires waste sorting as a pre-processing input into the system.

The next diagram in Figure 4-4 to follow is drawn from the "Waste to Energy Research Council" paper [55] and its purpose is to illustrate the basic process flow of a single stage, wet, anaerobic digestion plant.

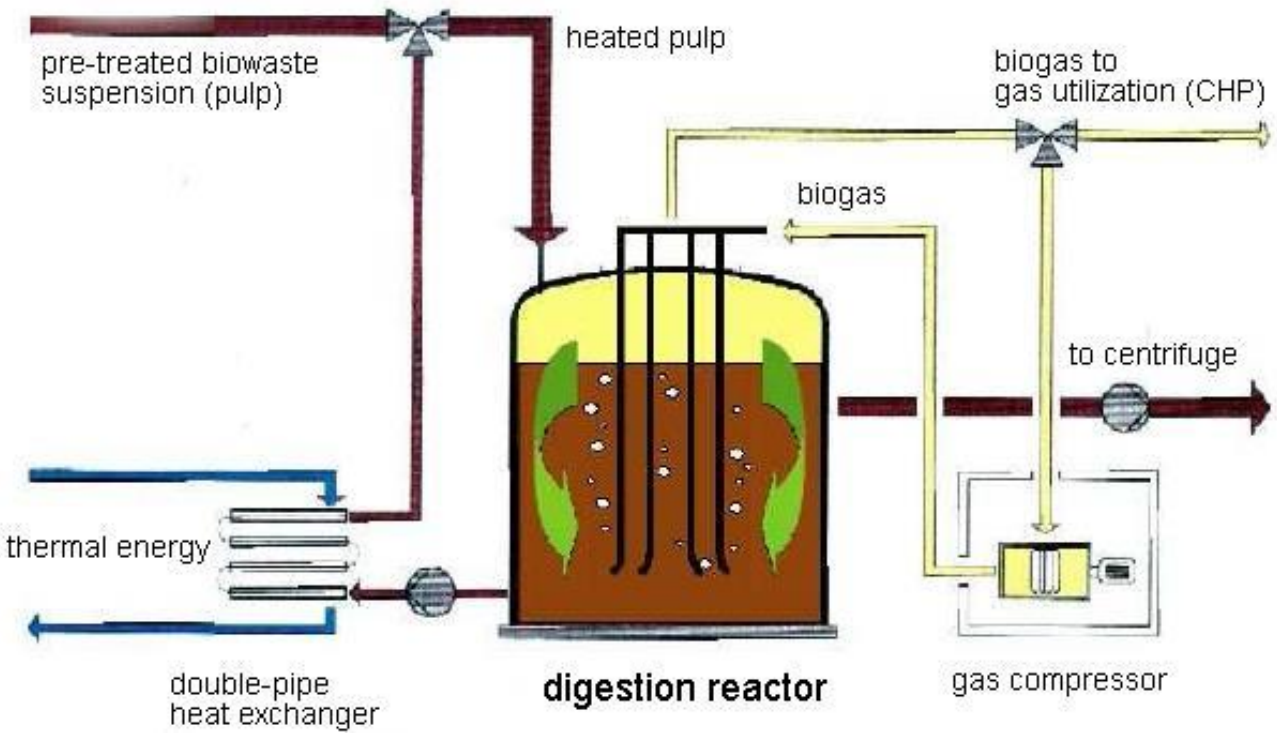

Figure 4-11 A figure illustrating the scheme of the BTA® Single-stage digestion reactor Source: BTA International GmbH [55]

From the diagram one sees that it is through the burning of the biogas produced that the conversion to electrical and thermal energy for use, either in electrical generation or direct heating and/or cooking applications, is achieved.

Banana biogas is in widespread use and, as described in "Growcom trials commercial biogas production from banana waste—high potential yields" publish in Bio pact news 2008 [56], has been cited as being applicable for use in powering farming machinery and vehicles which offer clear potential downstream benefits for the local economies of N'zeto and Tomboco which depend heavily on agriculture.

In an important reference paper "Biomass waste-to-energy valorisation technologies: a review case for banana processing in Uganda" by Gumisiriza [57] the historical uses of banana biomass waste products such as starch and flour making use of its high energy content are used to demonstrate the capacity of complimentary development of small scale banana biogas production. Information as to the agro processing of banana, banana peels or pulp, in N'zeto and Tomboco specifically were scarcely available however, as justified in Chapter 3, the climate conditions are somewhat similar indicating that at a minimum existing uses of banana waste in the areas under investigation ought to be thoroughly explored and surveyed for scale. In this study banana peels and leaves were cited as being suitable inputs into the anaerobic digester.

In a paper titled “Technical and Socioeconomic Potential of Biogas from Cassava Waste in Ghana” by Kemausuor et. al [58] a study was conducted investigating the viability of biogas production from cassava waste in two major agro-industrial processing sites in Ghana namely Asueyi and Akrofrom. These sites produce 7,000 to 8,000 tonnes per year of Cassava making them immediately comparable to N’zeto and Tomboco as seen in the FAO study data earlier in this section. This paper proposes a biogas plant making use of cassava peels as the waste product which, after pre-processing, is used in an anaerobic digester to produce biogas.

This study will consider the biomass waste resources of Cassava and Banana in the case of N’zeto & Tomboco as being best utilised through an anaerobic digester for the production of biogas. In order to assess the viability of their use, engineering design techniques will be used to estimate the peel quantity and biogas potential for N’zeto and Tomboco.

In order to make use of Banana and Cassava for the anaerobic digester described above, simulation will be performed using HOMER to assess the biomass potential of these resources. The table to follow summarizes key information on the nature of banana and cassava waste materials.[59][60][61]

Table 4-2 A table illustrating the characteristic properties of Cassava & Banana for use in Anaerobic digesters

Bio fuel	Description	Carbon Content (%)	LHV of Biogas (MJ/kg)
Cassava	Cassava is a tubercle between 10-15cm in diameter and 15-35cm lengthwise. It grows in tropical and subtropical conditions in harsh dry soil conditions and does require fertilization. Cassava is high in start content and is largely used	Organic Carbon: 48.7	Peel: 15

	for feeding purposes for both human consumption and for livestock.		
Banana	Bananas are a soft edible fruit that vary in size, firmness and is largely located in tropical areas. Bananas have high starch content and are a stable in many tropical communities.	Organic Carbon: 41.3	Stem: 7.57 Leaves: 8.51 Peels &Pulp: 10.42

Furthermore in practical applications with the use of Cassava and Banana biomass resources have been used in biogas systems pulp and peel by-products have utilised. The following properties have been found in literature for Banana and Cassava peels for consideration [58]:

Cassava Peel: $Peel - to - Whole\ (Ratio) = 0.303: 1;\ \sigma = 0.0016$

Banana Peel: $Peel - to - Whole\ (Ratio) = 0.125: 1;\ \sigma = Unknown$

4.4. CURRENT STATE OF ELECTRICITY SUPPLY, ROADS, AIRPORT AND HARBOUR

In order to develop feasible microgrid designs a basic understanding of the infrastructure available in the area surrounding N'zeto and Tomboco will be required.

4.4.1. ELECTRICAL INFRASTRUCTURE

Using data available from Angola Energia 2025 GIS map viewer, the following images highlight the existing and future electrical infrastructure in the region where N'zeto and Tomboco are located.

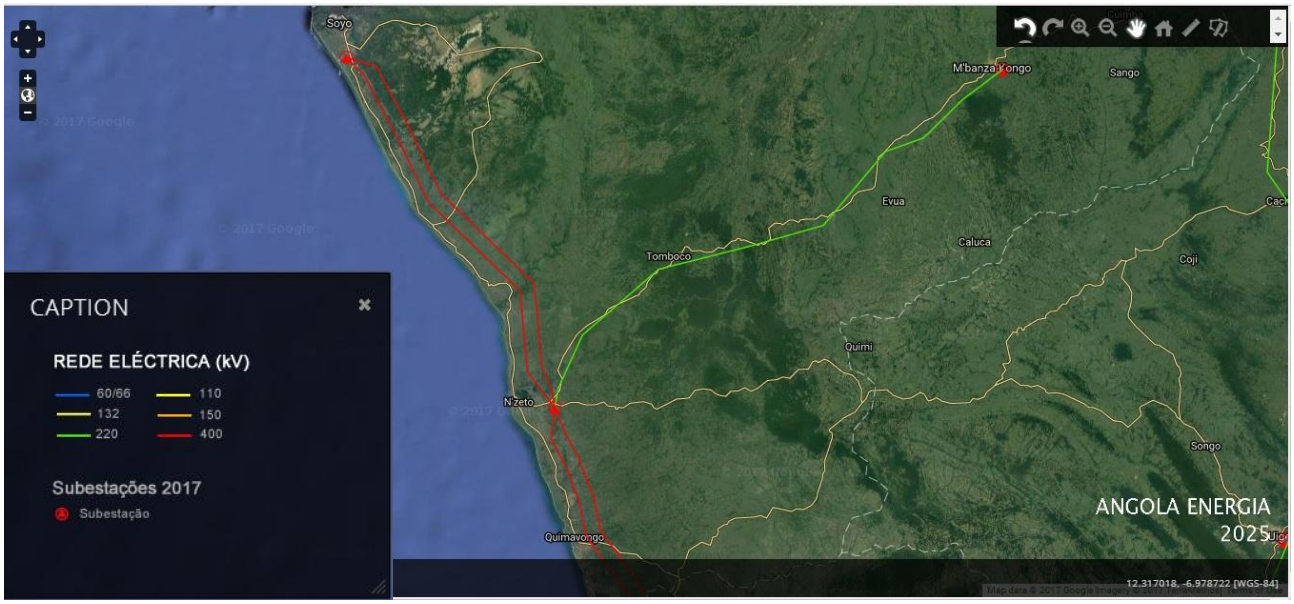

Figure 4-12 A visualisation of the existing infrastructure (2017) in the region surrounding N'zeto and Tomboco – Electrical Transmission lines and Substations

According to the Angola Energia 2025 Report, the transmission lines above were to be constructed primarily to distribute the power generated at the Soyo Natural Gas plant in the far North West of the Angola. However, it appears that the project has yet to reach completion.

Figure 4-13 A visualisation of the future prospected infrastructure (2025) in the region surrounding N'zeto and Tomboco – Electrical Transmission lines and Substations

The key infrastructure expansion plans in the region surrounding N'zeto and Tomboco include a distribution line between the two villages as well the installation of a substation in Tomboco.

From the Angola Energia 2025 plan the proposed infrastructure expansion will utilise local renewable energy resources in particular small scale biomass, solar and micro-hydro.

4.4.2. ROADS, AIRPORT, AND HARBOUR

The following three points are provided in respect of these infrastructure types (distances obtained from Google Maps):

- A major highway has been planned between N'zeto and Tomboco to upgrade the existing gravel road.
- M'banza Congo Airport is the closest airport to Tomboco and N'zeto and is 85km and 221km from Tomboco and N'zeto respectively.
- Luanda Harbour is the closest international harbour to N'zeto and is 281 km away by road.

4.5 CHAPTER SUMMARY

This chapter focuses on two aspects. The first is an assessment of the domestic availability of renewable resources required to establish and sustain a microgrid system in our study area in accordance with the null hypothesis of section 1.6 of chapter 1. The second aspect is an assessment of any electricity infrastructure already in existence, if at all, as well as the state of roads, airport, and harbour which would be needed to facilitate the transportation of heavy equipment required for the microgrid set up.

On the first aspect, the availability of solar irradiation, wind power, hydro power, and biomass from agricultural by-product described in some reasonable detail. For example, since a biomass-based power potential is chosen as one of the preferred electric power source, attention paid to it includes (i) the local availability of biomass raw materials in sufficient amounts *monthly* and (ii) the menu of technologies available for generation of electricity from biomass.

On the second aspect, there now exists tarred roads serving the municipality in which the study area is located. In contrast, however, the nearest airport and harbour are in the nation's capital which is 281 km from N'zeto by road.

CHAPTER 5

5. MICROGRID DESIGN

5.1. INTRODUCTION

We now have come to the phase of determining a microgrid design of our preference and this matter is the subject of this chapter and the next. The two options are **a Microgrid with a Single Command and Control Centre (Option 1) and a Microgrid with two independent command and control centres (Option 2).** The limitation to an initial choice of two candidates is based on the relative smallness of the area targeted for electrification, its state of under-development and therefore limited associated technical assessment tools , and the available domestic renewable resources .The final option adopted will be chosen on the basis of the following criteria, namely:

(i) The power generation source mixture chosen from those available domestically, notably, solar, wind, biogas (from cassava), and micro-hydro);

(ii) A design topology (sections 6.1.5 and 6.1.6 of the next chapter) based on appropriate:

- reticulation and conductor sizing and
- control approach.

and lastly;

(iii) A basket of key cost categories (see next section for a list of these and sections 5.3.3 and 5.4.3 for associated selected assessment estimates).

However, to simplify the computational component of the selection process, the final option preferred will be made on the basis of (i) and (ii) at the end of this chapter, leaving the computational aspects relating to (ii) to be limited to the selected option (see sections 6.1.5 and 6.1.6). Lastly, the software platform HOMER is used to generate assessment statistics needed in the above tasks.

5.2. PERFOMANCE ASSESSMENT TOOLS

A number quantitative measures may be used to discriminate the performance of each microgrid option. The measures selected reflected the key priorities of the required system which include financing the Microgrid system, cost competitiveness of the proposed scheme (in a low income context with low electricity costs, where available, used on the main grid) and the importance of making use of renewable energy resources in alignment with national and international policy commitments. The following are the key ones used in this chapter and chapter six:

a) Net Present Cost: Also termed "Life Cycle Cost", the Net Present Cost of a component of a microgrid or set of such components means the present value of all the costs associated with installing, operating and maintaining the system subtracted from the value of the expected revenues over the lifetime of the system.

b) Initial Capital: Means the "total project costs incurred in installing and beginning the operation of a project".

c) Operating Cost: Means the "sum of costs for a component or set of components while running an operation in the system."

d) Cost of Electricity (COE): Means the "average cost per kWh of available electrical energy produced by the microgrid system".

e) Percentage Age Renewable Energy: Means the "Percentage age of energy derived from renewable sources relative to the total energy generated/supplied".

f) Percentage Age Storage Autonomy: Means the "storage size of a battery bank expressed as a percentage age of the electrical load supplied".

g) DC/AC Inverter Output: Means the "load converted from Direct Current (DC) to Alternating Current (AC) electrical power by an inverter".

5.3. OPTION 1 MICROGRID

5.3.1. LOCATION

The location to follow was selected and proposed on the basis of its proximity to the availably distributed energy resources outlined in Chapter 4 (cassava biomass, high levels of solar irradiation and the river) as well being centrally located between N'zeto and Tomboco.

The region where the location of the command and control centre is being proposed, as shown in Figure 5-1, was selected on the basis of the resource availability assessment conducted in the last chapter.

Figure 5-1 A figure illustrating the topology of option 1

5.3.2. BASIC FEATURES

Figure 5-2 to follow, which is adopted from a paper titled “Trends for Microgrid Control”[25], presents the basic features of the o**ption**.

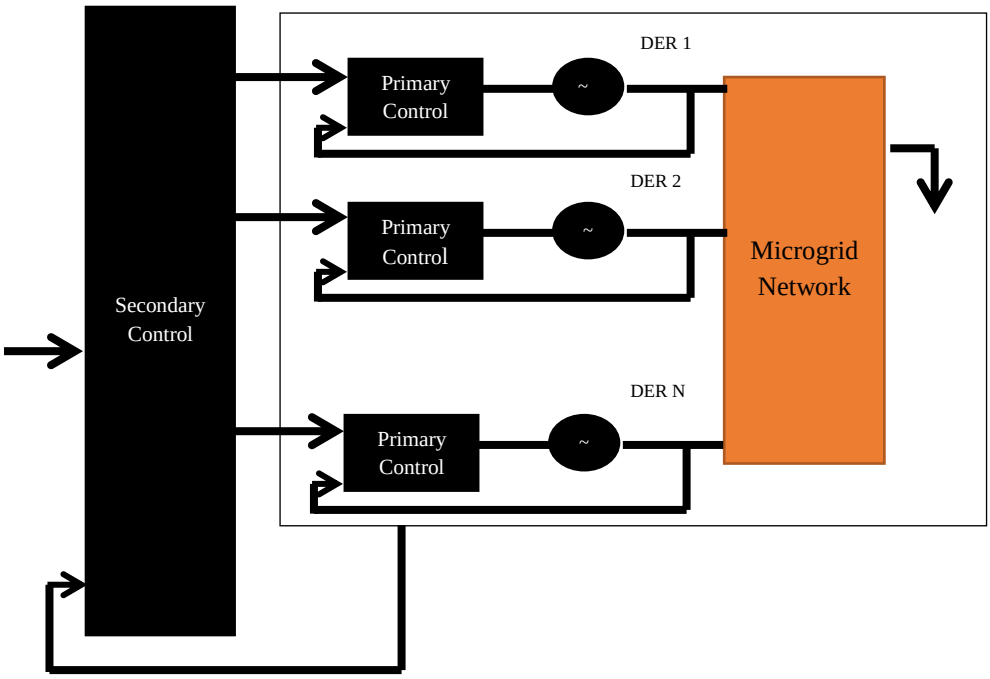

Figure 5-2 The basic features of Microgrid Option 1

Thus the option comprises of four basic features:

. A selected mixture of power generation sources shown generically in the diagram as DER 1, DER 2,

……, DER N;

. Distribution lines connecting the towns of N’zeto and Tomboco and the control centre, as shown by dark

lines in Figure 5-1;

. Substations at locations shown in Figure 5-1 by orange stars;

. A hierarchical set up of controls at primary, secondary and tertiary levels as indicated in Fig 5-2.

Section 2.7 of chapter two gave an account of the different roles that this control scenario plays;

. Lastly, the Lead Acid Battery is the storage technology to be adopted no matter what energy source mixture

option is chosen.

5.3.3. PERFORMANCE STATISTICAL ESTIMATES

a) GENERAL REMARKS

. This section presents Homer software generated performance statistical estimates which form *part*

of the basis for choosing between micro-grids option 1 and option 2.

. In some of the presentations, biogas fuel is presented in kilograms (of cassava peel) and the rows

of power generation performance are displayed in the ascending order *of the average cost per kWh*

of available energy (COE), as one moves down a table, even though COE may not be on the display

in that table.

