Community Distributed Energy Systems:
An End-User Energy Services Approach

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Declaration

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Abstract

In this study, a discomfort level framework is defined as a metric to interpret the improvement in energy services satisfied by different supply technology combinations. Generic distributed energy supply technologies including solar PV, wind power, small scale concentrating solar power (CSP), battery storage, diesel generators and solar water heaters were simulated (using hourly solar and wind resource data) to satisfy end-user energy services. To account for the unique nature of each residential community, a discomfort level was defined for the purpose of this study as an indicator to assess the ability of the supply technologies to satisfy energy services. The discomfort level is formulated based on the demand shortfall unique to the supply technology, the priority of end-use energy services from the user's perspective and the energy service usage at each hourly interval. The model was applied to three residential communities including (i) eShushu a conceptual community, (ii) an urban informal settlement in Thembelihle, Johannesburg and (iii) a residential community on Likoma Island, Malawi. The discomfort levels were compared to the levelised cost of electricity (LCOE) for each of the cases and it is evident that the same technology combinations offer unique discomfort levels for each community. In addition to this, specifying the energy services unsatisfied at each hour by different supply technologies, provides an opportunity for complimentary energy storage and energy efficiency technologies. Although comparing the discomfort levels to the LCOE often leads to a trade-off between the two, such an end-user approach offers the energy planner insight into the unique needs of the community when selecting distributed energy supply infrastructure key to socio-economic development and potentially the adoption of renewable energy technologies in developing countries.

Uittreksel

In hierdie studie word 'n ongemaklikheidsvlak verwysingsraamwerk gedefinieer as ŉ maatstaf vir die verbetering in energiediensverskaffing van verskillende tegnologie kombinasies. Generiese verspreide energievoorsieningstegnologieë, insluitend fotovoltaïese sonpanele (PV), windkrag, kleinskaalse gekonsentreerde sonkrag (CSP), batterye, diesel kragopwekkers en sonwaterverhitters is gesimuleer (met behulp van uurlikse son- en wind data) om die eindverbruiker se energiediensbehoefte te bevredig. Die unieke aard van elke residensiële gemeenskap is in ag geneem deur ongemaklikheidsvlakke te definieer sodat die vermoë van die energievoorsieningstegnologieë om die vereiste vraag na energiedienste te bevredig geëvalueer kan word. Die ongemaklikheidsvlakke is saamgestel op grond van die vraag tekort uniek aan die energievoorsieningstegnologie, die prioriteit vir energiedienste van die eindverbruiker en die energiediensverbruik vir elke uurlikse interval. Die model is toegepas op drie residensiële gemeenskappe, naamlik (i) eShushu, ŉ konseptuele gemeenskap, (ii) 'n stedelike informele nedersetting in Thembelihle, Johannesburg en (iii) 'n residensiële gemeenskap op Likoma Eiland, Malawi. Die ongemaklikheidsvlakke is vergelyk met die eenheidsverwysings waarde van energie (LCOE) vir elkeen van die gevallestudies en dit is duidelik dat dieselfde tegnologie kombinasies 'n unieke ongemaklikheidsvlak vir elke gemeenskap bied. Verder, deur die energiedienste wat nie in elke uur deur die verskillende energievoorsieningstegnologieë voorsien kon word nie te spesifiseer, bied 'n geleentheid vir komplimentêre batterye en energiedoeltreffendheid tegnologieë. Alhoewel die vergelyking van die ongemaklikheidsvlakke met die LCOE dikwels tot 'n kompromie lei, kan 'n eindverbruikersbenadering die energiebeplanner insig gee tot die unieke behoeftes van ŉ gemeenskap in die keuse van verspreide energievoorsieningstegnologieë, wat belangrik is vir sosio-ekonomiese ontwikkeling en moontlik ook vir die opneem van hernubare energie tegnologieë in ontwikkelende lande.

To a brave and beautiful 89 year old woman, Elizabeth Nyanisi Mabaso.

I stand in awe of you.

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Nomenclature

Symbol	**Description**	**Units**
η_i	AC wiring and inverter efficiencies	-
ρ	Air density	kg/m^3
θ	Angle of incidence	
A	Aperture area	m^2
h_h	Aperture height	m
h_w	Aperture width	m
D	Average daily load demand	kWh
P_c	Battery capacity	kWh
η_{batt}	Battery efficiency	%
η_{rt}	Battery roundtrip efficiency	%
C_{bw}	Battery wear cost	R/kWh
C_{pmax}	Beltz limit (0.59)	–
r	Blade length	m
$CF_{solarPV}$	Capacity factor of solar PV	-
η_{cell}	Cell efficiency	–
C_A	Collector array	m^2
η_c	Collector efficiency	-
C_Y	Collector yield	kWh/m^2
N	Day of the year	days
δ	Declination angle	radians
D_d	Depth of discharge	%
Q_{rec}	Design thermal energy from receiver to turbine	W$_{th}$
I_d	Diffuse horizontal irradiation	W/ m^2
I_b	Direct normal irradiation	W/ m^2
DNI	Direct normal irradiation	W/ m^2
r	Discount rate	%
k	Diversity factor	-
$\dot{m}_{draw}$	Draw rate	m^3/s
ρ	Effective ground reflectivity	–
P_G	Electrical power output	kW
E	Electricity generated	Wh
E_i	Energy consumption	kWh
EOT	Equation of time	minutes
x	Equation of time angle	radians
A_{ap}	Field aperture area	m^2
$\eta_{FieldOp}$	Field optical efficiency	–

α	Fixed tilt angle	radians
η_{DG}	Generator efficiency	%
I_g	Global horizontal irradiation	W/ m^2
S_R	Global horizontal irradiation	kWh/m^2
ρ	Ground reflectance	
C_p	Heat capacity	kWh/m^{2}K
h_a	Heliostat availability	_
h_f	Heliostat fouling	_
h_r	Heliostat reflectivity	_
ω	Hour angle	radians
v	Hourly velocity	m/s
$Hours_{TESS}$	Hours of TESS	hours
I	Incident power density	W/ m^2
η_{inv}	Inverter efficiency	_
η_i	Irradiation efficiency	_
L	Latitude angle	radians
L	Length per panel	m
$Q_{lifetime}$	Lifetime throughput of a single battery	kWh
LHV_{fuel}	Lower heating value of diesel fuel	MJ/kg
M	Maintenance	-
ΔC	Marginal change	-
$\dot{m}$	Mass flow rate of fuel	kg/hr
R_{max}	Maximum charge rate	%
D_m	Maximum demand	kWh
D_{dmax}	Maximum depth of discharge	%
P_{max}	Maximum power output (rated)	W
v_1	Min operating velocity	m/s
C_p	Modified coefficient of performance	_
N_{batt}	Number of batteries in battery bank	-
n	Number of consumers	-
N_{mod}	Number of modules	modules
O	Operation	-
η_0	Outage rate	-
P_{out}	Output Power	W
h	Panel height	m
α	Panel tilt angle	radians
η_{pb}	Power block efficiency	_
v_r	Rated velocity	m/s
P_{mod}	Rating per module string	kW

η_{Rec}	Receiver efficiency	–
η_{RecOp}	Receiver optical efficiency (solar to thermal)	–
$Q_{re,TESS}$	Receiver thermal energy with TESS	W_{th}
$C_{rep,batt}$	Replacement cost of battery	R
r	Resource quality	W/ m^2
y	Sign factor (-1, 0, 1)	_
φ	Solar azimuth angle	radians
SM	Solar multiple	_
SE	Solar thermal energy yield	kWh/m^2
LCT	Solar time	hours
t_s	Standard time	hours
A_{swept}	Swept area	m^2
E_d	System demand	Wh
η_{sys}	System efficiency (piping, storage)	-
η_{temp}	Temperature efficiency	_
Φ	Tilt azimuth	radians
t	Time	year
$Q_{delivered}$	Total heat capacity of storage tank	kWh
I_t	Total incident radiation	W/ m^2
η_{teff}	Turbine efficiency	_
$P_{turbine}$	Turbine rating	W
P_u	Useable capacity	kWh
w	Width per panel	m
ϑ_z	Zenith angle	radians

Abbreviations/ Acronyms

ADMD	After Diversity Maximum Demand
AHP	Analytical Hierarchy Process
BCR	Benefit Cost Ratio
BOP	Base of the Pyramid
CBA	Cost Benefit Analysis
COUE	Cost of Unserved Electricity
CPC	Compound Parabolic Collector
CPI	Consumer Price Index
CSIR	Centre for Scientific and Industrial Research
CRSES	Centre for Renewable and Sustainable Energy Studies
CSP	Concentrating Solar Power
DEA	Department of Environmental Affairs
DES	Distributed Energy Systems
DNI	Direct Normal Irradiation
DI	Discomfort Index
DoE	Department of Energy
DST	Department of Science and Technology
ERC	Energy Research Centre
ESMAP	Energy Sector Management Assistance Program
ESA	Energy Systems Analysis
FBE	Free Basic Electricity
FOM	Fixed Operations & Maintenance
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiation
GVA	Gross Value Added
GHG	Greenhouse Gas
GW	Gigawatt

HFC	Heliostat Field Collector
HTF	Heat Transfer Fluid
ICES	Integrated Community Energy Systems
IDC	Industrial Development Corporation
IEA	International Energy Agency
I-O	Input-Output
IPP	Independent Power Producer
IRP	Integrated Resource Plan
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt hour
LFR	Linear Fresnel Reflector
LCOE	Levelised Cost of Electricity
LSM	Living Standard Measure
MCDM	Multi-Criteria Decision Making
MEPI	Multi-Criteria Energy Poverty Index
MJ	Megajoule
MPPT	Maximum Power Point Tracking
MTF	Multi-Tier Framework
MVOE	Marginal Value of Electricity
MW	Mega Watt
NDP	National Development Plan
NERSA	National Energy Regulator of South Africa
NIC	Newly Industrializing Country
NPC	Net Present Cost
NPV	Net Present Value
NRECA	National Rural Electric Cooperative Association
NREL	National Renewable Energy Laboratory
NSWHP	National Solar Water Heating Programme

PDC	Parabolic Dish Collector
PSS	Power Systems Simulation
PTC	Parabolic Trough Collector
PV	Photovoltaic
RAE	Royal Academy of Engineering
RE	Renewable Energy
REDZs	Renewable Energy Development Zones
REI4P	Renewable Energy Independent Power Producer Procurement Program
REPS	Renewable Energy Postgraduate Symposium
SACN	South African Cities Network
SANEA	South African National Energy Association
SAPP	Southern African Power Pool
SD	Systems Dynamics
SDGs	Sustainable Development Goals
SE4ALL	Sustainable Energy for All
SEA	Sustainable Energy Africa
SEF	Social Enterprise Fund
SS-CSP	Small Scale CSP
SU	Stellenbosch University
SNA	System of National Accounts
SROI	Social Return on Investment
STERG	Solar Thermal Energy Research Group
SPL	School of Public Leadership
TESS	Thermal Energy Storage System
TOU	Time of Use
TSO	Transmission System Operator
TWh	Terrawatt hour
UN	United Nations

UNIDO	United Nations Industrial Development Organisation
USD	US Dollars
USDA	United States Department of Agriculture
VA	Value Analysis
VE	Value Engineering
VOM	Variable Operations & Maintenance
WASA	Wind Atlas for South Africa
WRI	World Resources Institute
WTP	Willingness To Pay
WWF	World Wildlife Fund For Nature
ZAR	South African Rand

1 INTRODUCTION

"[At the end of life], you can let a lot of the rules that govern our daily lives fly out the window. Because you realise that we're walking around in systems in society, and much of what consumes most of our days is not some natural order. We're all navigating some superstructure that we humans created."

- BJ Miller, *Tools of Titans*, 2016

1.1 Background

This study considers local solutions using distributed energy systems methods within the context of developing countries, specifically Sub-Saharan Africa. The International Energy Agency (IEA) (2014) estimates that 620 million of 915 million people in Sub-Saharan Africa did not have access to electricity in 2014. Energy access contributes to socio-economic development and is a potential enabler for household use, productive uses, and community activities (SE4ALL & ESMAP, 2015a). In support of this view, Hirmer and Cruickshank (2014: 146) explain that rural electrification schemes "improve living standards; increase income through income generating activities; and improve community services through education and healthcare". Ironically, amidst its energy challenges, the Sub-Saharan African region is wealthy in primary energy resources such as coal, gas, geothermal, hydro, solar, and wind resources (ACORE, 2015).

In order to support socio-economic development and increasing energy demand in Sub-Saharan Africa, there is a need for nationally co-ordinated capacity expansion including transmission and distribution in the power sector (IRENA, 2016a). Some arguments in literature by, amongst others, Ahuja and Tatsutani (2009); Bhattacharyya and Timilsina (2010); Urban et al. (2007); and Van Ruijven et al. (2008) and Jaglin (2014) suggest that developing countries are not only faced with energy security issues such as mounting environmental concerns and energy price volatility, but also the challenges associated with each country's context. Jaglin (2014) for example explains that service delivery challenges in developing countries are often attributed to poor governance and regulations but further argues that the conventional centralised network-based approach to service delivery is non-responsive to the demand in developing countries. Several literature sources (Castellano, Kendall, Nikomarov & Swemmer, 2015; IRENA, 2016a; Urban, 2009) assert that as a result of the ability of renewable energy to supply energy at the point of use; and declining renewable energy technology costs, efforts to improve energy security in developing countries should include a combination of a centralised national development energy planning approach and decentralised distributed renewable energy systems. Distributed or decentralised energy sources (DES) include generation, storage and control technologies not directly reliant on high voltage electricity or gas grids with the ability to deliver power at the point of use (Carson, Davies, Shields, Jones & Hillgarth, 2008).

Unlike industrialised countries which capitalised on the economies of scale from fossil fuel extraction-based centralised energy planning, developing countries are confronted with the trade-offs between decentralised energy provision and centralised national energy planning (Jansen & Seebregts, 2010). According to Nerini et al. (2016) cost-effective options to be considered for energy planning in developing countries include an energy mix of grid-based systems, stand-alone and mini-grid systems. Grid-based systems are able to either connect or disconnect from a grid network; stand-alone systems are autonomous from the grid network and function as island energy systems; and mini-grid systems include interconnected loads and supply sources which function in grid-based or stand-alone modes (IRENA, 2016a). Although Nerini et al. (2016: 1) strongly maintain that the same local approaches and solutions are seldom applicable to different regions, the same suggest that common key considerations for the scale of energy systems include "(i) target level and quality of energy access, (ii) population density, (iii) local grid connection characteristics and (iv) available local energy resources and technology cost". Energy services refer to the applications for which energy is consumed such as heating, lighting and cooking to name a few (Tomaschek, Dobbins, Fahl & Province, 2012). Van Ruijven et al. (2008) in critique of global energy models, are in agreement with Bhattacharyya and Timilsina (2010) and suggest that the key distinguishing issues for developing countries include (i) the use of traditional fuels and limited access to modern energy services, (ii) the role of the informal economy and income distribution, (iii) resource shortages and climate change as the context for development; and (iv) the differences between rural and urban areas.