. M denotes millions wherever costs appear.

. The "percentage Renewable Energy" calculated by the HOMER platform is referred to as the Renewable Energy Fraction. This percentage represents the relative contribution of energy derived from renewable energy sources deliver to the primary load in the system under design.

b) SUMMARY LOAD STATISTICS FOR SIMILAR DAY MANDELLI MODEL

Table 5-1 Load estimates under the assumptions of normally / beta distributed noise

Load Type/ Measure	Load under norm. noise	Load under beta noise
Average kWh/day	36 568 kWh/day	33 205 kWh/day
Average kW/hour	1 523.60 kW	1 383.50 kW
Peak Load (kW)	4 890.30kW	4 569.30kW
Load Factor	0.31	0.30

Table 5-2 Annual power generation performance from available renewable energy resources assuming noise is

normally distributed

	Solar Production (kWh)	Wind Production (kWh)	Biogas Fuel (kg)	Hydro Mean Output(kW)	Diesel Fuel (L) Cost: 0.8$/L	% Storage Autonomy	AC/DC Converter Inverter Output (kW)
1	24 838 484		6 435 855	40		35.50	1138
2	24 417 430		6 419 502	40		36.50	1099
3	35 866 396	75 5457		40		48	1417
4	36 211 136			40		49.40	1487

Table 5-3 Annual power generation performance of available renewable energy resources assuming noise is

beta distributed

	Solar Production (kWh)	Wind Production (kWh)	Biogas Fuel (kg)	Hydro Mean Output(kW)	Diesel Fuel (L) Cost:0.8$/L	% Storage Autonomy	AC/DC Converter Inverter Output (kW)

1	24 360 716		6 347 402	40		34.4	1004
2	19 623 842	1 292 129	6 58 542	40		32.7	891
3	33 837 980	14 886 000		40		47.7	1280
4	34 638 844			40		49.1	1347

Table 5-4 Costs per kWh (in US $'s) if a minimum of 75% of power generation derives from renewable energy sources and assuming noise is normally distributed

	Cost of electricity ($/kWh)	Net Present Cost ($)	Operating Cost ($)	Initial Capital ($)
1	0.21	319M	2.11M	85.3M
2	0.21	317M	2.02M	92.2M
3	0.30	438M	2.73M	134M
4	0.30	440M	2.87M	121M

Table 5-5 Costs per kWh(in US $'s) if a minimum of 75% of power generation derives from renewable energy sources and assuming noise is beta distributed

	Cost of Electricity ($/kWh)	Net Present Cost ($)	Operating Cost ($)	Initial Capital
1	0.21	284M	1.83M	80.3M
2	0.21	276M	1.6M	98.5M
3	0.30	400M	2.47M	125M
4	0.30	403M	2.61M	113M

c) LOAD STATISTICS UNDER PARTITIONED JARDINI et al MODEL

Table 5-6 Load estimates under normally / beta distributed noise

Property	Normal Distribution (Parametric)	Beta Distribution (Parametric)
Average kWh/day	39 831 kWh/day	39 259 kWh/day
Average kW	1659.60 kW	1635.80 kW
Peak (kW)	4 420.90kW	5 076.80kW
Load Factor	0.38	0.32

Table 5-7 Annual power generation performance of available renewable energy resources assuming noise is

normally distributed

	Solar Production (kWh)	Wind Production (kWh)	Biogas Fuel (kg)	Hydro Mean Output(kW)	Diesel Fuel (L) Cost:0.8$/L	Storage Autonomy %	AC/DC Converter Inverter Output (kW)
1	25 628 150	692 946.90	6 430 147	35.21		33.55	1210.74
2	26 170 210		6 508 629	35.21		34.92	1276.12
3	38 744 030	755 456.90		35.21		45.33	1545.29
4	39 435 520			35.21		46.99	1623.17

Table 5-8 Annual power generation performance of available renewable energy resources assuming noise is beta distributed

	Solar Production (kWh)	Wind Production (kWh)	Biogas Fuel (kg)	Hydro Mean Output(kW)	Diesel Fuel (L) Cost:0.8$/L	Storage Autonomy %	AC/DC Converter Inverter Output (kW)
1	26 212 150		6 373 332	35.21		34.27	1259.94
2	24 174 120	1638983	6 236 296	35.21		32.07	1127.63
3	39 263 470	231744.60		35.21		45.69	1573.22
4	40 644 990			35.21		45.84	1599.62

Table 5-9 Costs (in US $'s) if a minimum of 75% of power generation derives from renewable energy sources and assuming noise is normally distributed

	Cost of Electricity ($/kWh)	Net Present Cost ($)	Operating Cost ($)	Initial Capital ($)
1	0.21	332M	2.10M	103M
2	0.21	334M	2.20M	89.5M
3	0.28	459M	2.80M	144M
4	0.29	463M	3M	131M

Table 5-10 Costs (in US $'s) if a minimum of 75% of power generation derives from renewable energy sources and assuming noise is beta distributed

	Cost of Electricity ($/kWh)	Net Present Cost ($)	Operating Cost ($)	Initial Capital ($)
1	0.20	326M	2.10M	88.90M
2	0.21	328M	1.90M	120.10M
3	0.28	450M	2.85M	133.10M
4	0.29	456M	2.90M	132.60M

It is seen from the above annual power generation statistics for option 1 micro-grid that the minimum capacity threshold the *null hypothesis of this dissertation* is met under appropriate levels of COE.

5.4. OPTION 2

5.4.1. LOCATIONS OF CONTROL CENTRES

The location to follow was selected and proposed on the basis of its proximity to the availably distributed energy resources outlined in Chapter 4 (very high levels of solar irradiation near N'zeto and moderate wind speeds north of Tomboco).

The locations of the command and control centres for option 2 are shown in Figure 5-3 below.

Figure 5-3 A figure illustrating the topology of option 2

The sites of the CCC's were selected on the same basis as in the case of the option 1 microgrid.

5.4.2. BASIC FEATURES

The basic features of this option are:

. Two micro-grid systems with independent CCC's as shown in Figure 5-3.

. Distribution lines from each CCC transmit electricity to N'zeto and Tomboco local substations.

. a hierarchical set up of controls at primary, secondary and tertiary levels as in indicated in Figure 5-4 to follow.

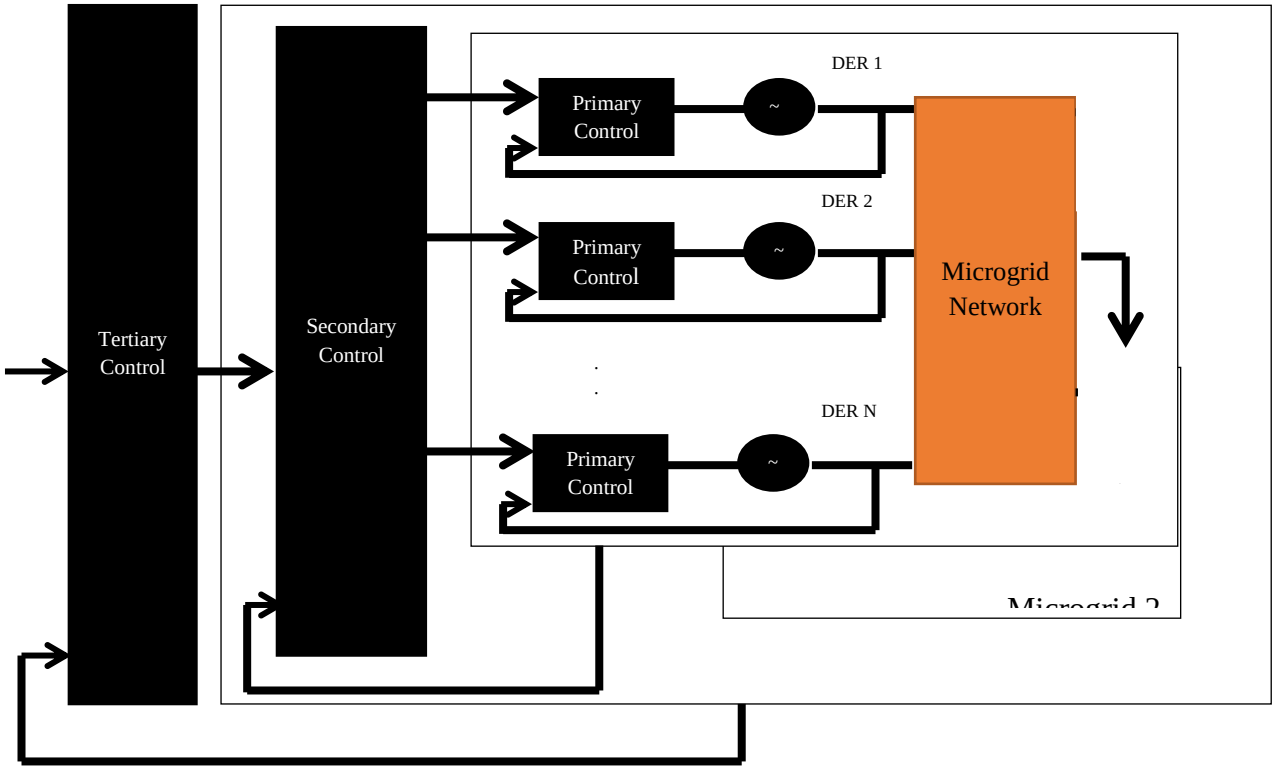

Figure 5-4 A figure depicting the topology proposed for the two Microgrid solution

The controllers, as in the case of the single microgrid solution, would be used to gain optimal utilisation of DER 1, DER 2, ……, DER *N* as well as achieve optimal economy and stability not only for each microgrid at the secondary level bur also for the overall network comprising of microgrid 1 and 2 at a tertiary level. See, again, section 2.7 of chapter two. Lastly, Figure 5-4 is also adopted from citation [25].

5.4.3. PERFORMANCE STATISTICS

a) LOAD STATISTICS UNDER SIMILAR DAY MANDELLI MODEL

Table 5-2 Load estimates under normally / beta distributed noise

Load Type/ Measure	Load under norm. noise	Load under beta noise
N'zeto – DER A		
Average kWh/day	18 984 kWh/day	17 583 kWh/day
Average kW	791.3 kW	732.65 kW

Peak (kW)	2 748.2 kW	2290 kW
Load Factor	0.29	0.32
Tomboco – DER B		
Average kWh/day	17 247 kWh/day	15 957 kWh/day
Average kW	718.64 kW	664.91 kW
Peak (kW)	2 597.4kW	2 224kW
Load Factor	0.28	0.30

Table 5-3 N'zeto's node annual power generation performance from DER A assuming noise is normally distributed

Solution Number	Solar Production (kWh)	Wind Production (kWh)	Biogas Fuel (kg)	Diesel Fuel (L) Cost:0.8$/L	Storage Autonomy %	AC/DC Converter Inverter Output(kW)
1	20 327 512	5 535 190	3 676 921		17.30	837.92
2	17 507 280	799 671			45.40	773.31
3	18 384 794				48.30	839.68
4	21 904 482	16 248 804			10.10	833.36

Table 5-4 N'zeto's node annual power generation performance from DER A assuming noise is beta distributed

Solution Number	Solar Production (kWh)	Wind Production (kWh)	Biogas Fuel (kg)	Diesel Fuel (L) 0.8$/L	Storage Autonomy %	AC/DC Converter Inverter Output (kW)
1	16 224 555	715 054			45.5	631
2	22 067 024	6 209 841	3 410 846		15.8	287
3	17 153 480				48.4	697

Table 5-5 N'zeto's node costs (in US $'s) if a minimum of 75% of power generation derives from DER A source and assuming noise is normally distributed

	Cost of Electricity ($/kWh)	Net Present Cost ($)	Operating Cost ($)	Initial Capital
1	0.26	203M	168 344	184M
2	0.29	223M	1.31M	77.2M
3	0.30	226M	1.47M	62.3M
4	0.52	398M	383 078	441M

Table 5-6 N'zeto's node costs (in US $'s) if a minimum of 75% of power generation derives from DER A source and

assuming noise is beta distributed

	Cost of Electricity ($)	Net Present Cost ($)	Operating Cost ($)	Initial Capital
1	0.29	206M	1.22M	70.8M
2	0.29	209M	49 251	203M
3	0.29	209M	1.36M	57.8M

Table 5-7 Tomboco's node annual power generation performance from DER B assuming noise is normally distributed

	Solar Production (kWh)	Wind Production (kWh)	Biogas Fuel (kg)	Diesel Fuel (L) 0.8$/L	Storage Autonomy %	AC/DC Converter Inverter Output (kW)
1	17 020 048	803 483			45	611
2	18 156 328				48.1	683
3	17 891 372	7 575 914	3 348 034		15.1	264
4	21 532 812	14 305 656			10.2	210

Table 5-8 Tomboco's node annual power generation performance from DER B assuming noise is beta distributed

	Solar Production (kWh)	Wind Production (kWh)	Biogas Fuel (kg)	Diesel Fuel (L) 0.8$/L	Storage Autonomy %	AC/DC Converter Inverter Output (kW)
1	14 657 146	436 046			46.40	586
2	15 431 130				48.40	629
3	23 282 468	7 358 654	3 103 630		13.90	239

Table 5-10 Tomboco's node costs (in US $'s) if a minimum of 75% of power generation from DER B and assuming noise is normally distributed

	Cost of Electricity ($/kWh)	Net Present Cost ($)	Operating Cost ($)	Initial Capital
1	0.29	205M	1.18M	74.3M
2	0.30	207M	1.33M	59.1M
3	0.30	212M	117 135	225M
4	0.52	361M	292 015	394M

Table 5-11 Tomboco's node costs (in US $'s) if a minimum of 75% of power generation from DER B and assuming noise is beta distributed

	Cost of Electricity ($)	Net Present Cost ($)	Operating Cost ($)	Initial Capital
1	0.29	186M	1.14M	59.7M
2	0.29	189M	1.23M	52.1M
3	0.34	219M	120 515	232M

CHAPTER 6

6. FINAL MICROGRID PROPOSAL

6.1. INTRODUCTION

The present chapter presents details of the micro-grid option just selected in the last chapter, followed by a sensitivity analysis of the option. Briefly, the chosen microgrid system comprises of:

(a) Three power generation resources, namely, a Micro-hydro-turbine (hereafter identified as DER A, a Solar PV array (DER B), and a biomass generator (DER C);

(b) A hybrid distribution bus, and

(c) A single command and control centre (abbreviated as CCC as before). The chapter is organised as follows: sections 6.2 to 6.7 respectively describe the geographical locations of DER A, DER B, DER C, details of (a), (b), and (c), as well as details of the energy efficiency and the overall plan of the system. Section 6.8 performs a sensitivity analysis while 6.9 addresses the question of costs beyond those indicated in the last chapter. Section 6.10, the last, hypothesises future load scenarios with special attention being on the potential impact the microgrid would have on the quality of life of the inhabitants as well as potential industrial economic development of the study area.

6.2. GENERATION SITES

Figure 6-1 to follow geographically proposes the location of the three power generation resources, the distribution bus (shown by lines), the command and control centre, and the local substations (shown by orange stars).

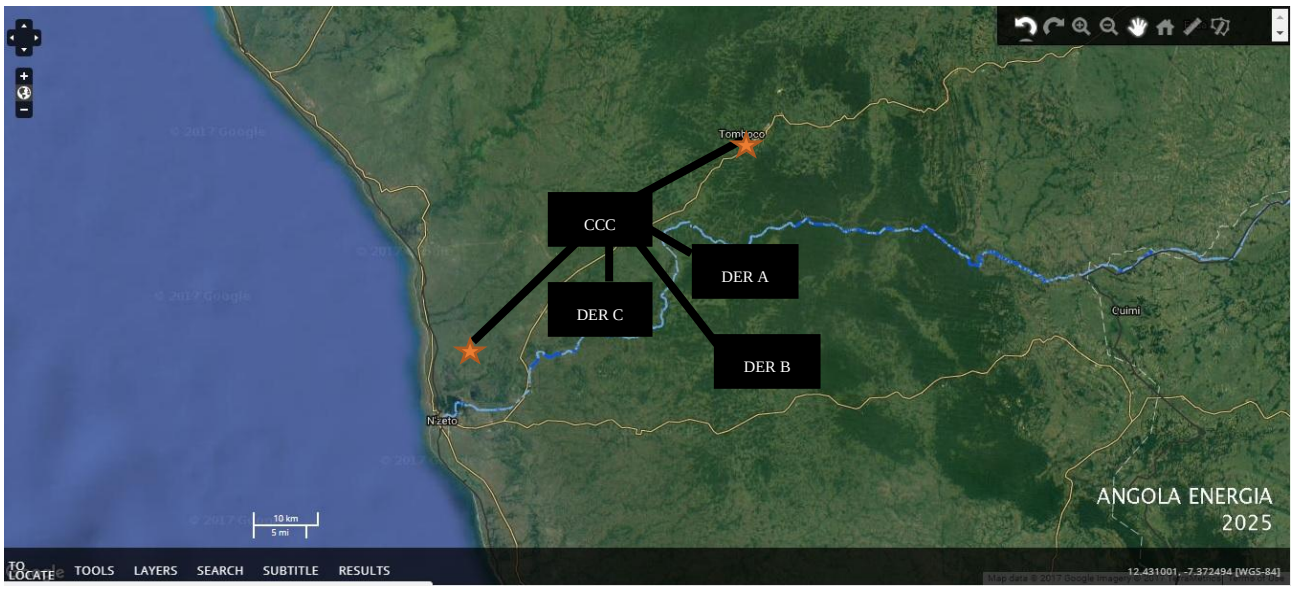

Figure 6-1 A geographic location of the proposed power generation sources and hybrid distribution bus network

6.3. DETAILS OF POWER GENERATION

6.3.1. GENERAL

Primary power generation and storage is contemplated to be provided by two sources, namely, a solar PV array and a micro-hydrokinetic turbine sited off the M'bridge River, and surplus power generated from this combination during periods of low demand is stored in a battery bank. In periods of low power generation from these sources the battery bank is drawn on and should this still be insufficient a biofuel plant would be activated as a *secondary* back-up. Load-shedding would be the last resort in extreme conditions.

Table 6-1 A summary of the technical specifications of the proposed hybrid microgrid

	Technical specifications
DER A: Micro-hydro Turbine	40kW Microhydro turbine (Francis Turbine – Electway Electric)[62]
DER B: Solar PV array	1kW Solar PV panel (Shenzhen Xinhonghua Solar Energy Co., Ltd) [63]
DER C: Biomass generator	500kW Biomass Generator (Fuzhou Electric Machinery LtD) [64]
Cassava Transport Truck	3L Toyota Danya (2017)[65]
Distribution voltage Level	Medium Voltage (MV): 34kV

6.3.2. SOLAR POWER

The use of solar PV in rural Angola already has precedents. According to the Angola Energia 2025 Report [45], it is projected to form a significant part of electricity provision in rural areas. In the area between and around N'zeto and Tomboco solar PV is a particularly low cost option.

6.3.3. HYDRO POWER

Hydro-power systems of varying scales have been in widespread use for almost as long as human societies have engaged in industrial activities. In its early period of use, hydro energy exploitation took the form of irrigation of farmlands and/or powering mills that ground grain [50]. In comparatively more recent times the exploitation has extended to domestic electricity provision[26].

In a Van Els et al [66] conference paper titled "Brazilian experience with hydrokinetic turbines", a historical account is given of the extensive use of hydrokinetic turbines in Brazil since early1980s including drawing attention to the role they have played in rural electrification programmes.

6.3.4. BIOFUEL POWER

6.3.4.1. AN OVERVIEW

Raw Cassava would be purchased from local farms between N'zeto & Tomboco and an industrial peeler would be used to extract the raw material for electricity generation. The inclusion of a bio fuel generator using cassava peel waste in our final proposal is based on fiver grounds. Firstly, it would provide a clean alternative to the current widespread use of diesel-based generators in rural Angola, particularly during peak electricity demand periods. Secondly, it would contribute to the growth of agro-industrial activity in the region which in turn would contribute to sustainable local job creation. Thirdly, a rural example of replacing domestic cooking using fast diminishing wood sources with a clean and easily renewable bio fuel alternative would be set. Lastly, cassava not only is locally available throughout the year in significant amounts but also the portion of annual yield that would be devoted to electricity generation relative to what is required for food security is very small as will be seen shortly.

6.3.4.2. OPERATION PLAN

The bio fuel plant is contemplated to operate by purchasing the required cassava and processing the vegetable through an industrial peeler which then feeds the waste peel into an anaerobic digester to produce the bio fuel. The peeled cassava by-product will be available for further processing into potential food products.

As noted from chapter four, N'zeto and Tomboco respectively produce approximately 8,000 and 12,000 tonnes *per hectare* per year of cassava crop, so that on a basis of two hectares of cassava farmland mentioned in the [49] study, the yearly *total* may be taken to be 40,000 tonnes approximately. Later in this chapter, the HOMER simulated optimisation results will show that a mere 6-6.5 tonnes of cassava waste per year would be required for the bio fuel leg of our power generation sources in our final proposal, meaning that the bio fuel plant would hardly impact on the cassava food security. So, with strong regulatory controls, planned purchasing schedules as well as through building relationships with local farmers and households that assure them of no potential threat to their food security, our microgrid solution has good prospects to succeed.

6.4. DISTRIBUTION NETWORK

6.4.1. GENERAL

A distribution line from the three generating sources is proposed to run between the two villages via a well-staffed command and control centre located halfway between N'zeto & Tomboco. The function of the centre, as has already been pointed out, will be monitor maintenance and operational control activities.

The distribution network shown earlier in figure 6-1 will make use of a radial distribution configuration. The radial distribution network is characterised by its single-path, single load flow between the set of interconnected loads and the generation point[67].

The benefit of the radial distribution network lies in its simple, cheap design however it's associated weakness lies in its use of a single power flow path as a fault or damage on the distribution line automatically leads to a fault at the load point. This can be clearly seen by the single distribution lines between the Command and Control Centre (CCC) in figure 6-1 and the substations in N'zeto and Tomboco respectively.

In an Australian-based study titled "Estimating the Value of Undergrounding Electricity and Telecommunications Networks" by Mcnair et al[68] a cost-benefit analysis on the use of overhead distribution lines compared to underground distribution lines was conducted in an urban context. Underground cabling held the advantage of holding the possibility of installing telecommunications cabling in pipes alongside the power network opening up the potential for affordable internet. Restrictions imposed on land use underneath overhead power networks were also reduced by undergrounding. However, not only was undergrounding proven to be costly but primarily beneficial to wealthier residents.

In South Africa in a paper titled "Cost effective rural and reticulation telecontrol systems for developing countries" by Mostert et al[69] working in the context of rural electrification, overhead cabling was described as most commonly practiced particularly over the long sprawling areas characterised by those set ups. The primary disadvantage of these systems lies in the susceptibility to storms and heavy winds to which the insulated cabling is exposed and subject to potential damage. Potential rising costs in maintainability also exist in rural areas where the logistical

infrastructure used to scale high monitoring poles would need to be transported to locations that may be far from the utility.

Given the comparatively low wind speeds between N'zeto and Tomboco and the present trends in rural electrification more generally overhead distribution lines will be made use of in this proposed solution.

6.4.2. HYBRID NATURE

The diagram to follow depicts the hybrid nature of the contemplated distribution bus.

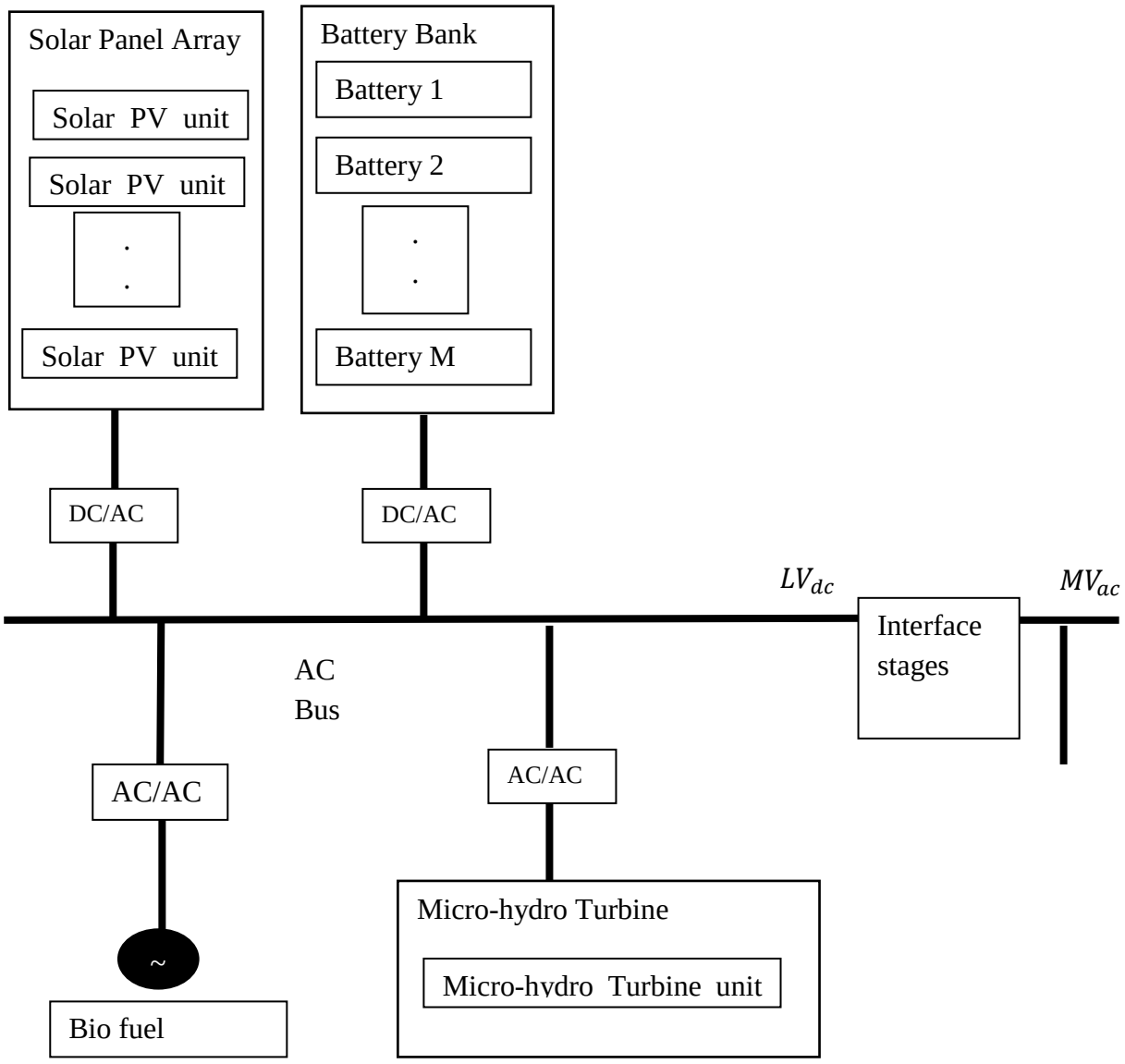

Figure 6-2 A diagram illustrating the hybrid nature of the distribution bus for the proposed microgrid

6.4.3. RETICULATION & CONDUCTOR SIZING

There are primarily two types of conductors in use for distribution networks, namely aluminium and copper. While copper was popular in the past due to its high electrical conductivity aluminium based distribution cables have taken precedence due to their comparatively lower resistance, high tensile strength and superior weight-to-strength ration reducing the number of poles required .The reduce reduced number of poles decreases the installation and maintenance costs particularly in rural areas where the remoteness of maintenance areas likely come with higher costs[70]. Furthermore, when comparing Copper and Aluminium conductors of the same resistance per unit length, the Aluminium conductor comes out 75% lighter than the copper cable and 1.6 times the area due to its light weight property[71]. For these reasons listed the proposed solution will make use of an aluminium conductor for power distribution.

Appropriate conductor sizing in distribution design reduces the lifetime cost of domestic electrification networks[15] and this is particularly important to consider in the Angolan context where out dated and decayed infrastructure has contributed to technical energy losses of approximately 14% of the overall energy consumption[45].

In C. Brown's 2006 PhD thesis titled ""Effect of conductor size on the total cost of electrical distribution feeders in South Africa", a method of optimal design for conductor sizing was applied to a South African Rural domestic network. Following from this investigation it was found that changes in consumer energy consumption and demand due to conductor voltage drop and load voltage dependency did not significantly impact the conductor size for the rural domestic consumers, instead the size was determined by the minimum voltage limits[72].

Furthermore, in a technical manual of manufacturer SIEMENS titled "Planning of Electric Power Distribution – Technical Principles"[73], international guidelines for medium voltage networks are proposed using insights obtained historically.

From the above literature, the following imperatives are relevant to our proposed single microgrid solution:

- For high density loads the distribution line voltage in "kV" is roughly half of the radius of the area

Between the supply side and the load point. Therefore the distribution line for the single microgrid system operating in a medium voltage network = 34kV at a radius of 68km. In practice in relation to the intervals of voltage networks in use the proposed system will operate at 33kV.

- In order to limit short circuit power in the Medium voltage network, substations should operate as separate sub-networks and not in parallel configuration. This will therefore require Substation 1 & 2 in N'zeto and Tomboco to operate as two sub-networks in each village.

Aluminium conductors come primarily in two categories namely All Aluminium Conductors (AAC) and Aluminium Conductor Steel Reinforced. AAC conductors are characteristically used over short distances for low voltages (typically 230-440V) however ACSR are commonly used in medium voltage networks (11kV, 22kV, 33kV). The ASCR comes in two main forms namely bare conductor, single Insulated conductor [71]. The bare conductor is suitable for overhead lines where adequate safety conditions can be guaranteed (low occurrence of heavy winds and storms) and monitored as cable faults and breakages pose significant safety risks to the areas underneath the overhead cables. Single insulated conductors are cheap, ASCR conductors covered by a plastic outer sheath usually made use of in applications far from the utility regulation services.

From the above information in the context of the proposed microgrid system its location, and the associated distribution distances and network distribution voltage, the ACSR Single Insulated conductor type is most appropriate for the solution.

In order to size the conductor appropriately, the voltage drop across the line must comply with the accepted tolerance. In alignment with the IEEE 1547.4 standard IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems [74] a voltage tolerance of no more than 5% will be considered.

To calculate the required voltage drop consider the following equations[75],

$$VD_i \approx I(r\ cost\phi + rsin\phi)L\ \ [V] \tag{6.1}$$

VD_i: Voltage Drop on the "ith" conductor line
r: resistance per km of the conductor
x: reactance of the conductor per km
L: Length of the conductor in km
I: Current through the conductor
$cos\phi$: Power Factor

Also consider[75],

$$r = \frac{18.4k}{A}\Omega/km \tag{6.2}$$

k: Material constant proportional to resistance per km of copper (k = 1.6 for Aluminium)
r: resistance per km of the conductor
A: Area of conductor

For this study the loads characterised for this rural electrification application are primarily used for lighting, cell phone charging with minor use of inductive loads such as fans for cooling. Hence the power factor used in this design will be $Power\ Factor\ (PF) = 1$.

Hence from (6.1)

$$,VD_i \approx I_{rms}rL \text{ [V]} \tag{6.3}$$

VD_i: Voltage Drop on the "ith" conductor line
r: resistance per km of the conductor
L: Length of the conductor in km
I_{rms}: Current (root mean square)

Following from this the "ith" percentage voltage drop is defined:

$$\%VD = 100 * \frac{VD_i}{E_s} \quad (6.4)$$

VD_i: Voltage Drop on the "ith" conductor line
$\%VD_i$: Voltage Drop on the "ith" conductor line
E_s: Voltage at source

Furthermore,

$$E_s = \frac{V}{\sqrt{3}} = \frac{33kV}{\sqrt{3}} = 19\,052.56V \quad (6.5)$$

Considering the system topology defined in Figure 6-1, and noting that the overhead distribution cables are installed alongside the road between N'zeto and Tomboco then the conductor segments between the Command and Control Centre (CCC) are given as follows:

- CCC to Tomboco substation: 21km
- CCC to N'zeto substation: 56km
- Generation points to CCC

Other key factors for calculating the appropriate distribution cable include the line voltage, 33kV, Peak active power from the two sets of interconnected load sets (N'zeto and Tomboco) estimated on average as 2.6MW and 2.2MW from section 3.7 summarising the synthetic load characterisation results.

Using equations 6.1.5.1 to 6.1.5.5 the following calculations were used, alongside cable data sheet information sourced from "Midal Cable ACSR Conductor Datasheet"[76], to specific the distribution cables.

a) Calculation for Conductor sizing from CCC to Tomboco substation:

Consider,

L = 21km, Test cable for calculation iteration = ASCR SWAN,
Diameter = 21.18mm^2, Tomboco Load = 2.2MW

Therefore,

$$r = \frac{18.4k}{A} = \frac{18.4 * 1.6}{21.18} = 1.390\ \Omega/km$$

$$I = \left(\frac{P_{active}}{V}\right) * \frac{1}{\sqrt{3}} = 38.49A$$

$VD_i \approx IrL$ = (38.49)*(1.390)*(21) = 1123.523V

$\%VD = 100 * \frac{VD_i}{E_s}$ = 5.90%

The percentage volt drop given by the ASCR SWAN cable is too high therefore a second iteration is required as follows,

L = 21km, Test cable for calculation iteration = ASCR SWALLOW,
Diameter = 26.69mm^2, Tomboco Load = 2.2MW

Therefore,

$$r = \frac{18.4k}{A} = \frac{18.4 * 1.6}{26.69} = 1.103\ \Omega/km$$

$$I = \left(\frac{P_{active}}{V}\right) * \frac{1}{\sqrt{3}} = 38.49A$$

$VD_i \approx IrL$ = (38.49)*(1.1013)*(21) = 891.21V

$\%VD = 100 * \frac{VD_i}{E_s}$ = 4.61%

b) Calculation for Conductor sizing from CCC to N'zeto substation:

Consider,
L = 56km, Test cable for calculation iteration = ASCR SWAN,

Diameter = 21.18mm^2, Tomboco Load = 2.6MW

Therefore,

$$r = \frac{18.4k}{A} = \frac{18.4 * 1.6}{21.18} = 1.390\ \Omega/km$$

$$I = \left(\frac{P_{active}}{V}\right) * \frac{1}{\sqrt{3}} = 45.49A$$

$VD_i \approx IrL$ = (45.49)*(1.390)*(56) = 3540.92V

$\%VD = 100 * \frac{VD_i}{E_s}$ = 18.59%

The percentage volt drop given by the ASCR SWAN cable is too high therefore a second iteration is required as follows,

L = 21km, Test cable for calculation iteration = ASCR ROBIN,
Diameter = 42.41mm^2, Tomboco Load = 2.6MW

Therefore,

$$r = \frac{18.4k}{A} = \frac{18.4 * 1.6}{42.41} = 0.694\ \Omega/km$$

$$I = \left(\frac{P_{active}}{V}\right) * \frac{1}{\sqrt{3}} = 45.49A$$

$VD_i \approx IrL$ = (45.49)*(0.694)*(56) = 1767.92V

$\%VD = 100 * \frac{VD_i}{E_s}$ = 9.28%

The percentage volt drop given by the ASCR ROBIN cable is too high therefore a second iteration is required as follows,

L = 21km, Test cable for calculation iteration = ASCR PIGEON,
Diameter = 85.12mm^2, Tomboco Load = 2.6MW

Therefore,

$$r = \frac{18.4k}{A} = \frac{18.4 * 1.6}{85.12} = 0.346\ \Omega/km$$

$$I = \left(\frac{P_{active}}{V}\right) * \frac{1}{\sqrt{3}} = 45.49A$$

$VD_i \approx IrL$ = (45.49)*(0.346)*(56) = 881.41V

$$\%VD = 100 * \frac{VD_i}{E_s} = 4.62\%$$

The iteration calculations shown above determining the appropriate conductor sizing for the proposing single microgrid system are summarised in table 6-2. The technical specifications and pricing are sourced from "Midal Cable ACSR Conductor datasheet"[76].