Apart from the centralised utility energy supply model, there are examples of 'on the ground' energy system interventions or what Mchenry and Doepel (2015) refer to as the 'low power revolution' designed in response to unique communities and development challenges. Energy supply at a decentralised scale is better suited to such a context but Van der Walt et al. (2015) argue that innovation in the approach especially with regards to the financial sustainability of this type of project is required given that such communities typically have low incomes. A household survey conducted by Van der Walt et al. (2015) in rural Eastern Cape, South Africa also shows that a significant number of people in this community are willing to travel long distances at high costs of time and money for services such as mobile phone charging. An example of an 'on-the-ground' energy system piloted in the Eastern Cape Province of South Africa is the Solar Turtle (Van der Walt, 2013), a solar photovoltaic (PV) kiosk container with a 'theft-proof' mechanical design for micro-utility rural electrification. Another example is the iShack Project (Mchenry & Doepel, 2015) which sells household solar PV home systems to residents of an urban informal settlement in Stellenbosch, South Africa where the community receives limited service delivery from the local government (Ambole, Swilling & M'Rithaa, 2016). Other examples of distributed energy solutions in communities with low buying power have taken advantage of mobile phone payments for end users with limited access to capital and savings with projects in Kenya, Uganda and Tanzania by companies such as M-Kopa, RVE.SOL and Off-Grid Electric (Mulder, 2016).

Although the 'on the ground' energy system interventions introduced in the background are recognised, these still appear to be disconnected from the top-down national government led energy planning activities. This leaves room for a method to consider such interventions not only as emerging bottom-up concepts only implemented as pilot studies but opportunities for modelling of distributed energy systems offering valuable lessons into the complex challenges of collecting data about end-use energy services, revenue models and key energy-related development criteria to plan for small-scale energy systems. In light of these challenges, modelling of energy systems is key to understanding the policy options available to policy makers specifically with regards to supply infrastructure of distributed energy systems not only in rural areas but also increasingly in urban residential areas.

1.2 Research Question and Motivation

The thesis statement (hypothesis) for this study is:

Developing countries in the 21st century have unique energy needs and energy planners should therefore make use of relevant approaches to model distributed energy systems specifically at community scale for these countries.

1.2.1 The Research Question

This hypothesis leads to the main research question for this study which is:

What are the approaches of quantitatively evaluating community scale energy systems such that the choice of technology combinations offers an improvement in terms of (i) satisfying the end-user's energy service needs, and (ii) representing a high penetration of distributed and renewable energy supply technologies in a developing country context?

The sub-questions from the main question include

i. What are the unique energy needs of developing countries?
ii. Which energy modelling and evaluation approaches are currently in use?
iii. Does the increasing availability and affordability of renewable energy technologies by default provide improvement in satisfying the end-user's energy service needs and can this be evaluated to find good solutions?
iv. Is it feasible to use energy services satisfied as a proxy to evaluate the value (qualitative) to the user and therefore broader developmental needs of the user?
v. Does the explicit use of energy services to represent demand in place of electricity in kilowatt hours (kWh) influence the selection of supply technology combinations?

1.2.2 Motivation for the Research Question

Planning an energy system specifically in a developing country, is riddled with the triple challenge of (i) improving energy security for socio-economic development whilst adhering to (ii) global environmental pressure to reduce carbon intensive industry emissions and (iii) finding cost effective solutions applicable to the socio-economic conditions and available resources. The question then surrounds the appropriate path of transition towards a sustainable growth trajectory, the types of technologies procured, the capacity required and the regions where these technologies are placed. These are some of the challenges that energy policymakers face, together with the challenge of: growing population rates mostly in the urban setting; resource constraints such as water shortages; and ageing infrastructure, amongst others (SEA, 2015).

First, one of the main recurring themes describes the challenges specific to the current era or what Pfenninger, Hawkes and Keirstead (2014) refer to as ‘twenty-first century energy challenges’. Twenty-first century energy models have to cope with the challenge of *“(i) resolving time and space, (ii) balancing uncertainty and transparency, (iii) addressing the growing complexity of the energy system, and (iv) integrating human behaviour and social risks and opportunities”* (Pfenninger *et al.*, 2014: 1).

Second, the challenges unique to developing countries are a key issue for energy modelling. From literature it is clear that the complex energy-related challenges in developing countries are unique and that energy modelling is a valuable tool for energy planning in such a context. The recurring concern raised is that energy systems models often fail to capture the informal sector, income distribution variations, levels of electrification, the differences between rural and urban sectors, development in the context of resource shortages, climate change, and the availability of data (Ahuja & Tatsutani, 2009; Van Beeck, 2003; Bhattacharyya & Timilsina, 2010; Kehrer, Kulin, Lemay & Wells, 2008; Keirstead, Jennings & Sivakumar, 2012; Schaeffer, 2013; Urban *et al.*, 2007).

Third, the challenge of modelling for a less fossil-fuel intensive energy system has raised questions which many established models were not designed to answer. A question for many is how best to integrate renewable energy technologies given their distinct behaviour. Traditionally, fossil-fuel or nuclear based energy systems could be modelled as either baseload or dispatchable by an operator. However this is not a reasonable assumption for renewable energy due to its variability through space and time (Pfenninger *et al.*, 2014).

Following from the three main challenges outlined, there exists a need for unique energy modelling tools and approaches that (i) account for local energy needs and resources, and (ii) allow for the integration of renewable and distributed energy supply technologies.

This study seeks to develop a modelling framework to evaluate different energy technology combinations in decentralised energy systems by its ability to meet the end user’s needs. This approach was selected because energy systems like the Solar Turtle or iShack are linked to broader socio-economic development challenges for low income areas and the business models of such projects are as Hirmer and Cruickshank (2014) predict, shifting from the traditional donor model to a market-based approach. However, Sustainable Energy for All (SE4ALL) (2015a) argues that energy studies assessing energy access of households in developing countries typically assess a household’s access to energy in a binary manner (ie. a household either has access or not). To address this, SE4ALL (2015a) points out that a household’s access to energy is not one-dimensional and suggests that a multi-tier framework satisfying multiple criteria including quality, capacity, reliability and affordability be used to assess a household’s access to energy in developing countries. (PwC, 2016).

The motivation for developing a framework for evaluating energy technology combinations according to the ability to satisfy end user energy services rests upon the view supported by Hirmer and Cruickshank (2014) that an energy system for a developing country context such as rural electrification has an extrinsic value. This means that electrification in such a setting is not an end to itself for the user because it provides instrumental value that leads to further outputs (Hirmer & Cruickshank, 2014). From the supply side, typical indicators from literature include Levelised Cost of Electricity (LCOE), reliability, emissions and fuel savings (Murphy, Twaha & Murphy, 2014). However, the actual benefit as perceived by the user on the demand side is the level of comfort from having an energy service satisfied at the time, place and in the quantity that it is needed. Zalengera, Blanchard and Eames (2015) are also in support of this view and point out that there is a gap of knowledge for energy technology practitioners to better understand (i) end user satisfaction with services, (ii) the priority of energy services and (iii) the perception of existing technologies. In a separate study Borbonus (2017: 9) expresses the need for, *“an assessment of the adequacy of energy services for an economy”*.

1.3 Research Objectives

The research questions lead to the primary objective of this study, which was to develop a method to quantifiably evaluate and explore the composition of energy supply solutions that lead to improved energy service delivery for a defined community within a larger system. One of the ways of testing the thesis statement is by exploring how an energy system manages to meet energy needs in a developing country context.

In order to meet this objective, the method aims to combine a bottom-up energy system model with a top-down end-user criteria based framework to evaluate or refine the solution. This is accomplished by evaluating multiple decentralised energy systems by way of quantifying the ability to meet end user energy services at each hour of the day. A conceptual ‘discomfort framework’ for the formulation of a discomfort level based on end-user energy services largely influenced by the work by Zalengera, Blanchard and Eames (2015) and Hirmer and Cruickshank (2014) is proposed to explore this research objective.

This is not a selection criteria but rather an end-user value indicator (pre-techno-economic analysis) used to filter different technology combinations with the idea that standard indicators such as LCOE (Levelised Cost of Electricity) and GHG (Greenhouse Gas) emissions can still be calculated for the selected cases.

The sub-objectives to satisfy the method are to

i. Represent the distinct behaviour of renewable and distributed energy supply technologies in an energy system with appropriate spatio-temporal resolution;
ii. Determine the end-user energy services withheld when energy is unserved for various energy supply technology combinations; and
iii. Identify multiple stakeholder priority criteria for evaluating the suitability of such a small scaled energy system project according to the context.

The findings from the study are aimed at both the energy modeller, planner and the energy policy maker.

1.4 Research Methodology

The research method is covered in more detail in Chapter 3. The high-level outline of the methodology is as follows:

i. Identification of problem and objective
ii. Review of relevant and current literature
iii. Development and validation of a bottom-up, spatio-temporal model suitable for the study
iv. Development of a discomfort framework to assess the value of energy services
v. Case study application
vi. Discussion of the method and the case
vii. Conclusions

1.5 Research Limitations

Due to the complex nature of the research question, simplification of the study was deemed necessary to ensure that the research study is adequately bounded. However, this results in limitations to the study. These include:

- A comprehensive systems analysis would have required system dynamics approaches. However, the scope and time did not permit this and the true complexities preclude it under any circumstances.
- A bottom-up approach which allows for good resolution on the provision of energy which can lead to good resolution on how to satisfy energy services was applied. However, energy services needs which are driven by top-down needs are complex and require much more work.

- This study made use of a limited number of methods combined with data proxies to present how the overall combination of methods could lead to quantifiable metrics relevant for a supply-demand mix based on the end-user context.
- Hydropower and biomass were not considered for energy generation because these resources are site specific and are highly dependant on seasonal variations.

1.6 Thesis Outline

This thesis includes eight chapters with a high level outline as follows:

Chapter 1 (Introduction) presents an overview of the study background and research objectives.

Chapter 2 (Literature Review) provides a review of relevant literature related to energy systems analysis approaches, tools and evaluation techniques.

Chapter 3 (Methods) presents the sequential flow of the study design and outlines the high-level research methods and gaps.

Chapter 4 (Evaluation Framework) proposes a conceptual framework for incorporating discomfort levels for energy services not satisfied into the bottom-up supply-demand model.

Chapter 5 (Simulation Description & Test Case) describes the detailed theory and equations applicable to formulating a simplified supply and demand model. This chapter also covers the sequential steps followed in creating and validating a model.

Chapter 6 (Application to Cases) applies the model framework to two cases, an urban informal settlement in Johannesburg and a residential community on an island in Malawi.

Chapter 7 (Discussion) presents a discussion of the model results and identifies key findings.

Chapter 8 (Conclusions and Recommendations) highlights the implications and limitations of the study. This chapter also proposes future work for improvement.

1.7 Chapter Conclusion

This chapter has provided a background and motivation for the research objectives of this study and an outline to help the reader navigate this document. Although presented in a linear structure, the study itself whirls around the question of how to keep the lights on, cook dinner and charge our cellular phones in a changing world.

2 LITERATURE REVIEW

This chapter presents a comprehensive literature survey which includes an overview of some of the factors influencing residential energy demand, various scales of energy supply and renewable energy supply technologies. This is followed by an introduction to energy modelling approaches and tools submitted as part of a journal article (Mabaso, Gauche, van Niekerk & Pfenninger, 2018) titled, "*Addressing energy challenges in newly industrialised economies with freely available modelling tools: the example of South Africa*".

The review at hand provides insight into the essential features of the energy modelling process and existing modelling tools for challenges stemming from the twenty-first century, unique contexts in developing countries and the integration of renewable energy technologies. A topic funnel showing the building blocks of the literature review is provided in Figure 1 for guidance. These topics are expanded on throughout the study.

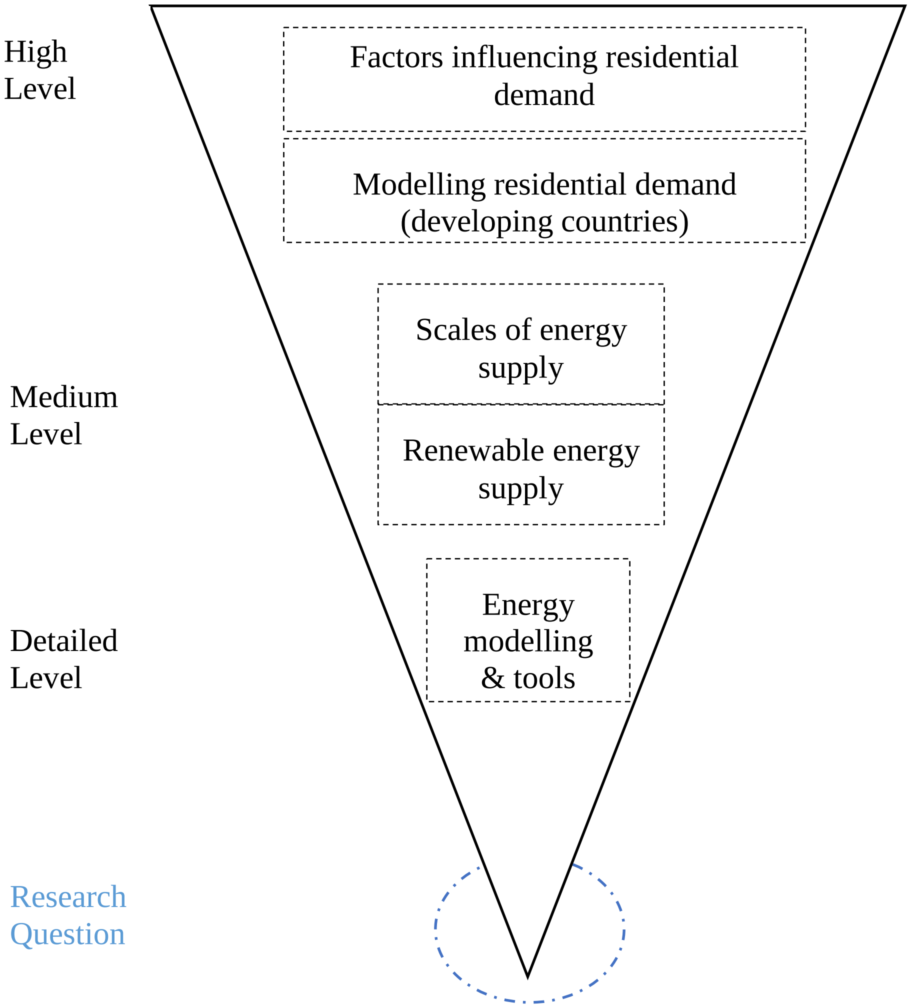

Figure 1: Topic funnel of the literature review

2.1 Factors Influencing Residential Sector Demand

Modelling of energy demand in developing countries is as Bhattacharyya and Timilsina (2010) explain not a straightforward process because of a rural sector that co-exists with a rapidly growing urban sector and a significant informal economy which nullifies some of the assumptions of a neo-classical approach. The implication of the changing economic structures in developing countries has wider implications for energy demand because of the resulting changes in income, lifestyles, the uptake of technology and sustainability issues (Bhattacharyya & Timilsina, 2010). Examples cited of this include India leapfrogging from an agrarian economy straight to a dominant service sector with only a small manufacturing sector (Bhattacharyya & Timilsina, 2010). Some of the literature sources presented here show that (i) energy demand in African countries is expected to rise but currently remains low; and (ii) income and cultural preference are some of the main drivers of residential energy demand whilst the price of electricity retains a less significant influence.