Table 6-2 A table illustrating a selection of the technical specifications listed for the proposed distribution scheme

Location	Distribution Cable	Diameter (sq. mm)	Weight	Rated Strength (kN)
CCC to Tomboco substation	ACSR SWALLOW	26.29	108kg/km	10.21
CCC to N'zeto substation	ACSR PIGEON	85.12	344kg/km	29.42

6.5. CONTROL OF THE SYSTEM

6.5.1. GENERAL

In a paper by T. Vandoorn et al[77] titled "Microgrids: Hierarchical Control and an Overview of the Control and Reserve Management Strategies" the authors point out challenges relating to

control and stability of Microgrid systems which operate independently of a national grid. In the traditional *macro*-grid system, typically a national utility grid, any imbalance arising between generation side and demand side is balanced by the rotating inertia within the system resulting in a change in frequency. In the case of islanded Microgrids, controllers based on an existing spinning reserve are not viable. For this reason hierarchical control schemes discussed earlier in chapter two, have been developed to standardize and simplify the operation and control of such microgrids.

By consider the work of J. Almada et al.[78] in a paper titled "A centralised and heuristic approach for Energy Management of an AC microgrid", we have figures 6-4 and 6-5 which depict the proposed architecture and topology for the hierarchical centralised control scheme for our final microgrid solution.

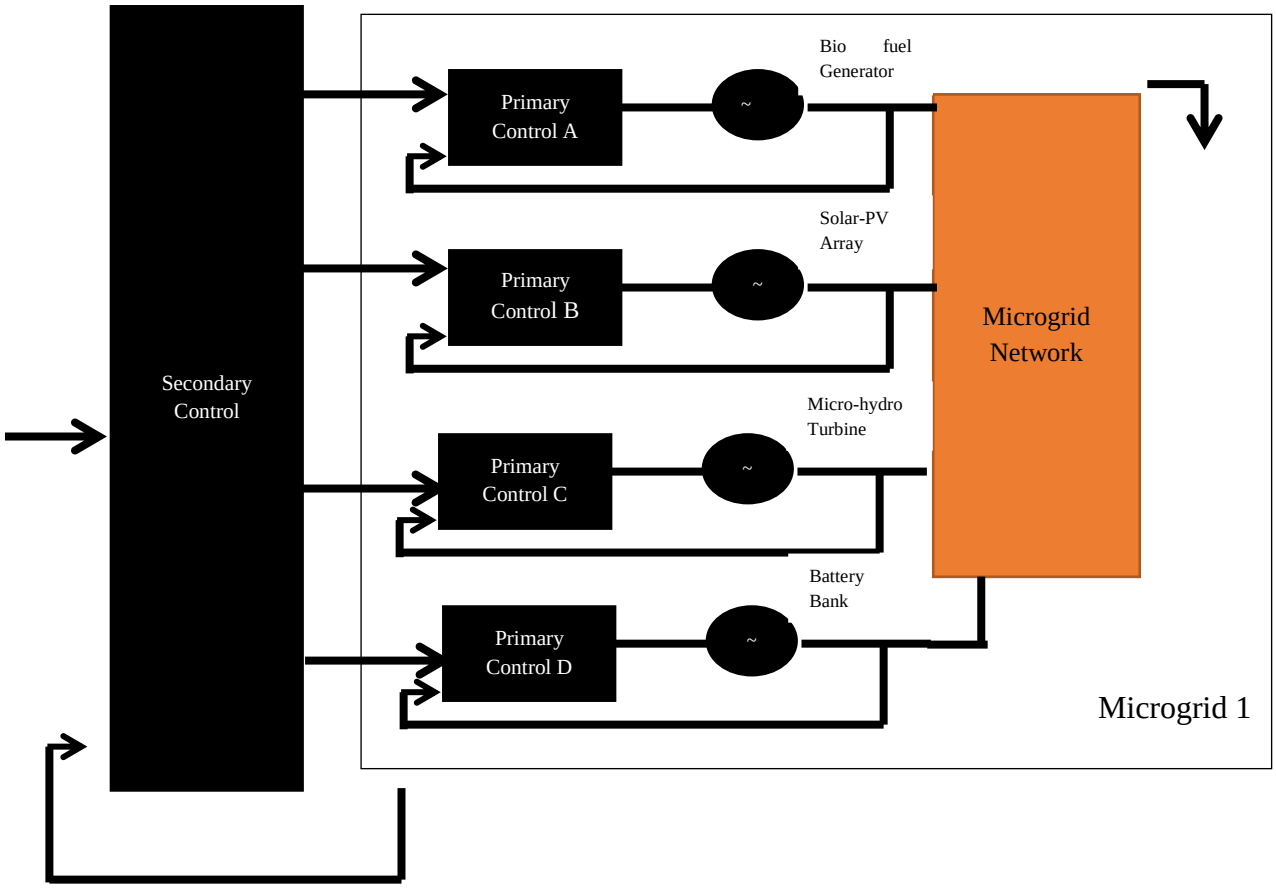

Figure 6-3 A figure illustrating the control scheme of the proposed hybrid Microgrid solution for the electrification of N'zeto & Tomboco area

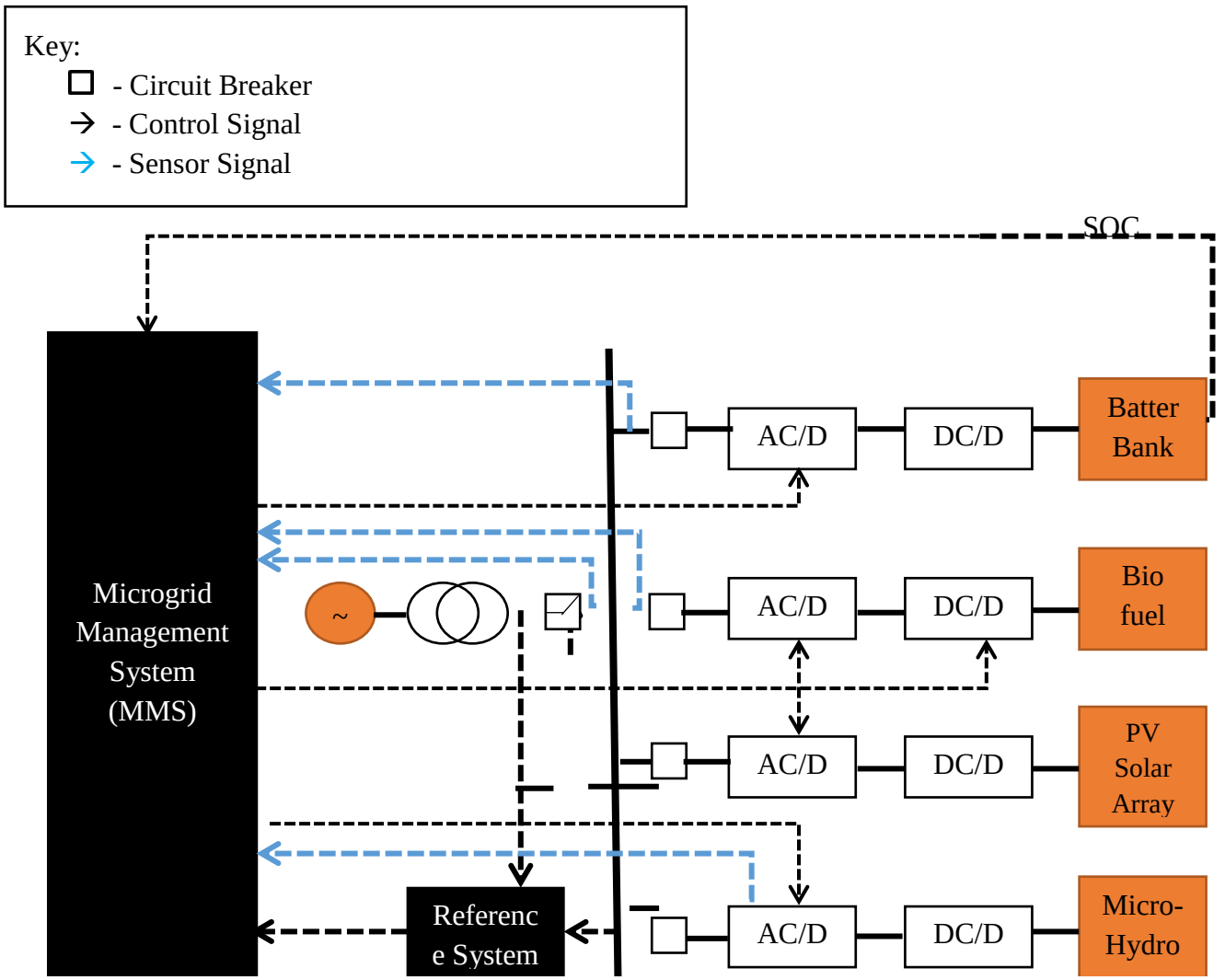

Figure 6-4 A figure illustrating the layout and connection scheme for the Microgrid Management System for the proposed solution

The hierarchical control scheme in Figure 6-4 comprises of three levels of control. At the primary level, autonomous control of any given distributed energy resource is achieved independently knowing the status of the other two in the system. At the secondary level control, corrective actions are effected through the Microgrid Management System (MMS) using sensor information on the demand side and with knowledge of the status of each DER on the generation side, the aim being that of achieving controllability. At the tertiary control level, optimisation of the Microgrid system on the basis of real-time economic and environmental impact indicators is utilised.

One of the challenges for islanded Microgrid systems is in the difficulty of achieving reliable reserve energy management at all times. This is because renewable energy resources sometimes are prone to intermittent supply, making them poorly suited to operate as a “grid-forming” source in a network. Moreover, there is, in the case of our final Microgrid solution proposal, a single

grid-forming unit available, namely the battery bank, meaning that our DERs would operate as "grid-following".

The hierarchical control system defined by figure 6-4 is proposed to operate the single microgrid solution as a grid-forming islanded microgrid system. The control elements of the aforementioned system consist of a cascaded control system making use of Voltage Source Inverters (VSI's) primarily to convert the DC generated voltage to an AC voltage for transmission in order to control voltage and frequency stability, ensuring acceptable power quality and enhancing overall system stability and performance as well as factoring in economic considerations. The following diagram to follow derived from an investigation of literature (citation needed) expands the proposed hierarchical control system as described in figure 6-4.

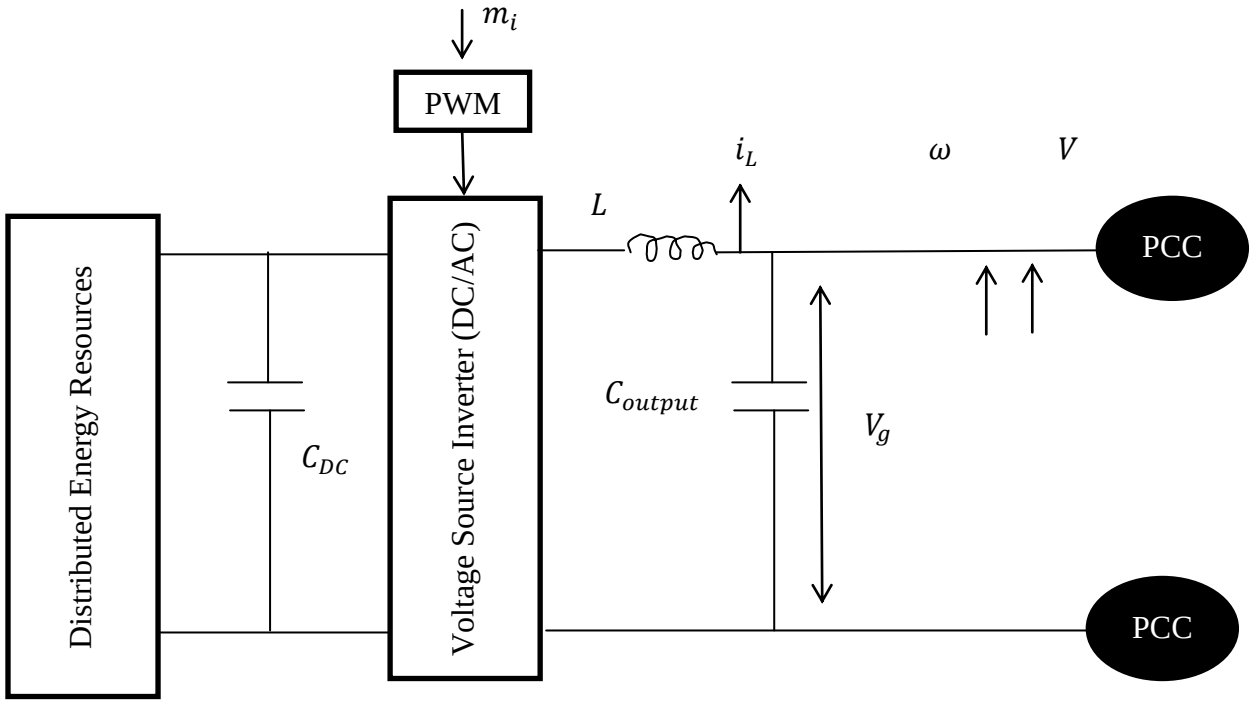

Figure 6-5 A diagram illustrates the operation of the Voltage Source Inverter control and the relevant signals used for tertiary, secondary and primary control of the distributed energy resources.

Figure 6-4 and Figure 6-5 form the basis of the hierarchical control scheme proposed for the single microgrid solution. The distributed energy resources, namely the Solar PV array; Micro hydro-turbine; Battery Array; Cassava based biogas generator, convert the available energy resources discussed in Chapter 4 into electrical energy over a DC voltage. The microgrid control system needs to ensure the stability of the overall network, balance supply and generation as well as meet the network performance specifications in operation. In this system a Voltage Source Inverter control law is implemented in a hierarchical structure to achieve stability and control at the various layers shown specifically in Figure 6-4. The control law makes use of a low pass filter

defined by the L-C circuit shown in Figure 6-5 from which the current (i_L), reference voltage (V_g) and active (P_m) and Reactive (Q_m) can be measured.

Furthermore using the reference signals highlighted in Figure 6-5 the supply voltage (V), frequency (ω) and other performance factors are controlled by the tertiary, secondary and tertiary control schemes used devolving from the architecture outlined in Figure 6-4 is shown to follow.

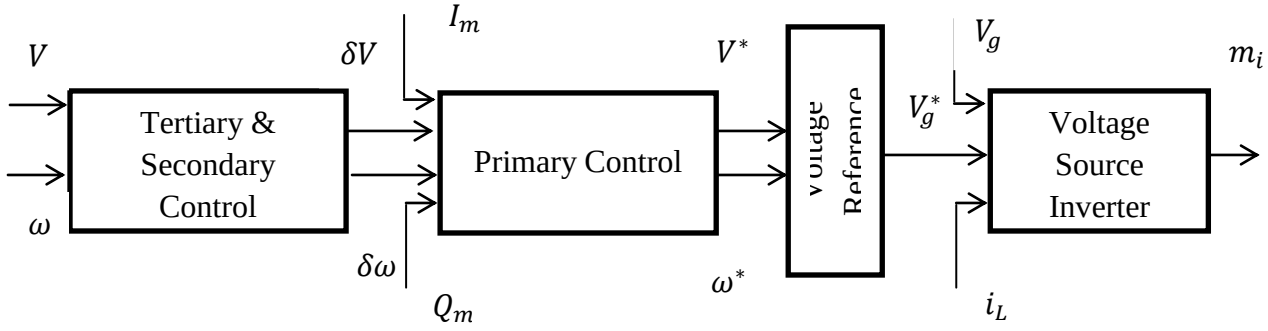

Figure 6-6 A diagram illustrating signal inputs into cascaded block diagram description of the hierarchical control system for the single microgrid solution.

Figure 6-6 demonstrates the cascaded control scheme for the Voltage Source Inverter operating under the hierarchical control system defined in Figure 6-4 using reference signals as inputs.

6.5.2. PRIMARY CONTROL

In Microgrid systems that apply a single grid-forming unit, primary control is achieved by voltage controllers using a predefined reference voltage as described in the reference system in Figure 6-5.

The droop control method is widely used at the primary control level [25]. The idea behind droop control is to create a virtual reference system that mimics the output of a synchronous generator by reducing the operating frequency as the active power increases [13].

6.5.3. SECONDARY CONTROL

The secondary control loop, operating in a MMS, provides voltage and frequency control, improves system power quality and mitigation against the effects of system harmonics. The danger with a centralised system is most easily identified in the secondary control loop where, as evidenced by the architecture adapted and proposed in Figure 6-5, the system failure of the MMS, located in the command and control centre, would result in a total system blackout[78].

A P/F droop controller (Power-Frequency) is proposed for the single microgrid solution due to suitability to medium and high voltage networks (citation needed) and simple implementation. The weakness of the P/F droop controller lies in its poor reactive power control however this is mitigated by the characteristics of the rural based loads discussed at length in Chapter 3 which suggest that low amounts of reactive power are required due to the absence of inductive loads. Should the region industrialise dramatically post-electrification, the P/F droop controller choice may need to be reconsidered in lieu of observed and forecasted system performance.

Explanation

$$\omega = \omega^* - K_f(P_i - P_i^*); i \epsilon N \quad (6.6)$$

Where,

ω: Angular velocity measured at point of common coupling

ω^*: Reference value for Angular velocity

K_f: Controller coefficient for frequency control

P_i: ith active Power measurement

P_i^*: ith active Power reference

$$V = V^* - K_V(Q_i - Q_i^*); i \epsilon N \quad (6.6)$$

Where,

V: Voltage measured at point of common coupling

V^*: Reference value for Voltage

K_V: Controller coefficient for voltage control

Q_i: ith reactive Power measurement

Q_i^*: ith reactive Power reference

Furthermore the controllers K_V and K_f are defined as follows,

$$K_V = \frac{V^* - V_{min}}{Q^* - Q_{i,max}};$$

$$K_V > 0 \qquad (6.7)$$

Where V_{min} and $Q_{i,max}$ are the specified minimum acceptable voltage and the maximum allowable reactive power.

$$K_f = \frac{\omega^* - \omega_{min}}{P^* - P_{i,max}} \qquad (6.8)$$

Where ω_{min} and $P_{i,max}$ are the specified minimum acceptable angular velocity (defined by minimum frequency) and the maximum allowable active power.

From our investigation based on this study, no state policies in Angola have been found identifying the acceptable grid quality criteria. If we consider the tolerance prescribed in legislation in continental Europe we find approximately 0.2Hz as the band of acceptability[79]. This band is represented as the difference between the operating frequency f and the control target f_0 which stands at 60Hz for Angolan power networks as shown in Figure 6-6. In accordance with the IEEE 1547.4 standard IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems[74], the tolerate prescribed for voltage distortion is represented as the ratio of difference between the operating voltage and the reference voltage, $\frac{|V - V_0|}{V_0}$, which is set to 5%.