In terms of electricity consumption, the average consumption rate per annum per capita in Sub-Saharan Africa (excluding South Africa) is only 150 kWh which is well below that of other emerging markets such as Brazil and India (Castellano *et al.*, 2015). In addition, approximately 34% of the residential sector in Sub-Saharan Africa was urbanised in 2010 with an average electrification rate of 38%. The urbanised population is expected to shoot up to 52% with an electrification rate of 71% by 2040 (Castellano *et al.*, 2015). The main drivers of an increase in residential demand for electricity include (i) the number of households, (ii) the rate of urbanisation, (iii) the rate of electrification, and (iv) consumption levels per household as a result of income (Castellano *et al.*, 2015).

Inglesi-Lotz and Pouris (2014) conducted a review of the factors influencing energy demand in South Africa and have found that literature does not reach consensus on the issue. However, some of the cases showed that the price of electricity proved to be insignificant or near zero elasticity for energy consumption in the short run. According to Inglesi-Lotz and Pouris (2014) price elasticity is not used by organisations such as the Centre for Scientific and Industrial Research (CSIR) because of the view that (1) price elasticity is too complex to model at national level and (2) at the time of the study in 2014 there were not enough historical trends of the sharp electricity price increases in South Africa.

Senatla (2011) reasons that the residential sector presents a challenge for the modelling process because of the dynamic nature of energy consumption in this sector. One of the reasons cited for this is that energy consumption data for the residential sector is collected through surveys. Senatla (2011) further explains that energy modelling studies often place households into categories, with some of the common categories being location and climate; household type; income type and quintiles amongst others. Amongst these, income is recognised as one of the main drivers of energy demand for the residential sector (Senatla, 2011).

Arthur, Bond and Wilson (2012) point out that it is not entirely correct to assume that income is the sole determinant of energy choice or that the price of energy will increase as the household increases its income. The argument presented by Arthur *et al* (2012) includes evidence from studies that show that biomass can be costlier when compared to kerosene or electricity but also that as a result of the high efficiency of use and subsidies, kerosene is relatively inexpensive on a per unit basis. Arthur et al. (2012) also refer to a survey of households in Ethiopia that shows that kerosene is an affordable source of energy compared to electricity which surpasses the affordability levels of non-poor households.

To add to the inconclusive debate around the drivers of energy choice, Arthur, Bond and Wilson.(2012) refer to another study conducted in Mozambique which shows that households without electricity access spend close to four times more per kWh than grid connected households. The perceptions of cost, safety , cultural preferences and convenience are some of the other factors that drive demand (Arthur *et al.*, 2012). According to the household survey census report by STATS SA (2016) , the primary energy services that South African households use include cooking, heating and lighting. It is estimated that 85% of urban households in South Africa use electricity for cooking (IRENA, 2016b).

2.2 Modelling Residential Demand in Developing Countries

Given the factors influencing demand, it is imperative for this study to survey the approaches used to model residential demand. Constructing a realistic residential demand profile is complex because residential consumption is typically stochastic and often dependant on environmental, occupant and dwelling features (Mcloughlin, Duffy & Conlon, 2010). Much insight is drawn from Bhattacharyya and Timilsina’s (2010) thorough review of literature on the adequacy of energy demand modelling methods to the unique features of developing countries. The pair asserts that the danger of relying on consumption data to model energy demand in developing countries is that only satisfied energy is captured and non-manifested demand is ignored (Bhattacharyya & Timilsina, 2010). A common simple demand forecasting approach is to use indicators and trend analysis (typically growth rates, elasticities, unit consumption and energy intensity). This approach is criticised by Bhattacharyya and Timilsina (2010) for lacking a theoretical background and for ignoring demand drivers. Less simple approaches either make use of top-down econometric models which focus on aggregated levels of demand analysis or bottom-up engineering-economy models which forecast demand based on the end-uses of energy (Bhattacharyya & Timilsina, 2010).

The main critique of econometric methods is that such studies use a representative consumer but some studies address this by making use of a representative consumer per sector (for example by income and location). Household surveys are credited for providing detailed information but the drawback is that this information is mainly insightful for a specific point in time and thus require frequent updates (Bhattacharyya & Timilsina, 2010). Aggregated analysis also does not consider the effects of technology diversity, changes in industry and spatial differences on energy demand (Bhattacharyya & Timilsina, 2010). The end-uses approach to demand forecasting in developing countries is credited for representing the changes in energy use as a result of income and representing local features such a housing stocks, technology choices and consumption behaviour (Bhattacharyya & Timilsina, 2010). However, these models do not reflect market-related price signals. Two bottom-up demand forecasting models (LEAP and MEDEE) and two hybrid models (POLES and WEM) are reviewed by Bhattacharyya and Timilsina (2010). While LEAP and MEDEE are found to be incapable of analysing price-induced policies, POLES and WEM offer no coverage and limited coverage of rural areas respectively (Bhattacharyya & Timilsina, 2010). While LEAP is able to provide a detailed end-use analysis including the uptake of technologies over time, the time step is limited to annual planning.

A significant take-away relevant for modelling energy demand in developing countries is that the results from studies that have adopted an aggregated demand forecasting approach using advanced statistical analysis methods are not significantly different from simple studies, often ignore the role of technology, rely on past demand and more than often conclude that income and not price is one of the primary drivers of energy demand in developing countries (Bhattacharyya & Timilsina, 2010). With reference to scale, Boait, Advani and Gammon (2015) assert that the demand prediction methods applied at national scale are not appropriate at mini-grid scale. Firstly, the variability of demand is higher for a smaller population and secondly that availability of energy consumption data is lower in comparison to national statistics (Boait *et al.*, 2015). In South Africa, a programme called the domestic Load Research (LR) project was launched in 1994 to record domestic electric load behaviour which would inform the government’s electrification services (UCT, 1994).

2.3 Scales of Energy Supply

The scale of energy generation and the type of technologies procured are often both policy-driven depending on the objectives of the national and local government policy for a specific period (Tait, Mccall & Stone, 2014). This section covers literature related to the distinctions at different energy generation and project scales. These include supply at utility scale, renewable energy utility scale, distributed energy technologies, and micro-grids.

2.3.1 Conventional Utility Scale Power Generation

Conventional utility scale power systems typically generate electricity from large centralized plants located near the primary energy source (Busch & Hodkinson, 2015). These generation plants transmit power over high voltage cables over long distances to a local distribution network from where the electricity is distributed to the final consumer as illustrated in Figure 2. The national transmission system is operated by transmission system operators (TSOs) who balance and control dispatch from a number of power stations to meet the demand (load) (Busch & Hodkinson, 2015). Historically, centralized infrastructure came with the benefits of efficient delivery of uniform services to high populations and the lower costs associated with economies of scale (Jaglin, 2014).

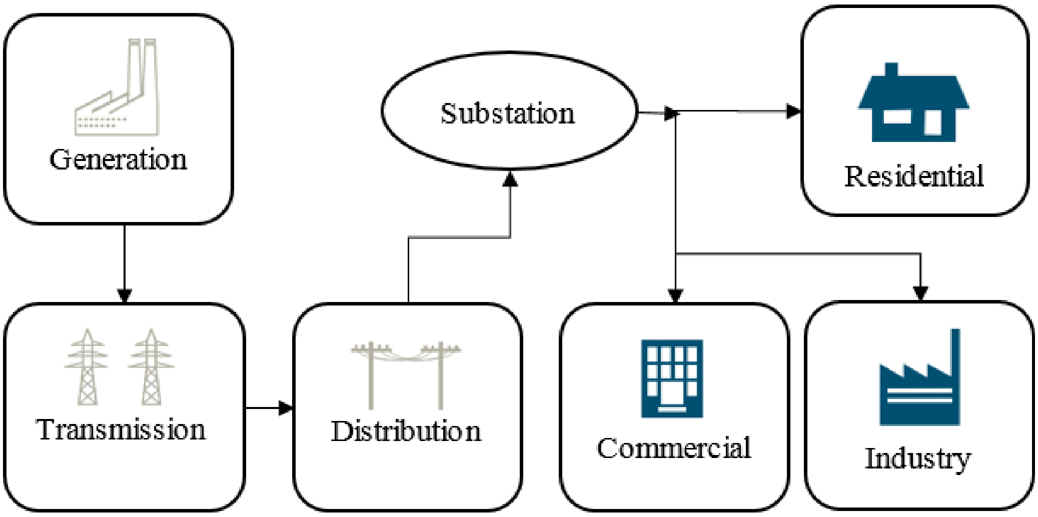

Figure 2: Utility power system adapted from Busch & Hodkinson (2015: 9)

2.3.2 Renewable Energy Utility Scale Generation

Renewable energy power plants include generation plants with a renewable power source such as wind, solar energy, bio-energy, hydropower or a combination in a hybrid system (IRENA, 2016b). There are several classifications of power plants based on scale (Buxton, 2015; IRENA, 2016a). GreenCape (2016) classifies the renewable energy sector in South Africa into three main segments based on scale, namely (1) utility-scale , (2) distributed generation (DG) and (3) embedded generation. Utility scale plants include installations above 5 MW_p while distributed generation installations are less than 5 MW_p (GreenCape, 2016).

South Africa is an example of an emerging economy in Sub-Saharan Africa with a recent high uptake of renewable energy through a nationally co-ordinated procurement programme called the Renewable Energy Independent Power Producer Procurement Programme (REI4P). Some of the listed contributing factors towards the growth of the utility scale renewable energy sector in South Africa include rolling blackouts as a result of constrained electricity supply; increased electricity tariffs charged by the state monopoly energy utility Eskom; and the reduction in global prices for renewables (GreenCape, 2016). In total, the REI4P has procured over 6 300 MW between the first bid in 2011 to the fifth bidding round including solar PV, CSP, onshore wind, biomass, small hydro and landfill gas (GreenCape, 2016). The trends in the South African utility scale renewable energy market show evidence of declining tariffs, increasing local content and increased investment into the development of local skills and manufacturing (GreenCape, 2017). It is estimated that onshore wind has decreased by 45% in price, whilst solar PV tariffs have decreased by 73% making these technologies “the cheapest new-build generation sources” on a R/kWh basis (GreenCape, 2016: 20).

2.3.3 Distributed Energy Generation

A distributed energy system (DES) is defined by Busch and Hodkinson (2015) as a term used in reference to the generation, storage, monitoring and control solutions using distributed generators (DGs) or distributed technologies. Distributed energy generation is distinguishable from utility scale generation by the type and size of generator technologies but distributed energy systems are also deployable at various different scales, including community, city, campus and building project scales (Busch & Hodkinson, 2015). There are various forms of arrangement schemes for distributed energy generation plants such as community networks, informal take-offs, individual installations and mini-grids but all often broadly referred to as 'local level power production plants' as a hybrid of renewable and non-renewable energy sources (Jaglin, 2014). Koirala (2017: 9) goes beyond power production and defines the concept of integrated community energy systems (ICES) as inclusive of "planning, design, implementation, and governance of energy systems at the community level to maximize energy performance while cutting costs and reducing environmental impacts". Although some literature sources (Castellano *et al.*, 2015; Howells, Alfstad, Cross, Jeftha & Bag, 2002; IRENA, 2016a; Montmasson-Clair & Ryan, 2014) suggest that distributed energy systems with a high share of renewable energy are expected to have the highest uptake by rural communities, commercial users and off-grid consumers, there are also examples of distributed energy systems with a high penetration of renewable energy in formal and informal residential urban areas located close to the grid and often with a grid connection (IRENA, 2016b; Keller, 2012; Slann, 2013; Sustainable Energy Africa, 2015).

2.3.4 Mini-Grid Generation

A mini-grid is defined by the US Department of Energy (US DoE) as, "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 a grid to enable it to operate in both grid-connected or 'island' mode" (Hanna, Ghonima, Kleissl, Tynan & Victor, 2017: 48). There are several literature sources (Densmore & Prasad, 2015; Dohn, 2011; Hanna *et al.*, 2017; IRENA, 2016a; R. Martínez-Cid, 2010; Xu, Nthontho & Chowdhury, 2016) which predict that micro-grids will become central to the transformation towards an electricity power system that is decentralised in supply and response. Micro-grids are not an entirely new concept but hybrid micro-grids which make use of a generation mix of energy present new challenges. Renewable energy technologies are relatively new for many countries which means that a process of best practice has not yet been established. For this reason, it is a learning experience for the world. For example, it is reported that Japan's Strategic Energy Plan has placed a focus on distributed energy networks in reaction to the Fukushima earthquake and tsunami which resulted in outages across Eastern Japan (Hanna, Ghonima, Kleissl, Tynan & Victor, 2016).

Micro-grids are attributed with improving the quality and reliability of macro grid services mainly due to the innovations in solar photovoltaic systems, smart metering, energy storage, fuel cells, micro-turbines, electric vehicles and controllers that have led to improvements in demand response and energy efficiency (IRENA, 2016a). However, it is further observed that the development costs associated with micro-grids are high and as a result, these have been easier to implement at three main customer groups; customers, such as hospitals and military bases whose priority of reliability makes them less sensitive to costs; research related initiatives (commonly found on university campuses) and; customers located in remote areas without access to the macro-grid (Hanna *et al.*, 2016). The development costs of micro-grids are also expected to decline with the favourable continuous decrease in the cost of renewable energy technologies, specifically wind and solar PV (IRENA, 2016a). There are also noticeable improvements in the economies of scale for batteries globally (IRENA, 2016a). In a study on mini-grid deployment in Tanzania by the World Resources Institute (WRI) (Odarno, Sawe, Swai, Katyega & Lee, 2017), three main types of models of operation and ownership are explored, namely community, private, utility and faith-based ownership.