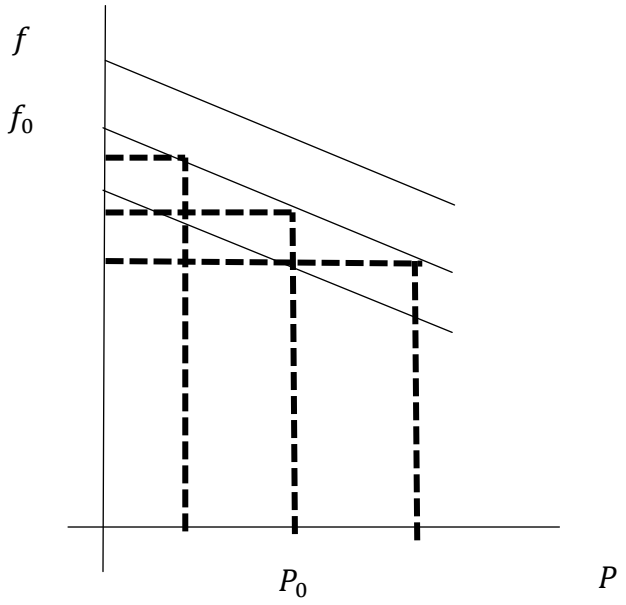

Figure 6-7 A figure illustrating a Frequency droop characteristic function

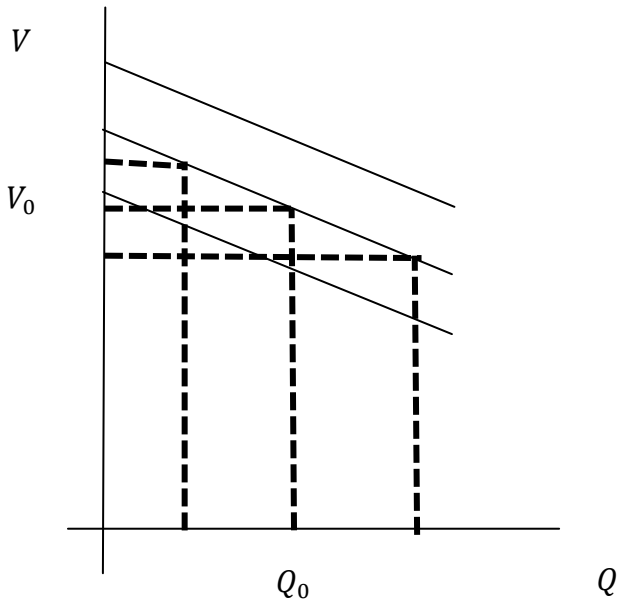

Figure 6-8 A figure illustrating the operation of a Voltage droop characteristic function

6.5.4 TERTIARY CONTROL

At the tertiary control loop, a cost function operates on the basis of a set of designed constraints ensuring optimal load sharing between distributed energy resources. Through engagement with literature [80][81][82] the economic dispatch problem defined by a cost function, as developed to follow, is proposed to operate at the tertiary control layer of the hierarchical control system for the single microgrid solution.
Consider,

Distributed Energy Resources: $P_{solar\ pv}; P_{hydrokinetic}; P_{cassava\ biogas}$
Energy storage: $P_{battery}$

In a paper titled "Dynamic Economic Dispatch for Microgrids Including Battery Energy Storage" a generalised objective function was proposed as follows:

$$COST\ FUNCTION: \min C = \sum_{k=0}^{N-1} \sum_{h=1}^{m-1} F_h(P_{hk}) + F_{grid}\left(P_{gridk}\right) + F_{bat}(P_{bat}) \qquad (6.7)$$

Where,
F_h,F_{grid} and F_{bat} represent Cost functions for the respective energy sources.
F_h,F_{grid} and F_{bat} represent Cost functions for the respective energy sources.

Now under islanded mode,

$$COST\ FUNCTION: \min C = \sum_{k=0}^{N-1} [\sum_{h=1}^{m-1} F_h(P_{hk}) + F_{bat}(P_{bat})]$$
(6.8)

Finally the cost function expanded in full is represented to follow:

$$\min C = F_{solar\ pv}\left(P_{solar\ pv}\right) + F_{hydro}\left(P_{hydro}\right) + F_{cassava\ biogas}\left(P_{cassava\ biogas}\right) + F_{bat}(P_{bat})$$
(6.9)

$F_{solar\ pv}$;F_{hydro} $F_{cassava\ biogas}$ And F_{bat} are cost functions defined by the costs per distributed energy resource per kW. This includes investment costs for infrastructure, government subsidies, associated taxes and in case of cassava biomass, fuel costs.

6.6 ENERGY EFFICIENCY

Achieving efficiencies in energy use over time, is one of the factors that would contribute to the overall long-term success of our N'zeto and Tomboco electrification project. Measures to this end include the following:

. Community education that promotes responsible in energy use;

. Public programmes that draw community interest in participating in the future energy projects;

. Measures that promote wide spread use of environmentally friendly and efficient lighting technologies

and;

. Promotion of wide spread use of low-cost water-heating geysers.

6.7 OVERALL MICROGRID OPERATION PLAN

The flow chart to follow, which summaries the overall operational plan of our microgrid solution proposal, is informed by ideas from [15] and [83]:

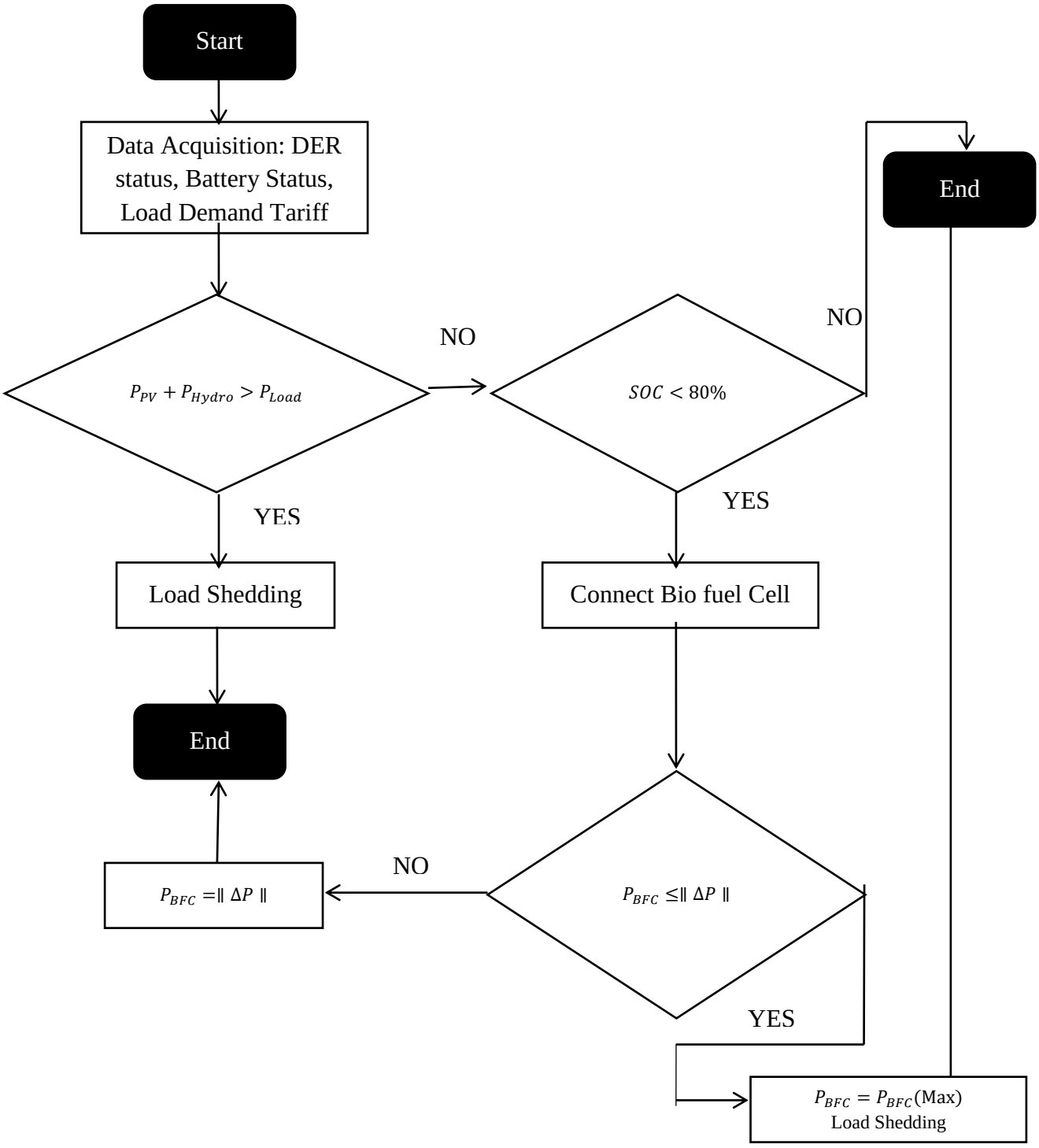

Figure 6-9 Flowchart illustrating the Single Microgrid solution operation of use process

In summary, the base of the power required by the demand side is provided by a Solar PV array and a micro-hydrokinetic-turbine that runs off the M'bridge River. When the combined input from the solar and hydro utilisation DERs is not sufficient to power the load demanded from both villages, the battery bank is drawn on to supplement the extra required power. If the solar and hydro DERs and the battery bank combination cannot meet the power requirements, the bio fuel cell generator is set into production mode. The cassava-peel-based biogas produced by the local anaerobic digester is burnt to supply balance of the power required. System implemented load shedding is then implemented as a last resort to prevent total blackout.

6.8 SENSITIVITY ANALYSIS

6.8.1. INTRODUCTION

In this section a sensitivity analysis of six key microgrid design variables is undertaken using the HOMER software, to assess the impact of changes in the amounts of those variables on the proposed microgrid as defined in sections 6.2 to 6.7. The variables in question are:

. Average Biomass Collected/Available (in tonnes per day);
. Average Flow Rate of M'bridge river (in cubic metres per second);
. Average Load Profile (in kWh per day);
. Average Solar Irradiation Available (in kWh per square metre per day);
. Estimated/Projected Cost of Electricity (in US dollars) and;
. Variability of Lead Acid Energy Storage Capacity.

Each of the first four variables is assigned a confidence factor as shown and motivated in Table 6-3 to follow.

Table 6-3 A table providing confidence factors assigned to Solar Irradiation, M'bridge River-Flow Rate, and Biomass Yield from Cassava, and Electrical Load (N'zeto and Tomboco)

Variable	Assigned Confidence Factor	Assignment Justification
Solar Irradiation	0.9	The high confidence factor assigned to Solar Irradiation reflects the fact that the data not only are derived from NASA GEOSAT satellite but also this data source is widely I used for Microgrid planning particularly with HOMER based studies.
River Flow rate (M'bridge River)	0.5	The low confidence factor assigned to the river flow estimates reflect the fact that the estimates are not based on reliable data. The estimation produced using the maximum flow rate rated for an old hydropower plant at different location on the river along with local environmental data.
Biomass Yield (Cassava)	0.7	The moderately high confidence factor allocated to this variable relates to the reasonably reliable FAO and Angola Municipal data.
Electrical Load (N'zeto & Tomboco)	0.6	The low confidence factor given for the Electrical Load estimated in N'zeto and Tomboco reflects the fact that the Similar Day and Jardini et al forecasting models that we use rely on synthetic data and not authentic data.

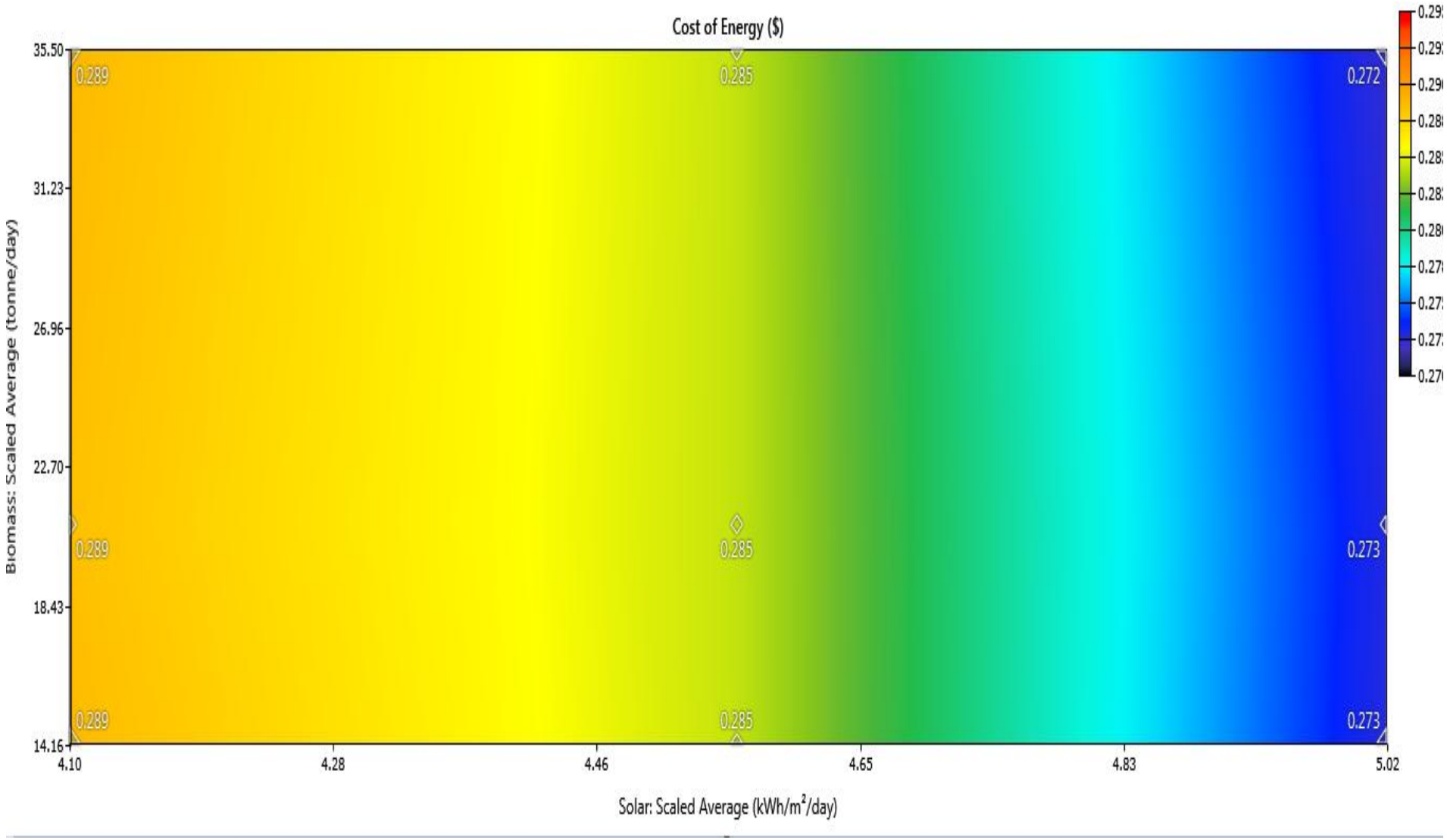

Figure 6-10 A graphical sensitivity analysis produced by HOMER software in the form of a plot of Scaled Average Cassava Biomass Collected against Scaled Average Solar Irradiation, demonstrating the impact of changes in these variables on the Estimated Cost of Electricity.

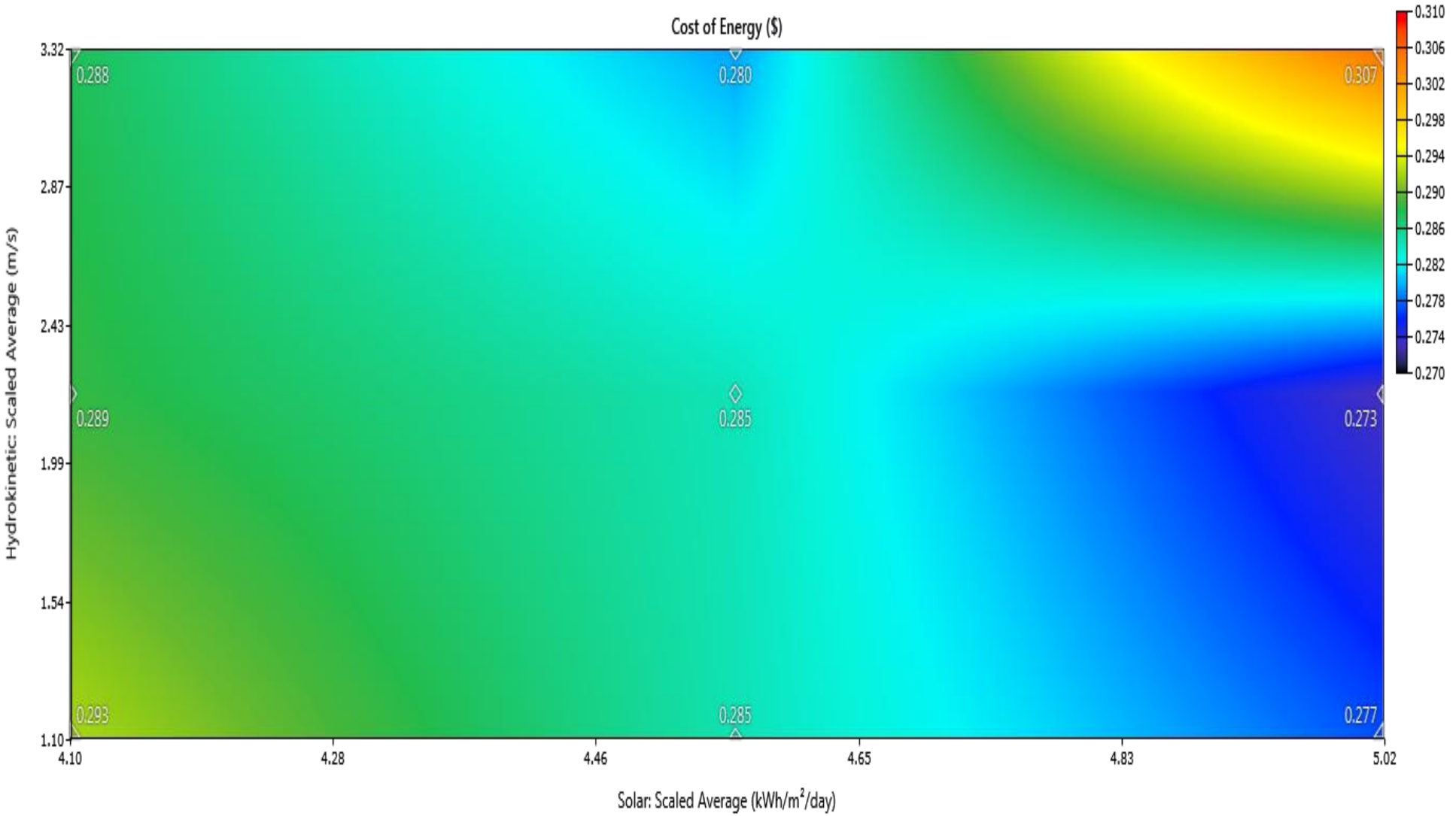

Figure 6-11 A graphical sensitivity analysis produced by HOMER software in the form of a plot of Scaled Average Flow of M'bridge River against Scaled Average Solar Irradiation, demonstrating the impact of changes in these variables on the Estimated Cost of Electricity.

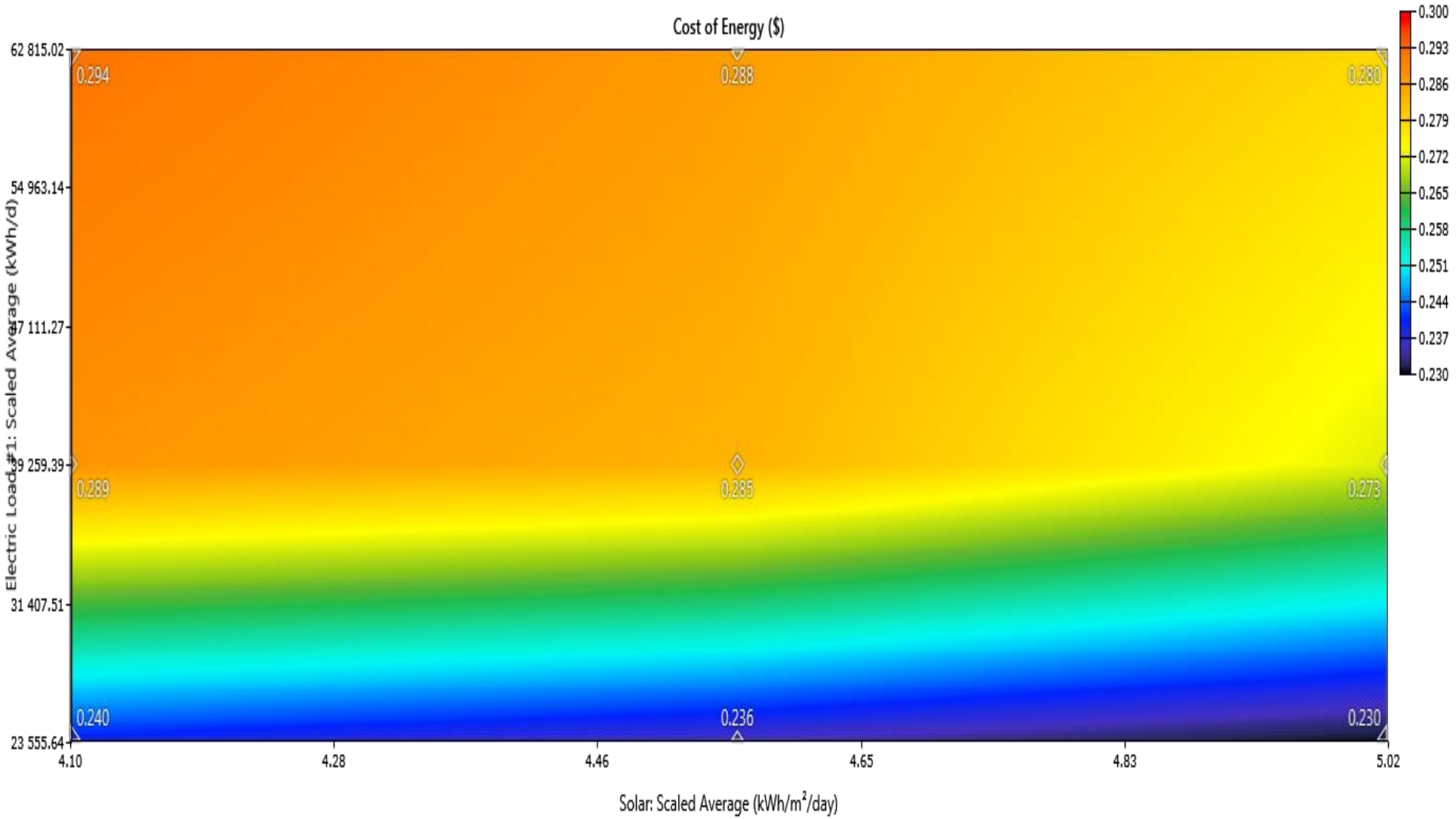

Figure 6-12 A graphical sensitivity analysis produced by HOMER software in the form of a plot of Scaled Average Load Profile generated from a single source against Scaled Average Solar Irradiation, demonstrating the impact of changes these variables on the estimated Cost of Electricity.

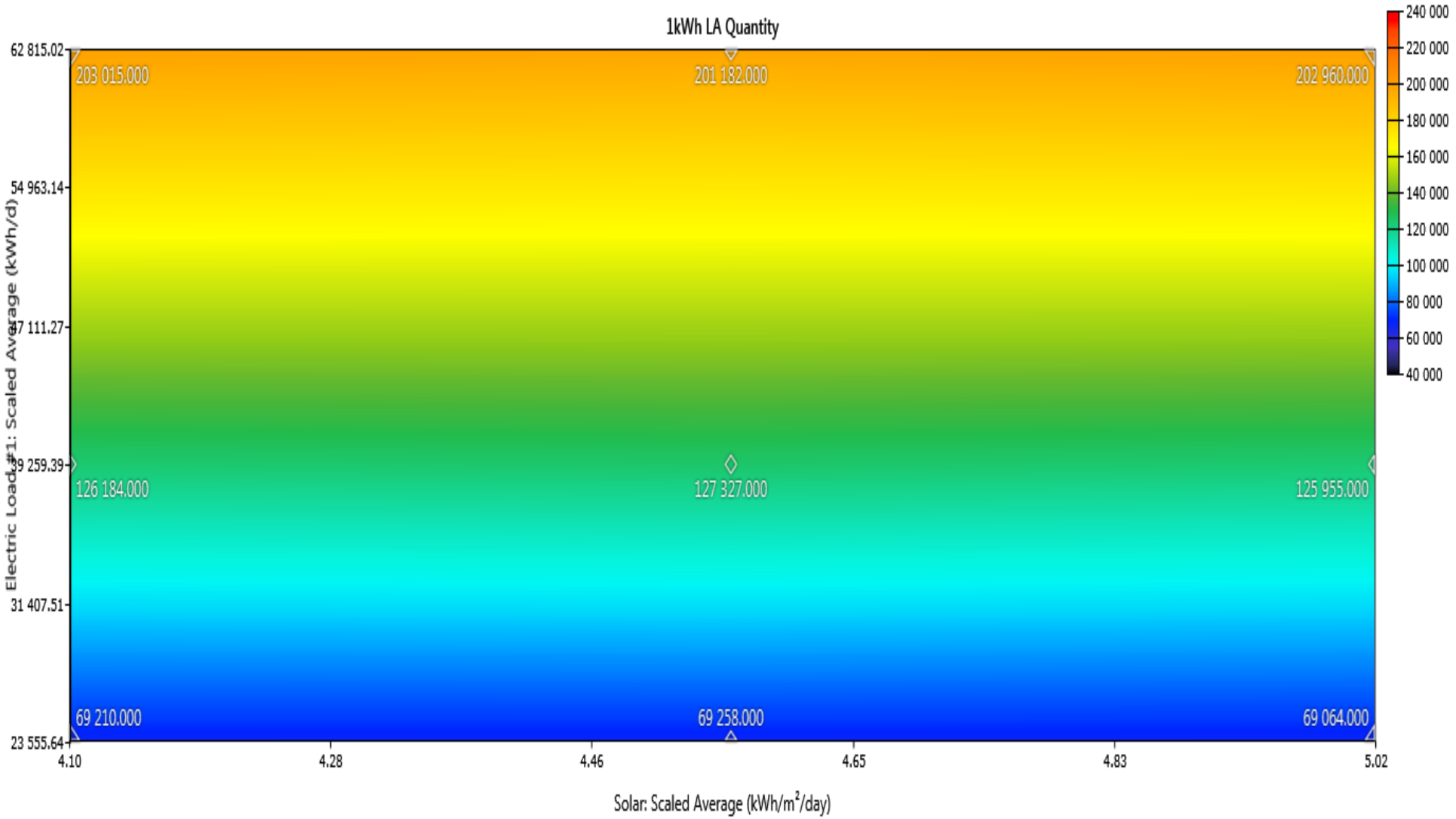

Figure 6-13 A graphical sensitivity analysis produced by HOMER software in the form of a plot of Scaled Average Load Profile generated from a single source against Scaled Average Solar Irradiation, demonstrating the impact of variability of these factors on the Lead Acid Energy Storage capacity requirement.

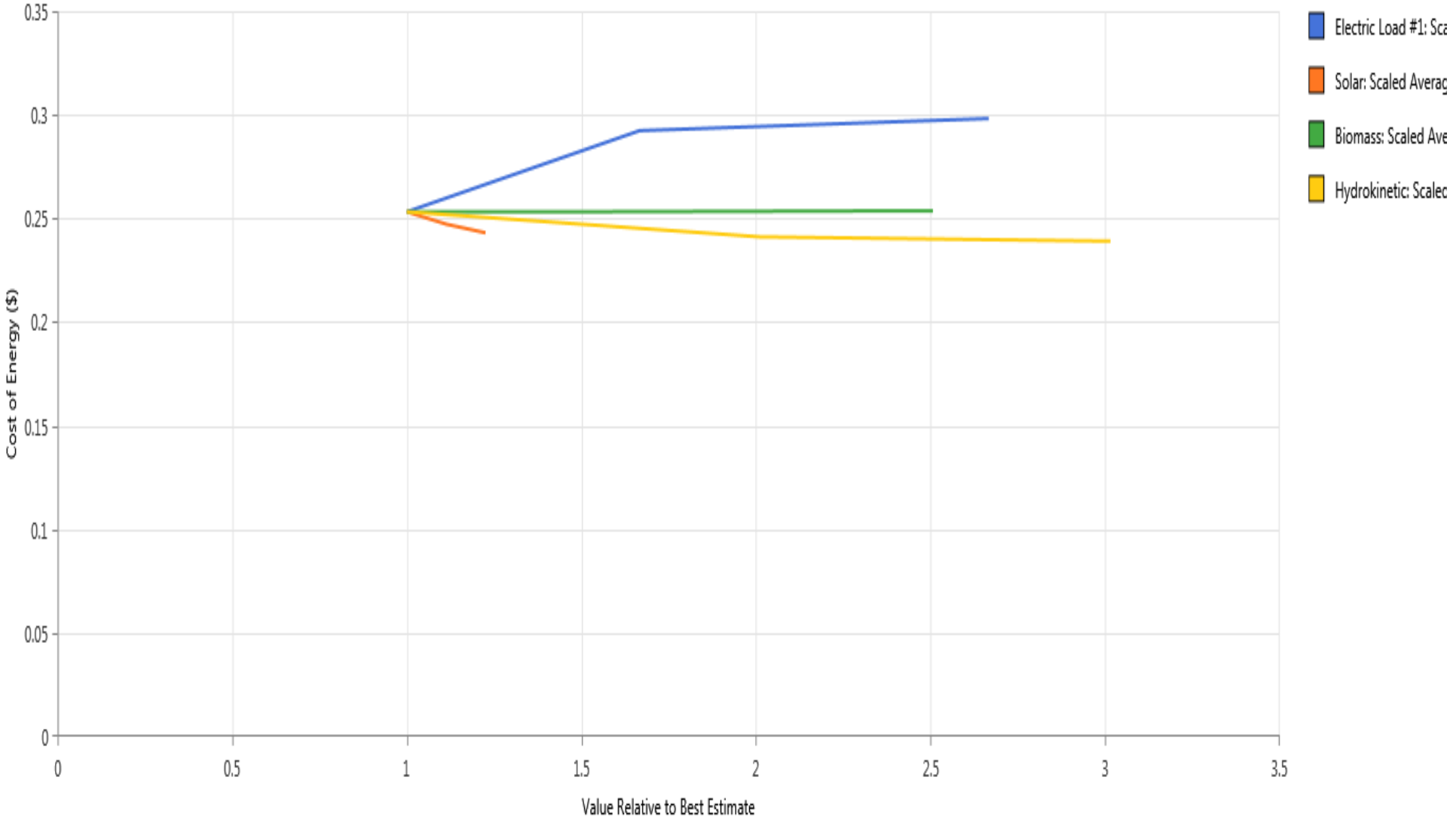

Figure 6-14 A spider plot produced by HOMER software demonstrating the impact of the uncertainty in the Electrical Load, Amount of Cassava Biomass Collected , and M'bridge river Flow Rates on the projected cost of electricity.

6.5.2. DISCUSSION

Figures 6-10 to 6-14 are graphical summaries of the sensitivity analysis conducted on the proposed final solution using HOMER software. The analysis purpose is to assess factors to which the cost of electricity is sensitive. The inputs to the HOMER based analysis are variables Cassava biomass, Solar Irradiation and M'bridge River flow and associated data from Chapter 4, synthetic Load Profiles from Chapter 3, and confidence factors which are used to scale their corresponding variables (Table 6-3).

From Figure 6-2 and the algorithm in figure 6-9, one recalls that (a) our final proposal operates primarily off a base of a Solar PV array and a small Hydrokinetic turbine that operates off the M'bridge River; (b) the river is assumed to flow all year round and every hour; (c) surplus energy during the day is stored in a lead acid battery; (d) during high demand periods, if the demand cannot be met by the available solar irradiation and hydrokinetic energy, bio fuel generated from Cassava peel biomass is burnt to supplement the deficit. Accordingly, :

. Figure 6-10 shows that the higher the available Solar Irradiation the lower the expected cost of electricity
and consequently the less biomass is required to be collected and converted to electrical energy.

. Figure 6-11 shows that the power generated from the hydrokinetic turbine is comparatively cheaper than
Solar Power. However, due to the optimal sizing of the component chosen in the proposed design the
contribution of the hydrokinetic turbine to the total load required is small and therefore more significant
reductions in cost are associated with higher values of Solar Irradiation.

. Figures 6-12 and 6-13 confirm the expectation that the higher the electricity load is demanded the more
likely increasing amounts of biomass are collected and burned to supplement solar and hydro sources, and
the larger the battery storage banks are required so that overall high electricity demand is expected to

increase the cost of electricity.

Lastly, the spider plot in Figure 6-14 shows that the high uncertainty in the Load Profile is the most decisive cause for variability in the HOMER estimated cost of electricity for the proposed single microgrid solution. The hydrokinetic and biomass input variable uncertainty is seen to have a comparatively low impact on the cost estimate while the high confidence factor Solar Irradiation has the second most impact on the cost of electricity, with cost savings being in periods of high solar irradiation.

6.9 OTHER COSTS NOT CONSIDERED THUS FAR

This section considers certain other relevant costs which have not been given attention thus far.

6.9.1.1. COST OF DISTRUBTION CABLES

The table to follow which is drawn from "Midal Cable ACSR Conductor datasheet"**[76]** and the "American Wire Group price list"**[84]**, illustrates the weighting and costing of distribution cables for the proposed microgrid solution.

Table 6-4 A table illustrating the weighting and costing of distribution cables for the proposed microgrid solution

Location	Distribution Cable	Length	Unit Weight	Weight	Unit Price	Cost
CCC to Tomboco substation	ACSR SWALLOW	21km	108kg/km	2268kg	984$/km	$20664
CCC to N'zeto substation	ACSR PIGEON	56km	344kg/km	19264kg	1410$/km	$78960
Total				21 532kg		$99624

6.9.2. TRANSPORTATION OF EQUIPMENT

The freight costs of importing DER infrastructural equipment are not included in the HOMER cost analysis and therefore are quoted and integrated into the improved cost estimate worked through this section as follows.

As an example we use a major DER component sourced from Chinese manufacturers and delivered by sea to Luanda Harbour and by road to N'zeto.

The table to follow contains a list of transport cost estimates obtained from Alibaba.com (for Sea Freight) and Orion Logistics (for Road Freight).[85][86]. We assume for road freight that each portion of the total payload will be delivered via single 34 ton side tipper trucks.

Table 6-5 A table listing the additional initial transport costs associated with installing the infrastructure of the Microgrid system

	Sea Freight Cost ($)	Total Mass (kg)	Road Freight Cost ($)	Cost
	Sea Freight (Shenzhen, China to Luanda, Angola)			
Solar PV	171 451.82	367 448	1 621 000	1 792 451.82
Bio fuel Generator & Industrial Peeler	1 797.96	6 110	26 955	28 752.96
Micro-hydrokinetic Turbine	473.91	1500	6 617	7090.91
Battery Bank	676 031.61	5 002 668	22 070 594	22 746 625.61
ASCR SWALLOW Conductor (21km)	1 058.25	2268	10 005.30	11 063.55
ASCR PIGEON	8 988.61	19264	84 983.30	93 971.91

Conductor (56km)				
Total	$859 802.16	5 337 726kg	$23 820 154.60	$24 679 95 6.76

6.9.3. ANNUAL OPERATION OF THE BIOFUEL PLANT

The location of the bio fuel generator has been pointed out as roughly midway between N'zeto and Tomboco. Assume that a truck and four permanent staff, two per vehicle, would collect cassava from nearby local farms at frequency and size dictated by the usage schedule managed at the command and control centre.