Renewable mini-grids are simply hybrid micro-grids based on a share of renewable energy technologies (IRENA, 2016a). One of the main benefits of renewable based mini-grids includes cleaner energy delivered to communities in remote locations far away from the main electricity grid or those faced with unreliable supply of electricity. IRENA (2016a) asserts that small hydropower and biomass power still remain relatively unexploited even though these could potentially act as base load supply sources. Although this means that small hydro and biomass could potentially be able to replace short term storage for mini-grids, these resources are site specific and are highly subject to seasonality (IRENA, 2016a). Two main findings from a study looking at the viability of micro-grids by Hanna et al. (2017) are that micro-grids for systems which are large enough to efficiently combine electric and thermal loads present the strongest business case; and that micro-grid policy intervention is needed the most for the costs charged for renewables.

2.3.5 Other Concepts of Energy Supply Configurations

There are relevant concepts about the configuration of distributed generation with a high uptake of renewable energy technologies moving into the future. Four of these concepts are discussed here including (i) energy democracy, (ii) multiple cells of generation, storage and load; (iii) energy hubs; and (iv) blockchain.

2.3.5.1 Energy democracy

Energy democracy is a loaded concept in energy governance which Szulecki (2018) deconstructs at various levels. It is established that there are three main characteristics which help to define this concept. Firstly, that it is driven by the transformation towards a decarbonised energy system with a high penetration of renewable energy infrastructure. Secondly that there is a shift from passive consumers becoming prosumers actively consuming and producing energy. Lastly that this transition from a highly centralised energy system towards a distributed one is an enabler for developing countries and communities to 'leapfrog from energy poverty to sustainability' (Szulecki, 2018: 22). Energy democracy is an energy governance concept that can be summarised as increased public participation not only in the decision making process but ownership of energy infrastructure in direct contrast to the traditional approach to energy planning and delivery in countries like South Africa.

2.3.5.2 Multiple cells of generation, storage and load

Bischof-Niemz (2015) defines a cell as a consumer of energy with a load such as a residential complex, commercial complex, individual buildings, a village or industrial customer. However, Bischof-Niemz (2015) predicts that a cell of the future will evolve from only being a load to include generation and storage. These cells of generation, storage and load are expected to form virtual power plants through smart grid interconnections (Bischof-niemz, 2015).

2.3.5.3 Energy hubs

Energy hubs are defined as " functional units where multiple energy carriers are converted, stored and dissipated" (Geidl & Andersson, 2007: 1). Geidl and Andersson (2007) advocate that future energy systems be designed as a coupling of different energy infrastructures such as electricity, gas, and district heating systems. The benefits of a hybrid energy hub in comparison to conventional energy supply include increased reliability since the load is no longer only dependant on a single infrastructure; improved load flexibility because energy carriers have higher responsiveness to tariffs for example; and the advantage of synergy which allows the system as a whole to benefit from the features unique to each carrier (Geidl & Andersson, 2007).

2.3.5.4 Blockchain and energy

Blockchain is a digital technology used as a decentralised ledger for public transactions originally developed for the virtual currency Bitcoin (The Economist, 2017). The Interchange (2017), an energy podcast explored the potential for the use of blockchain in energy contracts to decentralise traditional power system transactions managed by the system. It is predicted that the network of wholesale electricity market could potentially operate autonomously and therefore lower the costs of a traditional network (The Interchange Podcast, 2017). On a smaller scale, The Economist (2017) also published an article pointing out that technology firms such as Google and Amazon are currently investing in research towards smart-home management systems using technology disruptions such as blockchain.

2.4 Renewable Energy Supply Technologies

This section provides a brief overview of the state of solar photovoltaic (PV) technology, concentrating solar power (CSP), solar water heaters and biogas.

2.4.1 Solar PV

IRENA (2016c) reports that since the end of 2009, the cost of solar PV modules have fallen by approximately 80%. This report also suggests that solar PV is slowly overtaking hydropower as the dominant renewable energy technology on the African continent (IRENA, 2016c). It is further estimated that the capacity of solar PV globally has risen from 8GW in 2009 to approximately 47GW in 2015. In Africa, new solar PV capacity reached 800MW in 2014 and 750MW in 2015. IRENA forecasts that Africa's installed capacity is expected to exceed 70GW by the year 2030 (IRENA, 2016c). Some of the most favourable advantages of solar PV technologies include that it is highly modular and has short project lead times (IRENA, 2016c). Its highly modular design makes it easily scalable from small scale to utility scale plants and the short project lead times for solar PV is a direct result of its modularity. This according to IRENA (2016c) makes it a favourable technology option for the rapid deployment required to address energy scarcity and access issues in many African countries.

2.4.2 Concentrating Solar Power

Giovannelli (2015) defines small scale concentrated solar power (SS-CSP) as systems of 1MegaWatt or less. Rawlins and Ashcroft (2013) classify SS-CSP plants from 100kW up to 2MW in size. Bode and Gauché (2012) in a comprehensive review of the CSP system value summarise the four main value propositions of CSP as (1) the low carbon footprint of the technology over its lifecycle, (2) it has a high capacity factor as a result of its thermal energy storage, (3) a storage combination makes it dispatchable (most applicable when the Sun is not shining), (4) it allows for hybrid options and (5) the rotating heat engines are favourable for grid stability.

Rawlins and Ashcroft (2013) in a review of small scale CSP applications suggest that SS-CSP would be most beneficial in a rural setting in Sub-Saharan Africa such as Kenya and that the plant should be (1) a parabolic trough installation with manual tracking for cost reduction, (2) should include thermal energy storage and (3) local community should be trained to carry out maintenance and repairs. Unlike large scale CSP or small scale CSP industrial process where the barriers are of an economic or social nature, SS-CSP for off-grid or rural applications has not yet advanced past the technology development phase.

A recent review of small scale CSP by Mueller et al. (2016) shows a record of 124 projects of sizes up to 1MW output capacity of which only seven are located in Africa. Two findings from the report include that (i) over 50% of these projects are demonstration or research facilities; and (ii) SS-CSP fares well in regions where it is competing with fuel costs of distributed generators as opposed and are not competitive in regions with utility-scale power plants (Mueller *et al.*, 2016).

2.4.3 Solar Water Heaters

Solar water heaters are an important energy efficiency technology for demand side management and are deemed to have a high potential for local content and job creation (DoE, 2015). The South African Department of Energy launched the National Solar Water Heating Programme (NSWHP) in partnership with Eskom in an attempt to reduce electricity demand from the residential sector during peak hours in 2009. The aim of the project was to have a rollout of one million SWHs by

2014 (Eskom Holdings Limited, 2013). However, this project was not successful due to an influx of inferior products and poor installations by suppliers (DoE, 2015). This has since evolved to a long term target of 5 million SWHs by the year 2030 (DoE, 2015). An example of a local mass solar water heating programme was introduced by the City of Cape Town between 2011 and 2013 for the mid-high income residential sector. Another pilot solar water heater rollout programme in the Joe Slovo informal settlement in Cape Town was rolled out between 2012 and 2014 (SEA, 2015). Ijumba and Sebitosi (2010) approximate that households make up 35% of South Africa's peak demand and that water heating accounts for 40% of this. Ijumba and Sebitosi (2010) go on to explain that varying savings between consumers with the same technology installations and weather conditions can often be attributed to behavioural differences between consumers. The study makes use of a typical hot water consumption profile for South Africa dating back to 1997. In the CSIR's update report of the IRP 2010, Wright et al. (2017) point out that there is an opportunity for demand shaping the South African power system through electric water heaters (EWHs) in the domestic, commercial and industrial sectors.

2.4.4 Biogas

Biogas is obtained by transforming organic waste commonly from food waste, animal farms, breweries and agricultural residue amongst others into gas. This type of gas is typically used for cooking and heating. South Africa reportedly only has 50 registered large scale biogas projects nationwide with a capacity of 100kW or more (Methvin & Philipp, 2017). It is estimated that in order for a biogas digester to provide enough cooking gas for 2 to 3 hours for a household it requires approximately 20 -30 kg of biomass and 40 litres of water. It is mainly for this reason that biogas digesters are best suited in places with high amounts of organic waste and greywater. The challenge with biomass is that there needs to a set amount of feedstock. However, depending on the type of system size and environment, this is not always the case – especially with an urban residential community. Often this also assumes that there is enough organic feedstock and water required to run the system for biogas as highlighted by Methvin and Philipp (2017).

2.5 Introduction to Energy Modelling Approaches

Energy modelling or energy systems analysis (ESA), the focus of this study is a field concerned with the way that technologies and resources are combined within given constraints to meet specific supply targets (Nakata, Silva & Rodionov, 2011). ESA is increasingly becoming one of the preferred approaches used to design energy systems of various scales (Nakata *et al.*, 2011). Such models are beneficial as tools for the energy planning process in providing energy policy makers with insight into the implications of various energy policies (Van Ruijven *et al.*, 2008). According to Bhattacharyya and Timilsina (2010), some of the unique characteristics of developing countries that make energy modelling a challenge are that the availability of data is often a limitation; consumption behaviour varies significantly across income groups and location; and the existence of the informal sector. A model is simply a representation of reality with the purpose being to understand, change, manage and control a system (NREL, 2015).

Nakata et al. (2011) describe an energy system as a representation of the interactions between the production and consumption of energy services in a society. The basic elements making up an energy system include, (i) primary energy resource(s), (ii) the technologies used for conversion and supply to the end-user and (iii) the economic sectors that consume the energy (Nakata *et al.*, 2011). Energy modelling or energy systems analysis (ESA) is the approach used to design energy systems through the way that technologies and resources are combined within given constraints to meet specific supply targets (Nakata *et al.*, 2011). Some features of optimisation and simulation models are summarised in Table 1.

Table 1: A high-level comparison of optimisation and simulation models

Features	**Optimisation Models**	**Simulation Models**
Examples	PLEXOS	LEAP
Main Objective	Selection of an energy investment solution within given constraints (Connolly, Lund, Mathiesen & Leahy, 2010)	Identification of priorities for a mix of technology measures (Howells *et al.*, 2002)
Typical Uses	Energy investment strategy or cost-effectiveness analysis	Scenario analysis
Typical Applications	National utilities and municipalities	Planners, system designers
Modelling Techniques	Linear Programming, Mixed Integer Programming and Dynamic Programming (Van Beeck, 1999)	Macro-economics, statistical methods, forecasting (Neshat, Amin-Naseri & Danesh, 2014)
Advantages	Flexible application and applicable to technical total systems (Howells *et al.*, 2002) , Modularity	Useable without targeted optimisation (Van Beeck, 1999), Model can be designed modularly using various methods (Pfenninger *et al.*, 2014)
Disadvantages (Pfenninger *et al.*, 2014)	Rigid mathematical formulation, To remain manageable, models are often limited to nationally aggregated technology and annually or seasonally averaged supply and demand	Limited to the quality of expert knowledge, Often underrepresent the economy (Howells *et al.*, 2002)
Modelling of supply and production (Howells *et al.*, 2002)	Endogenous	Scenario Analysis

A comprehensive review of modelling tools submitted as part of the journal paper by Mabaso et al. (2018) is presented in Table 22 found in the Appendix. The National Renewable Energy Laboratory (NREL) lists three categories for energy analysis models and tools. These include technology and performance analysis; energy systems analysis; and economic and financial analysis (NREL, 2015). ESA provides a systems-view of an energy system useful for exploring alternative scenarios to inform government policy and is often used to select suitable technologies to meet a country's energy needs (Weyant & Kuczmowski, 1990). One of the challenges of technology assessment according to Musango and Brent (2011) is that there is a lack of a standard methodology that has been agreed upon for technology assessment. Other reviews of models suggest that there is not a single method of classifying energy system models partly because the challenges they address are complex and often fall within multiple sectors. Over the years, the list for classifying energy models has grown and includes but is not limited to purpose, structure, input assumptions, top-down versus bottom-up, time horizon, aggregation level, flexibility, simulation techniques and sectoral coverage (Van Beeck, 1999).

From the literature surveyed, each study found identifies different priorities. For example, Fouché (2014) identifies six main categories for classifying energy models, namely (1) bottom-up optimisation models of the energy system, (2) bottom-up simulation models of the energy system, (3) top-down econometric models, (4) hybrid models, (5) electricity system models and (6) spatial-temporal modelling. Connolly et al. (2010) use seven categories for each tool, namely (1) simulation tool, (2) scenario tool, (3) equilibrium tool, (4) top-down tool, (5) bottom-up tool, (6) operation optimisation tool, and (7) investment optimisation tool. Keirstead et al. (2012) on the other hand interestingly classify urban energy system models according to the ability of the tool to address the major issues of an urban energy system. Another way of classifying energy modelling tools is according to their geographical scale. There are two challenges identified from these classifications. First, some tools fall into more than one category and in some cases only partially fulfil the definition of a category. Second, some studies follow a classification according to the purpose of the model and not the tool specification (Urban *et al.*, 2007). Neshat, Amin-Naseri and Danesh (2014) and Van Beeck (1999) provide comprehensive definitions and detailed explanations of the classification and definitions of energy models for background. These challenges have also created opportunities for a shift in the approach towards energy modelling. For example, Bazilian et al. (2012) suggest that open source energy models provide the opportunity for developing countries to adapt these models to the local context. From the literature surveyed, there seems to be a growing number of publications concerned with energy modelling tools which incorporate an integrated approach towards the challenges of the twenty-first century, developing countries and the integration of renewable energy technologies.

Table 2 lists the reviews from the literature surveyed between 1999 and 2015. The titles of the publications suggest that studies or reviews of modelling tools are not only interested in technical specifications but how these specifications address more general complex issues.

Table 2: A list of recent reviews of energy modelling tools

Year	Author	Title of publication
1999	(Van Beeck, 1999)	Classification of energy models
2006	(Jebaraj & Iniyan, 2006)	A review of energy models
2007	(Urban *et al.*, 2007)	Modelling energy systems for developing countries
2010	(Connolly *et al.*, 2010)	A review of computer tools for analysing the integration of renewable energy into various energy systems
2010	(Bhattacharyya & Timilsina, 2010)	Modelling energy demand of developing countries: Are the specific features adequately captured?
2010	(Foley, Gallachóir, Hur, Baldick & McKeogh, 2010)	A strategic review of electricity systems models
2011	(Nakata *et al.*, 2011)	Application of energy system models for designing a low-carbon society
2011	(Gondal & Sahir, 2011)	Review of modelling tools for integrated renewable hydrogen systems
2012	(Keirstead *et al.*, 2012)	A review of urban energy system models: approaches , challenges and opportunities
2014	(Pfenninger *et al.*, 2014)	Energy systems modelling for twenty- first century energy challenges
2014	(Fouché, 2014)	A collaborative modelling network to transition the South African energy system
2015	(Després, Hadjsaid, Criqui & Noirot, 2015)	Modelling the impacts of variable renewable sources on the power sector: reconsidering the typology of energy modelling tools

2.6 Key Features of a Modelling Tool

This section summarises the key features of modelling tools based on suggestions made by Van Beeck (1999), Urban et al. (2007) and Pfenninger, Hawkes and Keirstead (2014), which explore energy modelling tools for local energy planning, developing countries and energy challenges of the twenty-first century respectively.

2.6.1 Local Energy Planning

For local energy planning in a developing country undergoing energy transformation, Van Beeck (1999) suggests that there are four main criteria to consider when selecting a modelling tool. These include (i) energy demand in terms of type and amount, (ii) energy supply systems needed to meet this demand, (iii) an impact assessment of using the energy systems, and (iv) a multi-criteria analysis (MCA) type of appraisal model. Van Beeck (1999) also insists that a bottom-up analytical approach is non-negotiable for local energy planning. The reason cited for this is that a bottom-up model allows one to describe in detail the end user energy services being supplied and the types of energy supply technologies. Interestingly, Van Beeck's (1999) review concludes that a flexible toolbox methodology is well suited for local energy planning in developing countries because of the changes in local circumstances caused by rapid development (Van Beeck, 1999).

2.6.2 Developing Countries

The review by Urban et al. (2007) classifies energy modelling tools according to nine characteristics of the energy systems and economies of developing countries to provide an assessment of whether present-day energy models adequately capture the main characteristics of developing countries, specifically in Asia. These characteristics include (1) the performance of the power sector, (2) supply shortages, (3) electrification, (4) traditional bio-fuels, (5) urban-rural divide/urbanisation, (6) informal economy, (7) structural economic change, (8) investment decisions and (9) subsidies (Urban *et al.*, 2007). The tools which apply to this review include LEAP, MiniCAM and RETScreen. However, only LEAP included the performance of the power sector and none of these capture supply shortages. In addition, none of these models capture the informal economy and structural economic change.

Only RETScreen considers investment decisions. One of the significant outcomes demonstrated in the review by Urban et al. (2007) is that bottom-up and hybrid models capture a higher number of these developing country characteristics in comparison to top-down models. Urban et al. (2007: 3479) assert that a top-down approach is often ill-suited for a developing country context because this approach is driven by market behaviour which is referred to a "limited driver of production and consumption frontiers". In addition to this assertion, they add that there is a wide part of the economy which is not accounted for by economic indices and so results in little to no representation of varying income distribution, energy supply and demand living standards (Urban *et al.*, 2007).

2.6.3 Energy Challenges

The implication for energy systems modelling, specifically bottom-up optimization energy modelling tools is that there is a need for both more temporal- and spatial-detail in the models used. In addition to this, Pfenninger, Hawkes and Keirstead (2014) suggest that the location of renewable technologies is of importance not only because it determines their generation costs but because fluctuations can be reduced using spatial distribution. Després (2015) agrees that a precise spatial and temporal resolution representation is required to model the integration of renewable energy sources to the power sector. Spatial temporal modelling refers to the process of representing a model with both geographic (in space) and time resolution (Gauché, Rudman, Mabaso, Landman, von Backstrom & Brent, 2017). WWF (2015) explains that temporal modelling has managed to provide the total capacity needed of a particular technology and not so much the location where the technology should be placed. The benefit of a spatial-temporal modelling approach according to WWF (2015) is that unlike conventional models where a PV capacity factor would be an input to the model, the environment of the power plant is built-in to the model so that the capacity factor of a PV plant is a result instead. A limitation of the spatial-temporal modelling according to WWF (2015) is that with the variable nature of renewable resources, multiple years of data are often required for reliable results.

A recent study by Bofinger and Bischof-Niemz (2016) gives weight to these arguments by exploring the effects of the aggregation of solar PV and wind in South Africa. The study found that spatial aggregation of wind and solar PV reduces volatility within a wide-spread interconnected electricity grid (Bofinger & Bischof-Niemz, 2016). Uncertainty and transparency are additional challenges for energy models (Pfenninger *et al.*, 2014). Frequently, code and data in energy models are not publicly released, making it difficult to accurately verify them. Overly-complex models in particular suffer from this. Complex models also make the treatment of uncertainty more difficult. Deterministic and stochastic methods are some of the ways of dealing with this, but it is the assumptions made by the modeller that will ultimately affect the quality of the results (Pfenninger *et al.*, 2014).

In an effort to address the complexity of integrating information across small and large scale systems within the correct time boundaries and resolution, Pfenninger, Hawkes and Keirstead (2014) advocate that interdisciplinary complexity science might be an appropriate approach. One way of doing this is to model agents as individual parts and "specify the rules they follow and their interactions with the environment" (Pfenninger *et al.*, 2014: 79). For power systems modelling, agent-based models are formulated according to this principle (Foley *et al.*, 2010). Agent based modelling (ABM) is defined by (Wilensky & Rand, 2015: 1) as, "a form of computational modelling whereby a phenomenon is modelled in terms of agents and their interactions". In this case, each agent is an autonomous object modelled with individual properties to perform specific actions.

2.7 Drivers & Current Status of Distributed Energy Projects

Koirala (2017) suggests that integrated community energy systems (ICES) in developed countries are typically driven by pro-active communities motivated by an increased climate change awareness and need for autonomy. For developing countries, Koriala (2017) cites energy access as the key driver for ICES.

A list of 'on the ground' distributed energy system projects was compiled as part of a paper titled, *"A literature review of hybrid renewable energy micro-grids in South*

Africa and neighbouring countries" (Mabaso & Gauché, 2018). The basic requirements for inclusion of projects are that (i) the project is classified as a distributed generation system (below 5 MW in size) (GreenCape, 2016), (ii) includes renewable energy generation sources; and (iii) should be located either in South Africa, Namibia, Botswana, Zimbabwe, Mozambique or Lesotho. A total of nineteen independent existing and planned projects of various types were found dated between 2002 and 2017. It is reported by Mabaso et al. (2018) that the majority of shortlisted projects are in the rural residential sector dating back to 2002 while two informal settlement projects were only developed between 2016 and 2017. This is in agreement with the suggestion that there is a growing number of distributed energy systems with a high penetration of renewable energy in formal and informal residential urban areas located close to the grid and often with a grid connection (IRENA, 2016b; Keller, 2012; Slann, 2013; Sustainable Energy Africa, 2015).

2.8 Key Modelling Metrics

From the studies and modelling tools reviewed, the techno-economic metrics found relevant to this study are briefly discussed in this section.

2.8.1 Flexibility and Ramp Rates

Papaefthymiou et al. (2014) describe the flexibility of an energy system both on the supply and demand side as its ability to continue servicing a load cost effectively when faced with rapid changes in demand or supply. Some of the indicators used to measure flexibility include ramping rates, minimum up and down time, and the time required for start-up and shutdown. Ramping rates refer to the reaction time of the power system. Papaefthymiou *et al.* (2014) highlight that the variability of renewable energy technologies as a result of weather resource has increased the uncertainty and in some cases the availability of supply. Renewable energy sources are themselves flexible but also increase the need for flexibility of a power system to maintain system balance. Flexibility options differ depending on operational timeframes and flexibility has different characteristics depending on the timeframe as shown in Papaefthymiou *et al.'s* (2014: 6) illustration of flexibility characteristics.

2.8.2 Capacity Factor

The capacity factor of a power plant is defined by Papaefthymiou et al (2014) as the ratio of actual plant output to the rated plant capacity over a given period of time. For renewable energy technologies capacity factor is dependant on the solar or wind resource. Fossil fuel generators typically make use of an equivalent metric called a load factor (Calitz, 2015).

2.8.3 Marginal Value of Electricity (MVOE)

The marginal value of electricity (MVOE) was developed by Gauché (2016) and is an indicator used to measure the marginal value to a system as a result of marginal changes such as capacity adjustments. Gauché et al. (2017) explain that MVOE represents the net value of a change to a system and LCOE does not capture this change. Mathematically, this means that MVOE is the difference in LCOE for two scenarios as a proportion of electricity generated due the change to the system as shown in equation (1) defined by Gauché et al. (2017).

$$\mathrm{MVOE}_{\Delta\mathrm{C}} = \frac{\mathrm{E_d}}{\mathrm{E}_{\Delta\mathrm{C}}}\left(\mathrm{LCOE_{system}} - \mathrm{LCOE}_{\mathrm{system}+\Delta\mathrm{C}}\right) \tag{1}$$

Where $\frac{E_d}{E_{\Delta C}}$ is the proportion of electricity generated as a result of the marginal change to the system to that of the electricity generated in response to system demand. The subscript ΔC represents any changes to the system (Gauché *et al.*, 2017).

2.8.4 Generation Load Factor and Capability Factor

A plant's reliability can be assessed from the generation load factor as shown in equation (2) (Eskom Energy Management, 1993). The generation load factor is equivalent to the capacity factor of a plant and indicates the ratio of the plant's actual energy generation to the maximum design capacity that the plant is capable of achieving.

$$\text{Generation load factor} = \frac{\text{Nett kWh Production x 100}}{\text{Average Nett Maximum Capacity x Hours in Year}} \tag{2}$$

2.8.5 Heat Rate

Calitz (2015) defines heat rate as the inverse of a generation plant's efficiency as shown in equation (3) (Calitz, 2015). A low heat rate is preferable because 100% efficiency implies that 1kWh of electric energy output, thermal input of 3.6MJ (equivalent to 1kWh) is required.

$$\text{Heat Rate} = \frac{\text{Thermal Energy Input(MJ)}}{\text{Electric Energy Output(kWh)}} \tag{3}$$

2.8.6 Levelised Cost of Electricity (LCOE)

Levelised cost of electricity (LCOE) is a universal economic metric for comparing the cost per kWh across different energy supply technologies. In financial terms, LCOE is defined by Nerini et al. (2016) as the cost of electricity over the project life cycle at which the project breaks even. The benefit of such a metric is that it accounts for the fact that different technologies have different generation profiles based on resource. This also accounts for the unique features of renewable energy technologies which are weather resource dependant and these technologies have high capital costs initially but no fuel costs over the life of the project. LCOE is typically calculated over the life (l) of the plant (Merven, 2016). Where subscript t represents the time and r is the discount rate. The running costs include power generation costs including fixed and variable costs. When the running costs are expanded, the following generic form of LCOE is given by equation (4).

$$\mathrm{LCOE} = \frac{\text{Capital Investment Cost} + \sum_{t}^{l} \frac{\mathrm{O\&M}_t + \mathrm{Fuel}_t}{(1+r)^t}}{\sum_{t}^{l} \frac{\text{Electricity Produced}_t}{(1+r)^t}} \tag{4}$$

Where O&M refers to both the fixed and variable operation and maintenance costs (Merven, 2016).

For solar thermal generated energy, Mauthner and Herkel (2016) replace the electricity generated term with solar thermal energy yield per square metre as shown in equation (5),

$$\mathrm{LCOE(solar\ thermal)} = \frac{\text{Capital Investment Cost} + \sum_{t}^{l} \frac{\mathrm{O\&M}_t}{(1+r)^t}}{\sum_{t}^{l} \frac{\mathrm{SE}}{(1+r)^t}} \tag{5}$$

Where SE represents the solar energy yield in the year t

Assuming that all parameters are constant, an average LCOE often referred to as simplified is derived from (Merven, 2016; NREL, 2016)

$$\begin{aligned} \mathrm{LCOE} = {} & \frac{(\text{Capital Investment Cost } \times \mathrm{CRF}) + \text{ Fixed O\&M}}{8760 \ \times \text{Capacity Factor}} + \\ & (\text{Fuel} \times \text{Heat Rate}) + \text{Variable O\&M} \end{aligned} \tag{6}$$

Where Capital Recovery Factor (CRF) = $\frac{i(1+i)^l}{(1+i)^l-1}$. For renewable energy sources, the fuel cost is zero.

2.8.7 Cost of Unserved Energy (COUE)

Minaar (2015: 1) defines the cost of unserved energy (COUE) as “the cost of electricity interruptions to electricity customers and the economy as a whole”. Unserved energy is only applicable for unplanned interruptions of duration less than three hours. The concept of assigning a value to unserved energy became relevant during the 2008 to 2015 period in South Africa when load-shedding took place (Minnaar, 2015). This metric, measured in R/kWh is useful for quantifying the reliability of the electricity network in economic terms. In practice COUE informs investment, planning and refurbishment of the electrical power system whilst also measuring the overall effect of network reliability on the rest of the economy (Minnaar, 2015).

There are two main types of COUE, the first being economic COUE and second residential COUE (Minnaar, 2015). Economic COUE measures the total impacts on the economy as a sum of direct, indirect and induced impacts. Direct impact is measured in GVA/kWh and refers to the "production opportunity forgone" while indirect impact measures costs to the economy as a result of cross-linkages. To calculate residential COUE, it is assumed that the utility gained by households is measured by expenditure on electricity dependant items which is then divided by domestic electricity used. Residential COUE is calculated as shown in equation (7) (Minnaar, 2015).

$$\text{Residential COUE} = \frac{\text{Household Expenditure in Rands}}{\text{Total Residential electricity use (kWh)}} \tag{7}$$

2.9 Frameworks for Evaluating Community Scale Energy Systems

Given the economic, social, political and environmental factors influencing the energy system, energy policy makers have the challenging task of using indicators to evaluate energy infrastructure options. This section provides an overview of some of the proposed frameworks for evaluating the suitability of energy systems - each of these highlight the value of energy systems beyond energy access.

2.9.1 An End-User Energy Approach

Zalengera, Blanchard and Eames (2015) carried out a study exploring the opportunities and barriers of the adoption of renewable energy technologies by low-income households. The empirical study in Malawi makes use of an end-user centred approach by measuring the prioritization of household energy services, household well-being and household purchasing power of energy. The study findings highlight that the household uptake of renewable energy technologies could be improved by an end-user centred approach with integrated financing mechanisms for low-income households to pay for *"good-quality systems capable of meeting their energy needs"* (Zalengera *et al.*, 2015: 101).

2.9.2 The Value of Energy to the End-User

Hirmer and Cruickshank (2014) propose a value framework for rural electrification as illustrated in Figure 3 categorised by functional value. The economy sub-branch is two-fold including the purchase economy and use economy (Hirmer & Cruickshank, 2014). Hirmer and Cruickshank (2014) highlight that the acceptance and sustainability of rural electrification project schemes is highly dependent on the ability to create value for the end-user. The purchase economy includes the standard cost of installation and the cost per unit of electricity. The use economy is further broken into financial benefit and operational benefit. The financial benefits of the use economy include the financial benefits gained through the project including savings on electricity spending or a rise in income. Operational benefits of the use economy include the non-financial benefits gained as a result of the operational energy services that the energy infrastructure serve. It is this operational benefit of the use economy that is applicable to end-user energy services. However, Hirmer and Cruickshank (2014: 146) also identify that there has not been sufficient focus on infrastructure development in, “*understanding the complex interaction between the user and the service itself*”.