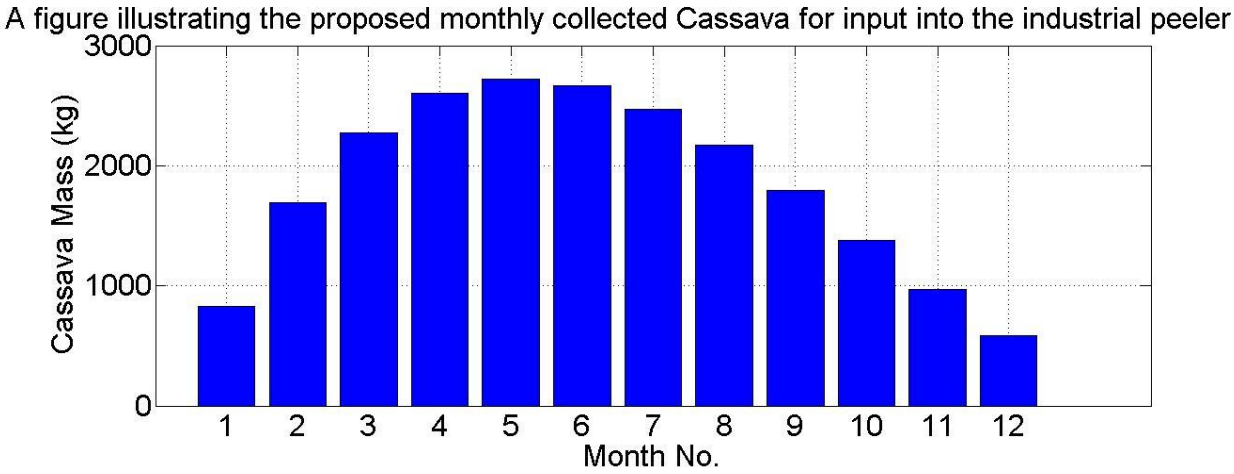

Figure 6-15 A figure illustrating the proposed monthly collected Cassava for input into the industrial peeler

Assume further a conservative requirement of 6.5 tonnes of waste peels. If we consider the total distance, via dirt road, between in N'zeto and Tomboco is 136km and that the proposed Microgrid solution is located roughly midway between the sites then for purposes of estimation it shall be assumed that the farms surrounding both N'zeto and Tomboco lie within a 50km radius of the command and control centre, as show in Figure 6-1.

If each Cassava tuber is conservatively assumed to be estimated as by the enclosed volume of a cylinder of radius 10cm and 40cm and length then the total assumed dimensions of each tuber stands at $0.013m^3$ and mass of up to 7kg [87].

If we consider each Cassava Transport vehicle, specified as Toyota Danya trucks, the maximum mass and volume permissible on each stands at 1525kg and $2.48m^3$[65].

The maximum numbers of Cassava tubers that are then able to fit into the Toyota Danya as a payload are approximately 191 at a total of 1337kg. If we then consider a safety margin of 10% such that the Cassava tubers are able to comfortably fit inside the vehicle on a rough road system then each vehicle load is able to carry 172 Cassava tubers at 1204kg.

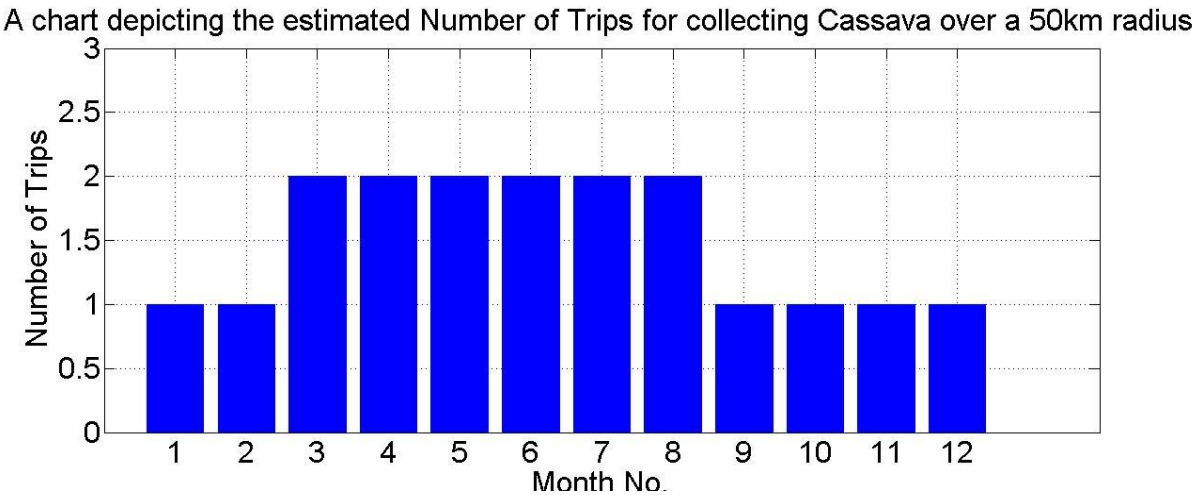

Figure 6-16 A chart depicting the estimated Number of Trips for collecting Cassava over a 50km radius

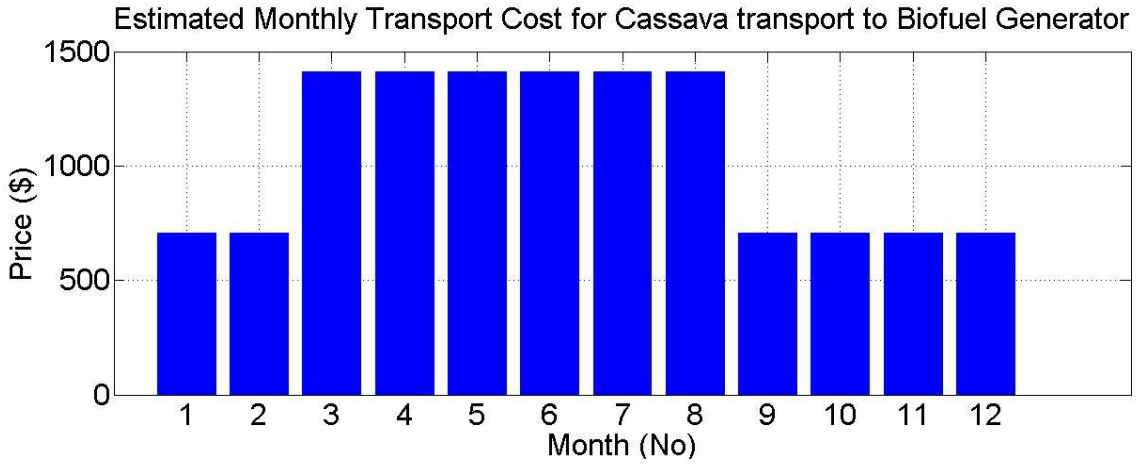

Figure 6-17 Estimated Monthly Transport Cost for Cassava transport to Bio fuel Generator

Figures 6-16 and 6-17 demonstrate the estimated number of vehicle trips to collect the required Cassava tubers and the monthly associated costs calculated at a diesel price of $0.81/L and at a vehicle consumption rate of 8.7 L/km.

Table 6-6 A table of the additional costs relating to the Biomass Generator annual operation plan

Item	Cost
Procurement Truck	$312 000
Industrial Peeler	$12 500
4 Permanent support staff	$652 000 [88]
Annual Petrol usage	$12 685
Total	$989 185

6.9.4. COST OF ELECTRICITY REVISITED: IMPROVEMENT ON HOMER ESTIMATION

The Cost of Electricity (COE) presented in sections 5.2 & 5.3 of the last chapter were computed using the following formula from [89], namely:

$$COE = \frac{C_{ann}}{E_{ls}+E_{grid\ sales}} \tag{6.8}$$

where C_{ann} is the annual cost, E_{ls} is the Total Energy Delivered to the load in a year, $E_{grid\ sales}$ is the Total Energy sold to the grid in a year, and COE is the Cost of Electricity

In the case of operating an islanded microgrid the equation simplifies to:

$$COE = \frac{C_{ann}}{E_{ls}} \tag{6.9}$$

Furthermore,

$$C_{NPC} = \frac{C_{ann}}{CRF(i,R_{proj})} \tag{6.10}$$

$$C_{ann} = C_{operational} + C_{initial} \tag{6.11}$$

where C_{NPC} is the Net present cost, CRF is the Discount recovery factor, and R_{proj} is the Project Lifetime

To improve 6.9, its numerator may be replaced by:

$$C^*_{ann} = \left(C_{operational} + C_{biofuel\ operation}\right) + \left(C_{initial} + \left(C_{infrastructure\ transport} + C_{dist.conductors}\right)\right) \tag{6.12}$$

where C^*_{ann} is the improved Annual Cost, $C_{biofuel\ operation}$ is the Cost of operation for the cassava biofuel plant, $C_{infrastructure\ transport}$ is the Cost of transporting microgrid infrastructure (incl. distribution conductors), and $C_{dist.conductors}$ is the Cost of distribution conductors for feeders between the source and the local substations.Furthermore,

$$C^*_{NPC} = \frac{C^*_{ann}}{CRF(i,R_{proj})} \tag{6.13}$$

where C_{NPC} is the improved Net present cost

Finally,

$$COE^* = \frac{C^*_{ann}}{E_{ls}} \quad (6.15)$$

where COE^* is the improved Cost of Electricity.

Last point of this chapter: in section 6.8 a sensitivity analysis was performed by applying a confidence factors onto the estimated input variables such as the Load Profile, Solar Irradiation, Cassava Biomass, M'bridge river flow rate using the HOMER optimisation tool. The revised optimal solution (revised from the values obtained in Chapter 5) was produced from the addition of the sensitivity analysis.

Table 6-7 to follow quantifies the impact of these factors taking into account infrastructure transport costs and annual biomass generator operation costs and summarises the results across the different load model estimates.

Table 6-7 A table illustrating the revised Cost of Electricity taking into consideration transport costs to N'zeto, Angola and the proposed operation plan for the cassava peel based bio fuel generator

	Similar Day - Normal	Similar Day - Beta	Parametric - Normal	Parametric - Beta
HOMER LCOE	0.26	0.25	0.25	0.26
Revised LCOE	0.33	0.31	0.33	0.40

CHAPTER 7

7. CONCLUSION

The solution ultimately proposed, as summarised in table 6-1 of the last chapter, consists of a grid-forming energy storage unit consisting of a lead acid battery bank along with a generation supply based on an array of 1kW Solar PV panels, a 500kW cassava based bio fuel generator and a 40kW Micro-hydrokinetic turbine operating off the river run of the M'bridge River between N'zeto and Tomboco with a distribution line rated at 34kV running between two substations at each village location respectively.

The Distribution Scheme proposed in table 6-2 proposes a two wire single phase system using feeders from the Command and Control Centre to the Tomboco (21km) and N'zeto (56km) substations respectively as show graphically in figure 7-1. The conductors selected are ACSR SWALLOW (3AWG) and ACSR PIGEON (3AWG)

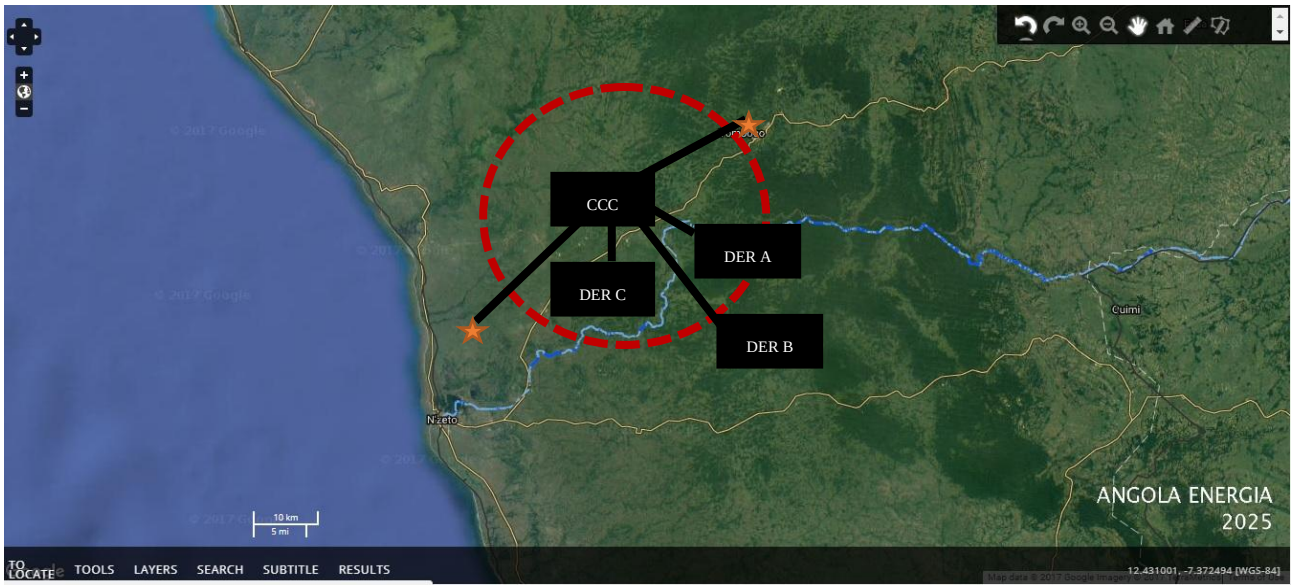

Figure 7-1 A figure illustrating the geographical location of the proposed Microgrid solution including the collection zone for Cassava biomass collection

For cassava biomass, it is proposed that this be obtained from local farms located within a 50km radius of the command and control centre shown in Figure 7-1 as CCC.

The design path also made use of two load modelling approaches: one that was called a “Similar Day” and another that was termed a “three-partitions-a-day”, if only for lack of a better competitor. The following key findings emerged through the investigation and design process of this mini-dissertation:

(a) If the microgrid proposed is installed, it will introduce to the local economy of a 500kW Cassava-based bio fuel generator which would operate off cassava peel waste collected from an industrial peeler using Cassava tubers collected from nearby local farms.

We are aware of a general concern regarding the threat to food security posed by the bio-fuel development, see e.g. a paper by Tomei et al[90]. However, we do not see this prospect occurring since from the operational plan proposed in the last chapter, the operation of our microgrid would require an annual collection schedule that would in no way affect cassava food security.

(b) Regarding other possible uses of a bio fuel generator in (b), it was also pointed out elsewhere that a potential exists to gradually decarbonise rural cooking by substituting existing wood-fire with bio fuel by-products produced from Cassava and banana peels.

(c) From the Brazilian experience, it also appears that the installation of a micro-hydrokinetic turbine off the M’bridge river to generate hydropower has an additional potential to scale up farming activity during dry season;

(d) The modular, hierarchical and centralized microgrid system we have proposed provides an architecture that is well suited for future integration with the national grid, in keeping with the national plan in (a). In particular, the design of the Microgrids control scheme would be fully compatible with the grid connection.

(e) The electrification we are proposing not only has potential to spur future economic activity but also would *fast-track* the provision of stable and affordable electricity to a rural area where national grid extension would otherwise only be a dream with no comparable realisable speed (recall Angola has a landmass of approximately 1246700 square kilometres but a population of only about 24 million).

In the case of ‘feasibility studies for projects’, typically the ‘purpose and nature of a project desired’ (the null hypothesis) is proposed, as articulated in Chapter 1. The design process and background study, encompassed in Chapters 1-6, cumulatively constitute a more detailed study which confirms and improves the feasibility of the hypothesized electrification scheme desired in the hypothesis H_0. This was achieved through a wide array of analytic estimation tools using models to for the load profile and energy consumption as well as the assessment of available energy resources which make use of a diverse array of remotely acquired data, contending with the reality of high levels of uncertainty. The solution proposed satisfying H_0 provides an environmentally desirable outcome meeting local and international imperatives to increase the use of renewable energy systems, as well as providing a potentially affordable service, provided subsidy trends for electricity tariffs continue at their current level of implementation.

8. REFERENCES

[1] W. E. Outlook, 2014. [Online]. Available: http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/.

[2] S. e. f. all, "Rapid Assessment and Gap Analysis: Angola," 2015.

[3] E. Boateng, "The potential socio-economic and environmental impacts of solar PV mini-grid deployment on local communities: A case study of rural island communities on the Volta Lake," Jyväskylä.

[4] J. JÄRVENPÄÄ, "MICRO HYDRO AND PHOTOVOLTAIC AS ALTERNATIVES FOR ELECTRIFICATION OF REMOTE VILLAGES IN NEPAL," TAMPERE, 2014.

[5] P. M. S. P. K. R. S. F. S. a. S. A. Loka, "A case study for micro-grid PV: lessons learned from a rural," *Prog. Photovolt: Res. Appl,* vol. 22, no. 7, p. 733–743, 2013.

[6] B. Parthan, "Literature Review: Rural Business Models in Asia," 2014.

[7] R. B. E. a. R. K. Bellanca, Delivering Energy for Development, 1st ed., Rugby: Practical Action Publishing, 2013.

[8] S. C. Bhattacharyya, 12 2017. [Online]. Available: http://www.dmu.ac.uk/research/research-faculties-and-institutes/institute-of-energy-and-sustainable-development/research-projects/oasys/index.aspx.

[9] U. S. o. A. D. o. Energy, "The Role of Microgrids in Helping to Advance the Nation's Energy System," June 2017. [Online]. Available: https://energy.gov/oe/services/technology-development/smart-grid/role-microgrids-helping-advance-nation-s-energy-system.

[10] A. R. N.W.A. Lidula, "Optimal sizing, operating strategy and operational experience," *Renewable and Sustainable Energy Reviews - Elsevier,* vol. 15, pp. 186-202, September 2011.

[11] J. C. Yanbo CHE, "Research on Design and Control of Microgrid System," *PRZEGLĄD ELEKTROTECHNICZNY (Electrical Review),* no. ISSN 0033-2097, pp. 83-86, 2012.

[12] J. A. B. Eneko Unamuno, "Hybrid ac/dc microgrids—Part I: Review and classification of topologies," *Renewable and Sustainable Energy Reviews,* vol. 52, pp. 1251-1259, August 2015.

[13] H. A. Alharkan, "A control algorithm for the solar village microgrid system," 2016.

[14] R. Huang, "Integration of Renewable Distributed Energy Resources into Microgrids," Los Angeles, 2015.

[15] L. R. Z. F. Li Fusheng, Microgrid Technology and Engineering Application, 1st ed., L. Reading, Ed., ELSEVIER, 2016.