Miller, Altamirano-Allende, Johnson and Agyemang (2015) define the social value of energy as the total benefit to the community or individual who make use of it. Miller et al. argue that there is a need for such a framework specifically in cases where the cost of renewable energy and off-grid energy projects reduce energy poverty. To support this argument, Miller et al. (2015) explain that in the case of energy poverty, there is often insufficient economic value to justify the investment but high social value. These authors add that the sustainability of energy projects is embroiled in socio-technical challenges which can be managed to enhance social value and not only economic cost.

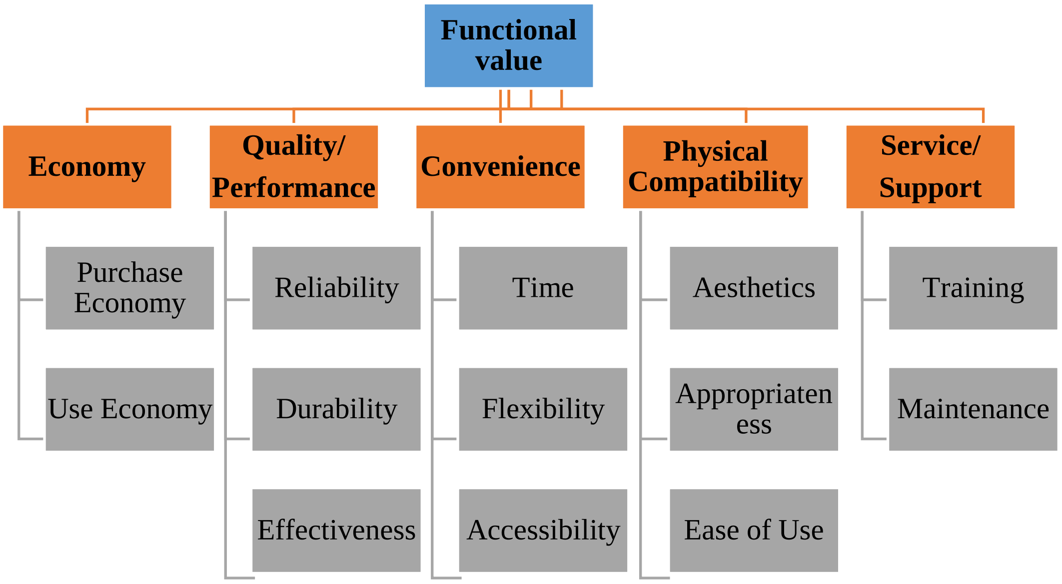

Figure 3: Electrification framework adapted from Hirmer & Cruickshank (2014)

An intuitive example to demonstrate the social value of an energy technology is explored by Miller et al. (2015) in the use of cookstoves shown in Table 3.

Table 3: Usage of cookstove designs adapted from Miller at al. (2015: 68)

Meal	**Percentage of meals prepared on cookstove (%)**	
	Traditional Stove A	**Traditional Stove B**
Breakfast porridge (thin)	7.78	92.22
Lunch or dinner porridge (thin) with sauce	7.34	92.66
Rice	50	50
Couscous	0	100

The study by Miller et al. (2015) in Table 3 demonstrates that the design of the cookstove directly influences the satisfaction of the cooking energy service offered by the cookstove. The improved cookstove incorporates the patterns of usage gathered from the end-users and this significantly improves the satisfaction of energy services as a result.

2.9.3 Value Analysis

Rich and Holweg (2000) classify value into two main categories, namely (1) use value which refers to the use of the product or service and (2) esteem value which refers to ownership of the product or service. The need to define the value of a product or service is primarily founded on the basis that the value of a product or service is not the same as the price paid for the product or service. For a typical manufacturing process, a value analysis process is carried out to reduce unnecessary costs or features of the product that do not add value to the customer (Rich & Holweg, 2000). The reasons for the value analysis approach varies according to each case but is either due to internal company reasons or external market induced conditions. Value analysis is a systematic review process applied to a product design. It is aimed at eliminating features which do not add value to the product purpose or customer but contribute to the product or service costs and is specifically for existing products and services (Rich & Holweg, 2000).

2.9.4 Cost Benefit Analysis

A cost-benefit analysis (CBA) is a popular method of determining the feasibility of a specific project by comparing the monetary value of the benefits and that of the cost of implementing a project (Zachariadis & Hadjikyriakou, 2016). There are two main types of CBAs, namely the financial type and the economic type. An economic CBA typically considers socio-economic factors such as external costs to the environment whereas the financial CBA is focused on the financial feasibility of the project which includes taxes and subsidies. It is less complex to conduct a CBA with factors which are reflected in the formal market and have a market value. Zachariadis and Hadjikyriakou (2016) argue that the economic CBA is most applicable to power generation technologies because of the long term investments and also that the value is often evaluated in terms of the costs and benefits to society as a whole and not just investors. A project is deemed feasible to pursue if the discounted present value of the benefits exceeds the discounted present value of the costs. This is known as a positive net present value (NPV) (Zachariadis & Hadjikyriakou, 2016). A benefit cost ratio (BCR) shown in equation (8) is also often used to express the ratio of discounted benefits to costs, with a BCR above one signalling that the project is feasible (Zachariadis & Hadjikyriakou, 2016). In equation (8) B_t represents benefits, whilst C_t represents costs for a designated time and r and i are the discount ratio and number of years respectively.

$$\mathrm{BCR} = \frac{\sum_{i=1}^{r} \frac{B_t}{(1+r)^i}}{\sum_{i=1}^{r} \frac{C_t}{(1+r)^i}} \tag{8}$$

2.9.5 Social Return on Investment

Social return on investment (SROI) is a framework used to measure the value beyond the financial cost of initiatives. The focus is on measuring the change that an initiative brings about to the relevant people and organisations. There are two main types of SROI analysis, namely forecast analysis and evaluative analysis (LG Improvement and Development, 2010). The forecast analysis is similar to a cost-benefit analysis is applicable when formulating business activity options to support a business case. An evaluative analysis on the other hand is applicable to evaluating the value of already tested options. Various stakeholders are involved in deciding what valuable impact is measured and how this is measured and valued (LG Improvement and Development, 2010). SROI is calculated from equation (9) (Social Enterprise Fund, 2010) as the ratio of the total impact to the input of resources to achieve the impact.

$$\mathrm{SROI} = \frac{\text{Total Impact}}{\text{Total Input}} \tag{9}$$

2.9.6 Modelling Framework for Local Energy Planning

Van Beeck (2003) suggests a linear modelling framework for local energy planning as illustrated in Figure 4. Van Beeck (2003) highlights that there are many assumptions made by the modeller which are not explicit in the model and therefore act as external assumptions which the decision maker should understand. Some of these assumptions include population growth; economic growth; energy demand; energy supply; price and income elasticities of energy demand; and the existing tax system and tax recycling.

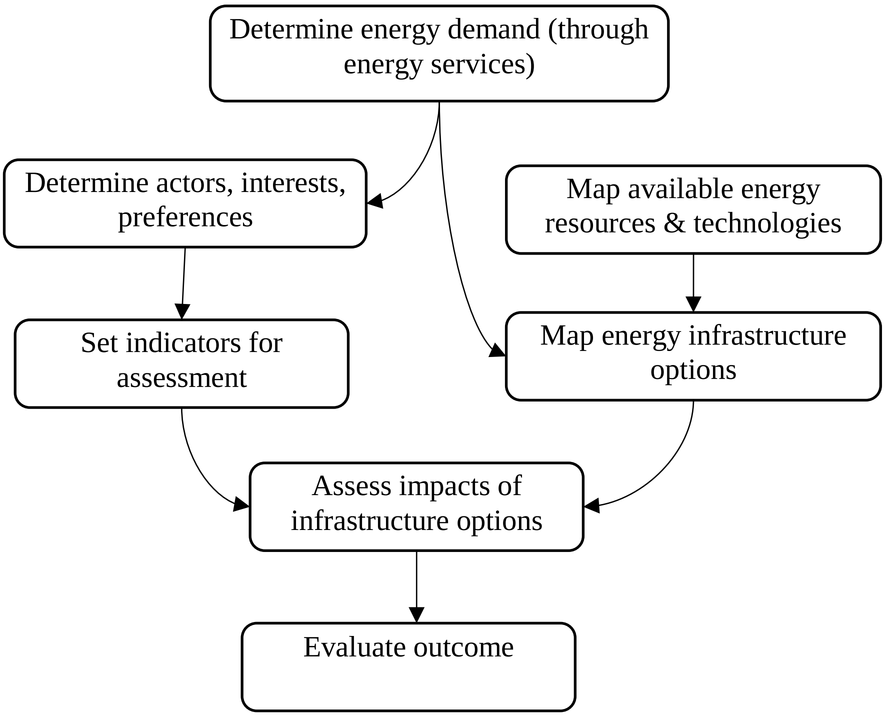

Figure 4: Local energy framework adapted from Van Beeck (2003: 47)

This framework is made up of four sub-models, namely (i) the energy demand model, (ii) energy supply model, (iii) impact assessment model with set indicators, and (iv) the appraisal model. The method for each of these models involves stakeholder participation at each step with the exception of mapping energy resource and technologies as indicated in Figure 4. This impact assessment model according to Van Beeck (2003) makes use of indicators to assess the impact of the energy resources; and the ability of technologies and infrastructure options to meet the energy demand.

2.9.7 Decision-Making for Uncertainty in Rural Electrification Projects

Bekker and Gaunt (2006) conceptualised a framework for evaluating successful rural electrification projects given uncertainties in the decision making process. According to Bekker and Gaunt (2006) the extrinsic value of rural electrification is in improving the quality of life of the end-user in a sustainable manner within the country's institutional structures. To achieve this, the authors point out that apart from the standard socio-economic and environmental factors influencing the success of rural electrification projects, other two main uncertainties include (i) the effectiveness of the institutional structures and (ii) human behavioural inertia. Institutional structures relate to maintenance, estimation of load and demand management while human behavioural inertia refers the resistance in human behaviour to change (Bekker & Gaunt, 2006).

2.9.8 The Multi-Tier Framework

The Multi-Tier Framework (MTF) is an approach developed by the World Bank (2015a) in an attempt to rank the different energy service levels offered by electricity access. The approach identifies that the current approach towards electricity and energy access is binary which simply means that one either has access or not. In order to address this, the MTF consists of five tiers which are rankings determined by the number of the required attributes for each service to determine how energy poor a household using an energy poverty index. Attributes for electricity for example include capacity, duration in the day and evening, reliability, quality, affordability, legality and health and safety (SE4ALL & ESMAP, 2015b). The MTF is said to be constrained by data collection because it is based on household surveys (SE4ALL & ESMAP, 2015b). The overall energy access index is based on the factors shown in Figure 5 where HH is household.

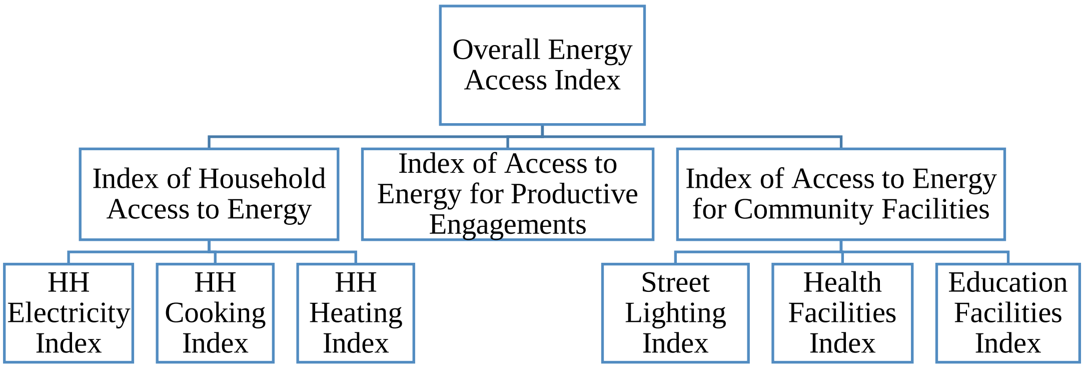

Figure 5: The hierarchy of locales of energy access (SE4ALL & ESMAP, 2015a: 46)

2.10 Chapter Conclusion

Chapter 2 provided a foundation from literature of the energy modelling approaches and tools appropriate for a developing country context. It can be concluded that there isn’t a single approach to ensure that modelling tools are adapted to the local context. In order to develop a test model with an end user approach, this literature survey points to key issues including good spatial and temporal resolution; a local energy planning approach and a method of evaluating the comfort levels of the energy system.

3 METHODS

> “Remember, always, that everything you know, and everything everyone knows, is only a model.”
>
> \- D. Meadows, Thinking in Systems, 2009

This chapter provides a snapshot of the simulation modelling research approach applied to develop a simulation of an energy system to address the research question of this study. First the research approach and design adopted are described. Next, a summarised comparison is made of the key features from the literature review of a traditional energy system versus a distributed energy system which inform the method. This is followed by an outline of the discomfort level framework defined and used to formulate a discomfort level - a metric used to interpret the improvement in satisfying the end-user’s energy services needs from supply technology combinations. The simulation includes a supply and demand sub-model, the outputs of which were used as proxy input data applied to the discomfort framework.

3.1 Research Design

Simulation modelling is the research design selected for this study. Simulation-based research modelling is according to Rose, Spinks and Canhoto (2015) a method for modelling systems, processes and events using computer software. To test the objectives of a study, a model is used to simulate the conditions of a case where real experiments are impractical due to the complexity and costs (Jarić, Budimir, Pejanović & Svetel, 2013). The simulation modelling process requires repeated iterations as shown in the generic outline of the main steps in Figure 6. These steps include (i) the formulation of the research question, (ii) design of the simulation model, (iii) building the model using computer software, (iv) verifying the input assumptions and data used in the model using reliable sources, (v) running the simulation model and (vi) formulating conclusions from the findings (Rose *et al.*, 2015).