[16] J. Ø. K.C. Divya, "Battery energy storage technology for power systems—An overview," *Electric Power Systems Research,* vol. 79, pp. 511-520, September 2009.

[17] V. T. R. N. P. H. M. Sam Koohi-Kamali, "Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review," *Renewable and Sustainable Energy Reviews,* vol. 25, pp. 135-165, May 2013.

[18] P. M. S. P. K. R. S. F. S. &. S. A. Loka, "A case study for micro-grid PV: lessons learned from a rural electrification project in India," *Progress in Photovoltaics: Research and Applications,* pp. 733-743, 2014.

[19] D. G. S. F. V. O. A. I. A. Z. L. a. J. T. S. Pudjianto, "Investigation of regulatory, commercial, economic and environmental issues in microgrids," in *IEEE - International conference on future power systems,* 2005.

[20] U. N. S. U. L. a. T. K. Kwhannet, "Impact of energy storage in micro-grid systems with DGs," in *International Conference on Power System Technology,* 2010.

[21] M. M. A. H. P. J. K. A. H. M. B. M. a. F. B. Faisal, "Review of energy storage system technologies in microgrid applications: Issues and challenges," *IEEE Access,* pp. 35143-35164, 2018.

[22] I. V. J. V. H. C. A. Etxeberria, "Hybrid Energy Storage Systems for Renewable Energy Sources Integration in Microgrids: A Review," in *IPEC,* Singapore, 2010.

[23] I. V. H. C. J. V. A. Etxeberria, "Comparison of three topologies and controls of a hybrid energy storage system for microgrids," *Energy Conversion and Management,* vol. 54, pp. 113-121, November 2012.

[24] Q. L. H. W. Xingguo Tan, "Advances and trends of energy storage technology in Microgrid," *Electrical Power and Energy Systems,* vol. 44, pp. 179-191, August 2013.

[25] D. E. O. e. al., "Trends in Microgrid Control," *IEEE Transactions on Smart Grid,* vol. 5, pp. 1905-1919, July 2014.

[26] Y. B. a. R. S. B. S. Hartono, "Review of microgrid technology," in *International Conference on QiR,* Yogyakarta, 2013.

[27] M. U. O. Erdinc, "Optimum design of hybrid renewable energy systems: Overview of different approaches," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 1412-1425, January 2012.

[28] S. C. Sunanda Sinha, "Review of software tools for hybrid renewable energy systems,"

Renewable and Sustainable Energy Reviews, vol. 32, pp. 192-205, April 2014.

[29] HOMER Energy, January 2018. [Online]. Available: https://www.homerenergy.com/support/index.html.

[30] MATHWORKS, January 2018. [Online]. Available: https://www.mathworks.com/help/simulink/index.html?s_tid=gn_loc_drop.

[31] University of Massachusetts Wind Energy Center, January 2018. [Online]. Available: University of Massachusetts Wind Energy Center.

[32] Natural Resources Canada, January 2018. [Online]. Available: https://www.nrcan.gc.ca/energy/software-tools/7465.

[33] iHoga, [Online]. Available: https://ihoga-software.com/en/caracteristicas/.

[34] S. Mandelli, "Strategies for access to energy in developing countries: methods and models for off-grid power systems design," Italy, 2016.

[35] R. F. Hamilton, "The summation of load curves," *Electrical Engineering* , vol. 63, no. 10, pp. 729-735, 1944.

[36] S. Rusck, "The simultaneous demand in distribution network supplying domestic consumers.," *ASEA Journal,* vol. 10, no. 13, pp. 59-61, 1956.

[37] N. L. S. K. Johnson, "Distributions in Statistics: Continuous Unvariate Distributions," *Houghton Mifflin,* vol. 1, 1970.

[38] C. T. S. A. S. C. J.A Jardini, "Measurements, Determination of the Typical Daily Load Curve for Residential Area based on Field," in *IEEE Proceedings Supplements, T&D 94*, 1994.

[39] S. M. E.-D. a. N. E. H. M. S. Kandil, "Long-term load forecasting for fast developing utility using a knowledge-based expert system," *IEEE Transactions on Power Systems,* vol. 17, no. 2, pp. 491-496, 5 2002.

[40] H. W. E. K. C. B. B. E. Frédéric Fettweis, "Angola Municipal Atlas".

[41] S. Rajanna, "Modeling of integrated renewable energy system for electrification of," *Renewable Energy,* vol. 90 , pp. 175-187, 1 2016.

[42] C. B. E. C. M. M. Stefano Mandelli, "Effect of load profile uncertainty on the optimum sizing of off-grid PV," *Sustainable Energy Technologies and Assessments* , vol. 18, pp. 34-47, September 2016.

[43] N. D. o. W. (DNA), "A Rapid Water Resources and Water Use Assessment for Angola," 2005.

[44] D. o. E. a. W. -. Angola, "The National Energy Security Strategy and Policy," 2011.

[45] D. o. W. a. E. -. Angola, “Angola Energia 2025,” 2015.

[46] AGRIX, “Report on the Agroangola fair and a field trip to the Malanje region,” Angola, 2015.

[47] I. N. d. E. d. Angola, 2014. [Online]. Available: http://www.ine.gov.ao/xportal/xmain?xpid=ine.

[48] W. Bank, 2017. [Online]. Available: http://data.worldbank.org/country/angola.

[49] Food and Agriculture Organisation of the United Nations, World Food Programme, “CROP AND FOOD SUPPLY ASSESSMENT MISSION TO ANGOLA,” 1998.

[50] M. S. S. P. N. V. Srđan Kostić, “Modeling of river flow rate as a function of rainfall and temperature using response surface methodology based on historical time series,” *Journal of Hydroinformatics,* pp. 1-15, January 2016.

[51] GAUFF engineering, June 2014. [Online]. Available: http://www.gauff.net/fileadmin/daten/Pressespiegel/EN/20140601_Universo_GAUFF_lo.pdf.

[52] V. I. G. D. H. L. Bosmans A, “The crucial role of Waste-to-Energy technologies in enhanced landfill mining: a technology review,” *Journal of Cleaner Production,* vol. 55, pp. 10-23, September 2015.

[53] D. Cirne, “Evaluation of biological strategies to enhance hydrolysis during anaerobic digestion of complex waste. Biotechnology,” 2006.

[54] L. A. B. L. B. L. Cirne DG, “Hydrolysis and microbial community analyses in two-stage anaerobic digestion of energy crops,” *Journal of Applied Microbiology,* vol. 103, pp. 516-527, September 2007.

[55] Waste-to-energy research and technology council, “Wet Anaerobic Digestion Plant,” July 2017. [Online]. Available: http://wtert.eu/default.asp?Menue=13&ShowDok=43.

[56] Biopact Team, “Growcom trials commercial biogas production from banana waste—high potential yields,” 2008.

[57] J. F. H. M. O. a. O. H. Robert Gumisiriza, “Biomass waste-to-energy valorisation technologies: a review case for banana processing in Uganda,” *Biotechnology for Biofuels,* vol. 10.1, January 2017.

[58] A. A. L. D. Francis Kemausuor, “Technical and Socioeconomic Potential of Biogas from Cassava Waste in Ghana,” *Biotechnology Research International,* vol. vol. 2015, p. 10 pages, July 2015.

[59] S. W. V. K. Ana M. Rosso Ceróna, “Generation of Electricity by Plant Biomass in Villages of the Colombian Provinces: Chocó, Meta and Putumayo,” *CHEMICAL ENGINEERING TRANSACTIONS,* vol. 43, pp. 577-582, 2015.

[60] A. B. B.A. Adelekan, “Comparison of biogas productivity of cassava peels mixed in selected ratios with major livestock waste types,” *African Journal of Agricultural Research,* vol. 4, pp. 571-577, July 2009.

[61] U. S. N. P. Chananchida Nathoa, “Production of Hydrogen and Methane from Banana Peel by Two Phase Anaerobic Fermentation,” *Energia Procedia ,* vol. 50, pp. 702-710, 2014.

[62] E. Electric, “40kW Micro-hydrokinetic turbine - Francis Turbine,” 2017.

[63] L. Shenzhen Xinhonghua Solar Energy Co., “1kW Solar PV panel,” 2017.

[64] F. E. M. LtD, “500kW Biofuel Generator,” 2017.

[65] A. Vans, September 2017. [Online]. Available: https://www.anchorvans.co.uk/specifications/toyota/dyna/.

[66] A. C. P. B. J. Rudi Henri Van Els, “The Brazilian experience with hydrokinetic turbines,” in *7th International Conference on Applied Energy*, 2015.

[67] E. K. E. B. R. P. Hossain, “Microgrid testbeds around the world: State of art,” *Energy Convers. Manag. ,* vol. 86, p. 132–153, 2014.

[68] B. McNair and P. Abelson, “Estimating the Value of Undergrounding Electricity and Telecommunications Networks,” *Austrialian Economic Review,* vol. 43, no. 4, pp. 376-388, 2010.

[69] C. Mostert and K. Richards, “Cost effective rural and reticulation telecontrol systems for developing countries,” in *AFRICON '92 Proceedings., 3rd AFRICON Conference*, 1992.

[70] K. P. Vijayaragavan, “Feasibility of DC Microgrids for Rural Electrification,” 2017.

[71] A. Inversin, “Mini-Grid_Design_Manual,” 2000.

[72] C. Brown, “Effect of conductor size on the total cost of electrical distribution feeders in South Africa,” 2006.

[73] SIEMENS, “Planning of Electric Power Distribution - Technical Principles”.

[74] IEEE Std 1547.4-2011, “IEEE Std 1547.4-2011,” 2011.

[75] The Aluminium Association, Aluminium Conductor Handbook, Third Edition ed., Washington DC: The Aluminium Association, 1989.

[76] Midal Cable, December 2017. [Online]. Available: https://www.midalcable.com/sites/default/files/ACSR-metric.PDF.

[77] J. V. J. D. K. J. G. L. V. T. Vandoorn, “Microgrids: Hierarchical Control and Overview of the Control and Reserve Management Strategies,” *IEEE Industrial Electronics Magazine,* no. 13, p. 42, December 2013 2013.

[78] R. S. G. C. B. R. Leao, “J. Almada, A centralised and heurstic approach for energy management of an AC microgrid,” *Renewable Energy Reviews,* vol. 60, pp. 1396-1404, July 2016.

[79] M. L. L. Z. W. Huang, “Survey on Mircogrid strategies,” *Energy Proceedia,* vol. 12, pp. 206-212, October 2012.

[80] D. M. H. J. H. P. P. Y. Liu Xiaoping, “Dynamic Economic Dispatch for Microgrids Including Battery Energy Storage,” in *IEEE International Symposium on Power Electronics for Distributed Generation Systems*, 2010.

[81] W. S. ,. R. G. W. K. Eun-Kyu Lee, “Design and Implementation of a Microgrid Energy Management System,” *Sustainability,* vol. 8, pp. 1-19, August 2016.

[82] S. S. P. M. K. S. Noel Augustine, “Economic Dispatch for a Microgrid Considering Renewable Energy Cost Functions,” in *Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES*, Washington, DC, 2010.

[83] R. S. G. C. B. R. Leao, “A centralised and heuristic approach for energy management of an AC microgrid,” *Renewable and Sustainable Energy Reviews,* vol. 60, pp. 1396-1404, July 2016.

[84] American Wire Group, December 2017. [Online]. Available: http://www.buyawg.com/contact-american-wire-group.html.

[85] Alibaba.com, September 2017. [Online]. Available: https://www.alibaba.com/.

[86] O. L. Road-Sea-Air, September 2017. [Online]. Available: http://www.orionlogistics.co.za/index.php/en/contact.

[87] F. -. A. F. R. I. systems, September 2017. [Online]. Available: https://www.feedipedia.org/node/527.

[88] C. E. -. B. P. Plans, September 2017. [Online]. Available: http://www.claverton-energy.com/owning-and-operating-costs-of-waste-and-biomass-power-plants.html.

[89] K. B. Omar Hefez, “Optimal planning and design of a renewable energy based supply system for microgrids,” *Renewable Energy*, vol. 45, pp. 7-15, July 2012.

[90] R. H. J.Tomei, “Food versus Fuel? Going beyond biofuels,” *Land Use Policy,* vol. 56, pp. 320-326, November 2016.

[91] U. Nations, September 2000. [Online]. Available: http://www.un.org/millenniumgoals/.

[92] U. N. (. D. Goals), September 2015. [Online]. Available: http://www.un.org/sustainabledevelopment/sustainable-development-goals/ .

[93] P. O. d. G. d. R. d. Angola. [Online]. Available: http://www.governo.gov.ao/.

[94] M. S. PURSER, "A TECHNICAL AND ECONOMIC FEASIBILITY STUDY OF IMPLEMENTING A MICROGRID AT GEORGIA SOUTHERN UNIVERSITY," Statesboro, Gerogia, 2014.

[95] L. Ljung, System identification, 2nd ed., J. Gwyn, Ed., New Jersey: Pearson Education, 1999.

[96] W.Gilchrist, Statistical Modelling, London: Wiley, 1984.

[97] P. N. P. McCullah, Generalised Linear Models, 1st ed., London: Chapman & Hall, 1983.

[98] S. W. V. M. S. Makridakis, Forecasting: Methods and Applications, 2nd ed., John Wiley & Sons, 1983.

[99] C. M. Haanyika, "Rural electrification policy and institutional linkages," *Energy Policy,* vol. 34, pp. 2977-2993, July 2006.

[100] W. K. Stephen Karekezi, "Renewable energy strategies for rural Africa: is a PV-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-Saharan Africa?," *Energy Policy,* vol. 30, pp. 1071-1086, 2002.

[101] I. Bugaje, "Renewable energy for sustainable development in Africa: a review," *Renewable and Sustainable Energy Reviews,* vol. 10, pp. 603-612, November 2004.

[102] J. D. Kramer and C. Jacky, "How to write biblos," vol. 1, no. 1, 2006.

[103] V. T. N. R. N. P. H. M. Sam Koohi-Kamali, "Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review," *Renewable and Sustainable Energy Reviews,* vol. 25, pp. 135-165, May 2013.

[104] C. A. o. t. 1. S. A. Parliament, June 2017. [Online]. Available: http://www.gov.za/documents/constitution/chapter-2-bill-rights#10.

[105] H. Winkler, "Energy policies for sustainable development in South Africa," *Energy for Sustainable Development,* vol. 11, no. 1, 2007.

[106] R. Herman, "Voltage Regulation analysis for the design of low voltage networks feeding stochastic domestic electrical loads," 1993.

[107] K. M. J. C. C. Oliveira, "A new method for the computation of technical losses in electrical power systems," in *16th International Conference and Exhibition on Electricity Distribution*, London , 2001.

[108] R. H. M. D. R. S. S. H. CT Gaunt, "Data collection, load modelling and probabilistic analysis for LV domestic electrification," in *International Conference on Electricity Distribution (CIRED)*, Nice, 1999/6.

[109] D.-R. Thiam, “Renewable decentralized in developing countries: Appraisal from microgrids project in Senegal,” *Renewable Energy,* vol. 35, no. 8, pp. 1615-1623, August 2010.

[110] P. Umbrella, “Report on uncertainty modelling,” 2013.

[111] D. Palit and A. Chaurey, “Off-grid rural electrification experiences from South Asia: Status and best practices,” *Special issue on off-grid electrification in developing countries,* vol. 15, no. 3, pp. 266-276, September 2011.

[112] COBA Group, “CAMBAMBE HYDROPOWER DEVELOPMENT - POWER STRENGTHENING,” Angola, 2011.

[113] C. L. G. J. C. M. António Pereira da Silva, “Focus on Angola,” December 2005. [Online]. Available: http://www.waterpowermagazine.com/features/featurefocus-on-angola/.

[114] C. T. T. W. S. S. Vincent Okudoh, “The potential of cassava biomass and applicable technologies for sustainable biogas production in South Africa: A review,” *Renewable and Sustainable Energy Reviews,* no. 39, pp. 1039-1052, July 2014.

[115] M. T. K. D. A. M. B. J. M. Muhammad Tahir Khan, “Anaerobic Digestion of Banana Waste, a Potential Source of Energy in Uganda,” in *Biophysical and Socio-economic Frame Conditions for the Sustainable Management of Natural Resources*, Hamburg, 2009.

[116] World Bank Data, 2016. [Online]. Available: http://www.doingbusiness.org/data/exploreeconomies/angola/getting-electricity.

[117] Trading Economics, 2017. [Online]. Available: https://tradingeconomics.com/angola/indicators.

[118] S. T. C.W. Gellings, “Load Management,” in *IEEE Press*, New York, 1987.

[119] W. G. F. I. A. I. R. L. A. P. A. Capasso, “VALIDATION TESTS AND APPLICATIONS OF A MODEL FOR DEMAND-SIDE MANAGEMENT STUDIES IN RESIDENTIAL LOAD AREAS.,” in *Electricity Distribution, 12th International Conference*, Rome, Italy, 1993.

[120] A. Seppälä, “Load research and load estimation in electricity distribution,” Helsinki, 1996.

[121] I. U. o. P. a. D. o. E. E. UNIPEDE, “The study of load curves in electricity supply economics = Manual of Theory and Practical Procedure,” 1973.

[122] J. S. T. Molony, “Briefing - Biofuels, Food and Energy,” *Africa Affairs,* vol. 109/436, pp. 489-498, April 2010.

[123] Y. Abrahams, “Knowledge, Power: Rethinking Climate Change, Energy and Gender in South Africa,” *In Women and Climate Change: Gender CC - Women for Climate justice,* pp. 38-42, 2015.

[124] N. A. J. Hastings, “Statistical distributions; a handbook for students and practitioners.,” 1974.

[125] T. S. T. S. KE Masekoameng, “Household energy needs and utilization patterns in the Giyani rural communities of Limpopo Province, South Africa,” *Journal of Energy in Southern Africa* , vol. 16, no. 3, pp. 4-9, 2005.

[126] D. B. a. J. Schäffler, “The potential contribution of renewable energy in South Africa,” 2006.

[127] United Nations, December 2017. [Online]. Available: https://unstats.un.org/unsd/demographic/sconcerns/housing/default.htm.

[128] General Cable, December 2017. [Online]. Available: https://www.generalcable.com/eu/en/.

[129] Grand Voltage, December 2017. [Online]. Available: http://grandvoltage.ro/en/hersatene/146-hersatene-endesa-rhz1-ol-1830-kv-h16-al-1830-kv.html.