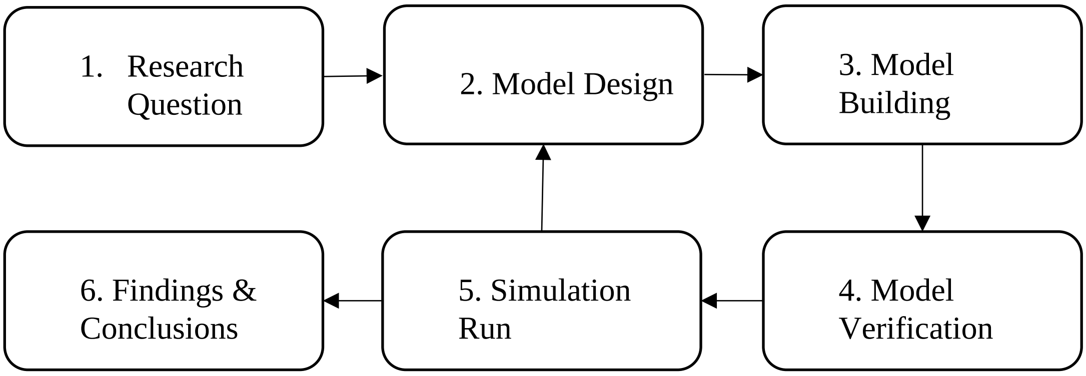

Figure 6: Simulation modelling steps adapted from Rose et al. (2015: 3)

Some of the strengths of a simulation-based research approach are that it allows the researcher to investigate complex and often non-linear systems, processes and events over time in cases with limited data, real experiments are costly to carry out or where conventional methods are limited (Rose *et al.*, 2015). However, the technical precision required for such models can in some cases make models susceptible to misspecification, misguided assumptions and generalisations (Van Beeck, 1999). Simulation modelling is adopted for this study because it is well suited to analysing multiple scenarios using a simplified simulation of an energy system. A simulation modelling approach is preferred over an optimisation modelling approach because simulation modelling allows one to depict parts of reality and the economic interactions between different actors while optimisation modelling presents the ideal case given a specific objective (Borbonus, 2017). From the energy systems modelling methodologies reviewed in Chapter 2, Van Beeck (1999) highlights that simulation models can either be static or dynamic. In the static case the time period is frozen and in the dynamic case the model is affected by different periods in the form of back-casting or forecasting. For this study, a static simulation modelling approach was adopted to simulate the operation of an energy system over one year.

3.2 Key Literature Trends Informing Methodology

From the modelling tools considered, there was not a shortage of modelling tools for a developing country context specifically for a local energy planning approach. Examples include Homer, DER-CAM and TEMPO to name a few. However, there has not been a clear framework for evaluating the improvement in satisfaction of energy services for the designed energy systems. These largely make use of standard metrics such as levelised cost of electricity (LCOE) and carbon emissions. The Multi-Tier Framework comes closest to evaluating energy access levels but this still does not assess the satisfaction of energy services as a direct result of integrated supply technologies. Although Miller et al.’s (2015) motivation for the need of a framework for evaluating the social value of energy services is only in the form of a discussion, this provides a good starting point for what is often only a techno-economic analysis of energy systems. Miller et al. (2015: 68) explain that, “The tendency in mid-scale projects is to focus almost exclusively on energy supply, leaving aside questions about the design of socio-technical arrangements that transform energy supplies into energy services that deliver social value”.

This leads to the discomfort level framework which stems from the arguments and concepts found in literature to explore the possibility of a discomfort level which interprets the improvement in satisfaction of energy services within a distributed community energy system. To test the framework a simplified energy system was developed for the study, the outputs of which were used to formulate a discomfort level. It was informed by the evidence from several sources (Azimoh, 2016; Bhattacharyya & Timilsina, 2010; City Power, 2011; IRENA, 2016a; Murphy *et al.*, 2014) that energy systems in developing countries have low reliability in meeting demand .

From the literature reviewed in an attempt to address the sub-questions of the research question for this study, the following key features of a traditional energy system versus a distributed energy system inform the methodology:

Table 4: Key literature trends informing research questions

Research Question	Traditional Energy System	Distributed Energy System
What are the unique energy needs of developing countries?	Energy access Urbanisation Electricity focused Network grid reliability	Energy access Increasing population Energy focused Reliability of supply
Which energy modelling approaches are being used currently?	Utility scale resources Centralised integrated resource planning Typically carbon intensive Peak and off-peak supply and demand matching (Koirala, 2017) Passive consumers Grid-connected Complex modelling tools with costly licenses Homogenous demand Demand forecasting Long and medium term planning	Distributed energy resources Local energy planning Integrated energy systems approach Flexible supply and demand matching (including storage) Spatio-temporal modelling Interchange between consumer and producers Off or on-grid connections Increase in open, free and affordable modelling tools Smart meter management Dynamic demand profiles Demand forecasting Short, medium and long term planning
What evaluation approaches are currently being used?	Techno-economic focus	Techno-economic focus Environmental Value to the end user

3.2.1 Research Approach Description

This section provides a high-level overview of how the simulated model was designed. The model aims to show

i. the types of energy service needs unique to an income group using the probabilities of time of use of electrical appliances as a proxy for demand data;
ii. the unique generation profiles of energy supply options which include solar PV, small scale concentrating solar power (SS-CSP), wind generation, diesel generators and solar water heaters using real time series weather data; and
iii. the discomfort levels in terms of meeting end-user energy services compared to levelised cost of electricity (LCOE) for different combinations of energy supply technologies.

For this study, the levelised cost of electricity (LCOE) and discomfort level are the metrics used for evaluating the energy systems explored. The purpose of the discomfort level which is defined in *Chapter 4 (Evaluation Framework)* is to interpret the improvement in satisfying the energy service needs of the end-user as a result of different energy supply infrastructure options.

A simplified test case was used to test the energy system balance between supply and demand over a one year period. The test case is a simplified conceptual residential community called eShushu (meaning hot place in isiZulu) with a demand profile simulated using end-user appliance probabilities for time of use. Real hourly weather data was used to determine solar and wind resource. The population numbers influence the number and type of appliances used, capacity of energy carrier options and the income group determines the types of energy services modelled.

The question posed for the test case is,

> *For a set number of decentralised technology options, how do these options satisfy the required end-user energy services in terms of discomfort levels compared to LCOE?*

Figure 7 shows the main steps of the methodology followed after a discomfort framework was defined. These steps include (i) modelling of components; (ii) modelling of the system; (iii) application to a case; (iv) ranking of technology combinations by discomfort level and LCOE; and (v) drawing findings and conclusions. These steps have been designed such that the process is repeatable for case studies with unique features. The uniqueness referred to here is as outlined in *Chapter 1 (Introduction)*, and includes the site specific weather resource and the energy demand which influences the types of supply infrastructure selected to service energy needs.

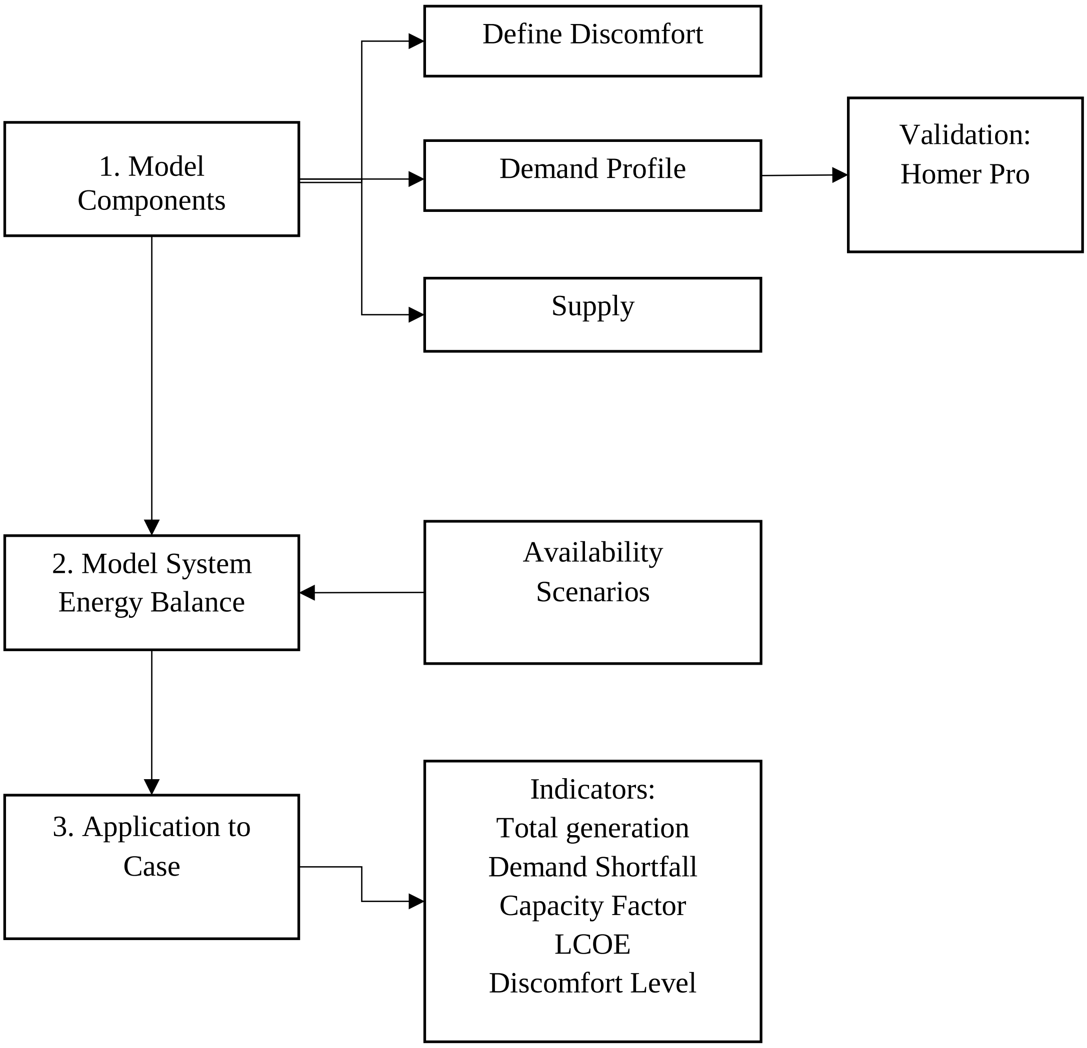

Figure 7: Outline of the method application steps

Each step is briefly outlined next and in greater detail in *Chapter 4 (Evaluation Framework)* and *Chapter 5 (Model Description & Test Case).*

3.2.2 Model Components

This section gives a description of the three main building blocks of the model, namely energy demand and energy supply output.

3.2.2.1 Define a Discomfort Framework

The concept of discomfort level stems from the residential cost of unserved energy (COUE) defined by Minnaar (2015) as a Rand per kilowatt hour (R/kWh) indicating the discomfort of lost opportunity as a result of disruptions to the supply of electrical energy. However the COUE described in *Chapter 2 (Literature Review)* is calculated based on electricity usage as opposed to the energy services derived from electricity usage which is the core focus of this study. The focus for this study is placed on energy services for the reason that supply infrastructure provides access to energy but it is the energy service satisfied that provides extrinsic value to the end-user in a developing country context (Nussbaumer, Bazilian & Modi, 2012; SE4ALL & ESMAP, 2015b).

Different technology combinations result in distinct levels of satisfied end-user energy services for various reasons such as availability of weather resource, varying levels of storage and scheduled maintenance amongst others. It is proposed that a discomfort level be quantified from the end-user energy services unmet at each hour for a selection of technology combinations based on the varying priority (according to the end-user) of these services and the end-user's usage patterns. The discomfort level is measured on an hourly basis shown in equation (10) and is dependant on the (i) priority index of energy services as perceived by the user, (ii) energy service usage patterns of the user and (iii) the demand shortfall ratio representing unserved demand per hourly time step.

$$\begin{aligned} &\text{Discomfort Level}_\text{h} \\ &= \text{Priority index}_\text{h} \times \text{Energy service usage}_\text{h} \times \text{ Demand shortfall ratio}_\text{h} \end{aligned} \tag{10}$$

The detailed steps of how this is calculated are provided in *Chapter 5 (Discomfort Framework)*. As set out in the objectives, the discomfort level is to be compared to the levelised cost of electricity (LCOE) for different technology combinations.

3.2.2.2 Modelling a demand profile from energy services

The domestic demand profile for an electrified household is according to Mcloughlin, Duffy and Conlon (2010) made up of three categories, namely (i) cyclical appliances; (ii) appliances randomly switched on or off; and (iii) continuous or standby appliances such as refrigerators. Continuous appliances are approximated using deterministic methods but modelling of cyclical and randomly used appliances requires stochastic methods because the usage patterns of these are less predictable. Examples in literature of stochastic modelling methods for constructing demand profiles include Markov chain modelling (Mcloughlin *et al.*, 2010), Monte Carlo simulation (Baur & Eisner, 2017) and statistical regression forecasting. Markov chain modelling is based on transitional probability where a probability matrix is used to model the transition from one discrete state to the next (Mcloughlin *et al.*, 2010).

A Monte Carlo simulation is a stochastic method used to model the probability of a number of random outcomes based on a probability distribution (Buxton, 2015). Statistical regression is obtained from long term data logging and using regression equations for energy consumption and influencing factors (Richardson, Thomson, Infield & Clifford, 2010). Huang et al. (2015) classify statistical regression into two approaches, namely time series and key factor forecasting. The difference between the two approaches is that the key factors approach analyses the correlation between energy consumption and independent variables such as population, economic group, climate and lifestyle to name a few (Huang *et al.*, 2015). For community scale projects, simulating the energy demand requirements or load index of every building is also a common method of constructing a load profile (Huang *et al.*, 2015).

The demand was limited to end use energy services including lighting, water heating, refrigeration, cooking and phone charging. Household electrical appliances are a proxy for end-use energy services to simulate an hourly demand profile. The energy services defined for this study are adapted from the Multi-Criteria Energy Poverty Index (MEPI). The MEPI was developed by the United Nations Industrial Development Organisation (UNIDO) and uses the lack of ownership of modern energy appliances for various energy services as a proxy for deprived energy (SE4ALL & ESMAP, 2015a: 38). The index is made up of five dimensions developed by Nussbaumer (2013) including cooking, lighting, services provided by other household appliances, entertainment or education and communication. The discomfort level is complimentary to and were compared to the levelised cost of electricity (LCOE) to evaluate community scale energy systems.

3.2.2.3 Modelling of supply technologies

The generic energy supply technologies modelled for this study include solar PV, wind turbines, diesel generators, small-scale concentrating solar power (SS-CSP), diesel generators and battery storage. Solar water heaters (SWHs) were treated as energy efficiency (EE) technologies applicable to thermal energy demand for water heating. The grid, diesel fuel, paraffin and biomass were treated as external flows to the system boundary. The design specifications of each supply technology were based on empirical data, first principles and assumptions based on literature outlined at each step of this study.

3.2.3 Model System Energy Balance

A system energy balance of supply and demand was modelled at an hourly resolution depending on the availability of each supply technology. Excess solar PV and wind was used to charge battery storage.

3.2.4 Application to Case

Two cases were selected for application of the model. The first, Thembelihle is an informal settlement located in Johannesburg, South Africa with unreliable access to the electricity grid during peak times when the grid is constrained (City Power Johannesburg, 2015). The second is a residential community in Likoma Island, Malawi which is highly dependant on an independent grid supplied by costly diesel generators (Zalengera *et al.*, 2015). Real solar and wind weather data with an hourly resolution was used for both locations. Additional data about the two locations was gathered from literature. The reason for not gathering data through surveys and interviews is that the model described is not meant to be a prescriptive design solution for each case study but rather a demonstration of (i) the unique needs in a developing country context and (ii) the ability of different supply technology combinations to satisfy end-user energy services on an hourly basis. A simple comparison was made between discomfort levels and LCOE for different supply combinations given the unique end-user needs of each community. Base scenarios for solar PV, wind and CSP were modelled using a sensitivity analysis for system sizing. From the selected system sizes the total generation, demand shortfall, capacity factor and LCOE were calculated for each scenario.

3.3 Software Simulation

From the modelling tools reviewed in *Chapter 2 (Literature Review)*, *PLEXOS, HOMER, PSST, Calliope, and Python* were shortlisted and compared in Table 5. The main key issues identified from literature for selecting a tool from the shortlisted options include limitations as a result of (i) the user software license; (ii) the optimisation capability of the tool; and (iii) the tool's flexibility to local energy planning scales including community scale and even single projects as listed in Table 5. Additionally the Power Systems Simulation Tool (PSST) developed by Landman and Gauché (2017) based on the PhD thesis by Gauché (2016), "*Spatial-temporal model to evaluate the system potential of concentrating solar power towers in South Africa*" was used for system simulation of the model components at various stages. The Homer PRO Microgrid Analysis Tool (Lambert, Gilman & Lilienthal, 2006), a popular optimisation modelling tool for micro-grids was also used to validate the case study model results.

Table 5: Comparison of modelling tools shortlisted for this study

Feature	**PLEXOS (Academic license)**	**HOMER (Trial academic license)**	**PSST**	**Calliope (Open source license)**	**Python (Open source license)**
License limitations	None	Only valid for 21 days	None	None	None
Optimisation capability limitations	Lack of transparency	Lack of transparency	No optimisation	Open access	Libraries available
Flexibility to local energy planning scales	Low	High	High	Low	High

PSST was the modelling tool used because of its open-source license and the well-established international user community of Python, the language platform it uses (McKinney, 2013). Supply generators in the PSS tool are easily added while the final solution is only based on the capacity and availability of generators at each hour to formulate an energy balance.

As highlighted in the literature review, the optimisation of software tools such as Homer and PLEXOS are not transparent to the user (Mabaso *et al.*, 2018). Calliope on the other hand is open source but is better suited to utility scale modelling (Pfenninger, 2015). Excel was also used to model the load and to process the Python output files.

3.4 Weather Files and Permissions

Solar and wind data with an hourly resolution was used for modelling of supply technologies. The wind speed data used was obtained from the Wind Atlas for South Africa (WASA) by SANEDI (2017). WASA is a wind atlas that maps the wind resource of South Africa through an online initiative by SANEDI and partner institutions (SANEDI, 2017). The wind and solar data used to model the test case was verified using the study by Gauché (2016) and includes data for a full year beginning in July 2015. Hourly solar and wind data for both Thembelihle and Likoma Island were obtained from HelioClim-3 Archive Database of Solar Irradiance and Meteorological Data (SoDA, 2017) for a year from 2005/07/01.

3.5 Model Validation

The reliability of the method relies on modelling of the technologies and the assumptions made. Through the use of validation techniques, the reliability can be tested. The use of hourly resolution spatial-temporal data will improve the reliability of the supply model results. For verification, the solar PV model was based on and verified against Gauché's (2016) bottom-up model while the wind model and idealised battery model was verified using *Homer* (2017a). The small scale CSP model was compared to a verified generic model of a central receiver model by Landman and Gauché's (2017) Power Systems and Simulation (PSS) tool. All other assumptions regarding economic and technical indicators such as costs and efficiencies are provided at each step of developing the model. For system sizing, sensitivity parameter analyses was used. For the discomfort framework, the demand shortfall and energy service usage are a direct output from the validated demand-supply model. The priority index of energy services was derived from proxy data.

3.6 Model Exclusions and Limitations

The model only represents an operational snapshot frozen for a single year. It does not account for forecasting of demand, population growth, learning rates of technologies and the transmission system. Some factors which are excluded from the study due to resource and time constraints but are considered important include and are not limited to (i) convertors and inverters, (ii) space heating, (iii) retrofitting of buildings or building types, (v) solar cookers, (vi) paraffin use and (vii) the grid transmission system. Validation of the proxies used to formulate the priority of energy services through surveys was not carried out for the Thembelihle case study.

3.7 Chapter Conclusion

The method proposed in this chapter although simplified is bounded, well aligned with the research objective and makes use of building blocks to simplify the modelling process. The following chapter will explore some metrics and frameworks used to evaluate energy systems and justify the proposed discomfort level.

4 EVALUATION FRAMEWORK

“Not all kWh's are the same and designing and operating them as if they were will surely be inefficient, or simply unrealistic”.

- G. Ireland, Sustainable Energy Systems – ERC UCT, 2018

This chapter presents a summarised list of key metrics reviewed in Chapter 2 (Literature Review) for evaluating distributed energy systems. From the review carried out, a framework or metric to interpret the improvement in satisfying end-user energy services for different technology combinations was not found. As a result of this, a metric called the discomfort level was formulated for the purpose of this study. The discomfort level is a proxy metric that interprets the improvement in satisfying end-user energy services at each hourly time step given different technology combinations. A detailed outline of the discomfort framework is provided in this section.

4.1 Review of Priority Indicators

Borbonus (2017) in a discussion about the socio-economic value from renewable energy points out that ‘access to energy’ is an indicator commonly used but it lacks a clear definition. For example, she suggests that it could imply *“a minimum level of electricity demand met within a given budget”* or *“a minimum level of reliability in terms of hours of interruption”* or *“a number of electrified villages”* amongst others (Borbonus, 2017: 9). The findings from the literature review carried out for this study concurs with this argument – there exists a wide range of evaluation indicators and metrics used to evaluate energy systems. To translate this information into a form useful for this study, a summary of priority factors for evaluating energy projects were identified for discussion in Table 6 mostly from literature. A total of twenty-one factors were identified and classified into technical, economic, techno-economic, socio-economic or environmental. The diverse nature of factors highlights the complexity of evaluating the suitability of energy systems.

Table 6: A list of energy project evaluation priority factors

Priority Factor	Category	Description	Metric
Grid connection (SE4ALL & ESMAP, 2015a)	Technical	Access to an electrical grid	Distance from the grid
Capacity (SE4ALL & ESMAP, 2015a)	Technical	Refers to the size or scale of the system	Capacity
Availability (SE4ALL & ESMAP, 2015a)	Technical	Duration of the energy service being offered	Number of available hours, Resource assessments

Priority Factor	Category	Description	Metric
Reliability (SE4ALL & ESMAP, 2015a)	Technical	Number of outages or disruptions	Number of outages or disruptions
Quality (SE4ALL & ESMAP, 2015a)	Technical	Limitations to the types of appliances which can be used due to voltage challenges	Voltage problems, appliances that one can use
Affordability (SE4ALL & ESMAP, 2015a)	Economic	The cost of electricity generation	LCOE
Maintenance	Technical	Ease of maintenance	Level of skills required
Replacement of parts (Azimoh, 2016)	Techno-economic	Ease and cost of replacing system parts	Local availability of parts Lead delivery times
Local Economic Development (Azimoh, 2016)(Arthur *et al.*, 2012)	Socio-economic	Productivity or the use for income earning activities(SE4ALL & ESMAP, 2015a)	Businesses and community facilities in the project area
Emissions (CO2) (Bischof-niemz & Wright, 2016)	Environmental	Emissions during operation	Tonnes of CO2
Water Usage (Bischof-niemz & Wright, 2016)	Environmental	Usage of water during operation	Litres of water used for operation
Modularity	Techno-economic	Potential of capacity expansion	Modularity
Min Stable Generation Levels	Technical	Minimum allowed generation level	% Min stable level and ramp rates
Subsidies (Urban *et al.*, 2007)	Socio-economic	Applicable government subsidy policies	% of subsidies
Security	Socio-economic	Theft of PV panels is an example	Number of associated thefts of system parts and crime levels
Vulnerability to inflation	Techno-economic	For example fuel costs and import taxes	Historical changes in the cost of fuel
Learning rate	Techno-economic	The expected reduction in cost of	

Priority Factor	Category	Description	Metric
		the technology over time	
Dispatchibility (Ramp rates)	Technical	The generator's ability to adjust power output upon request or on demand	Ramp rates
Revenue Model	Socio-Techno-economic	Financial sustainability of plant (is it self-sustaining?)	Tariff scheme
Implementation period	Technical	The time taken from procurement to operation	Period of installation
Health (SE4ALL & ESMAP, 2015a)	Socio-economic	The occurrence of accidents or the perception of high risk	Health related concerns, waste from operation

4.2 Discomfort as an End-User Approach

The discomfort level framework is defined in this section. To begin with, a definition for discomfort is outlined followed by a formulation of the discomfort level metric. The terms making up the discomfort level are described as (i) the priority index of energy services, (ii) energy service usage and (iii) the demand shortfall ratio.

4.2.1 Discomfort in an Energy System?

The research question of this study a part of which is repeated here for emphasis is as follows: "**What are the approaches of quantitatively evaluating community scale energy systems such that the choice of technology combinations offers an improvement in terms of (i) satisfying the end-user's energy service needs…"**. From this question, there is an implicit assumption that the satisfaction of end-user energy service needs has an extrinsic value to the user, specifically a user within a community scale energy system in an emerging economy. Although various literature sources reviewed in Chapter 2 provide evidence for this argument, there was not a metric or framework found to interpret the improvement in satisfying the end-user's energy service needs as a result of different supply technology combinations. Koirala (2017) highlights that apart from carbon emissions and costs, improved comfort and resistance to the utility model are some of the key drivers of integrated community energy systems (ICES). Although Koirala (2017: 15) does not model comfort, he defines it as, "having electricity around the clock". Miller et al. (2015) also only discuss a social value index which describes the benefit derived by an individual or community from an energy system. Another closely related concept to this is reliability. Reliability as listed in Table 6 is defined as a supply-side technical metric measuring the number of outages or disruption to the energy system (SE4ALL & ESMAP, 2015b).

This study proposes an end-user indicator, a discomfort level to reflect the energy services unmet at each hour for a selection of technology combinations. The discomfort level is not a novel concept as its formulation is based on various arguments, frameworks and concepts found in literature all based on the premise that energy services in an emerging economy offer extrinsic value beyond "energy access" to its end-users. Discomfort level for this study describes the improvement in satisfying the end-user's energy service needs as a result of different supply technology combinations. The main steps for formulating an index for research purposes are outlined by Crossman (2017) and include (i) the selection of items to be evaluated, (ii) examining of empirical relationships and (iii) validating the index. This approach was applied in formulating a discomfort index. For the priority of energy services, a pairwise comparison method by Koczkodaj and Szybowski (2015) is used to formulate a weighting index. The energy service usage is calculated from the hourly share of energy services calculated in the energy system model. Finally the demand shortfall ratio for each technology combination is calculated from the demand shortfall for each scenario.

The discomfort level is formulated in equation (11).

$$\begin{aligned}&\text{Discomfort (per hour)}\\&=\text{Priority index}_{\mathrm{h}}\times\text{Energy service usage}_{\mathrm{h}}\times\text{Demand shortfall ratio}_{\mathrm{h}}\end{aligned}\tag{11}$$

Where h represents an hourly time step. An overview of how each of the three components of the discomfort level were formulated is provided in the proceeding sections and demonstrated using eShushu. An explanation of each term is provided in the next section with supporting concepts from literature where relevant, followed by a flowchart demonstrating the integration of discomfort level into an energy system. The formulation of discomfort implies a zero discomfort level when all energy services are satisfied. In reality, end-user data can be obtained from surveys but proxy data will be applied to test the framework for this study.

4.2.2 The Value of Discomfort Level

At this point it has been demonstrated that there are various approaches found in literature showing that the value of energy to the end-user in an emerging economy extends beyond energy access. What then is the benefit or use of a discomfort level? The discomfort level can be used and will be tested in this study in direct comparison to the levelised cost of electricity (LCOE), typically used as a supply-side techno-economic indicator. The benefit of the discomfort level is that it captures the unique end-user side energy usage patterns and preferences which means that the satisfaction of energy services is not only as a result of the technologies but is also influenced by the unique end-user context such as the type of appliances used as a proxy for the energy services used. To better understand the 'social value of an energy system' coined by Miller et al. (2015), the discomfort level is a practical demonstration that this requires an understanding of the unique end-user's usage and preference patterns. In this case, a community scale approach was adopted. Energy systems experience unmet demand for a number of reasons such as a shortage in supply, unplanned increases in demand, operational and maintenance challenges to name a few. In reality, the discomfort level helps in interpreting the energy services (and the social value thereof) forfeited in the case of unmet demand as a result of supply technology combinations. From this, this can inform the evaluation of technology combinations but also help to align the type of technology combinations well suited to the energy services of a unique community.

4.2.3 Priority Index of Energy Services

The priority index of energy services simulates the end-user's perception of how important energy services are in comparison to each other at each hour of the day.

From literature, Zalengera, Blanchard and Eames (2015) explore and use the notion of 'the prioritization of energy services' to rank energy services based on a household survey. The study shows that different energy services are perceived to have varying levels of importance by end-users. For example, lighting and cooking are perceived to be of highest importance by the household survey participants in Likoma Island, Malawi (Zalengera *et al.*, 2015). In a separate study, Nussbaumer et al. (2013) developed the Multi-dimensional Energy Poverty Index (MEPI) which is an indicator used to determine how energy poor a household is. MEPI is calculated based on a weight assigned to each energy service (lighting, cooking, communication, entertainment, etc) and a final energy poverty index is calculated indicating the level of energy access that a household has as shown in Table 7 (Nussbaumer *et al.*, 2013) . Although both the MEPI and the household survey approaches provide evidence that there are varying levels of priority for energy services as perceived by the end-user – these authors do not account for these variations on a temporal basis. In reality, energy services do not retain the same perceived priority throughout the day. An example of the varying priority of energy services is shown in an advertisement from a hotel in Stellenbosch offering a once-off phone charging service for R50 which is a good example of the consumer's varying willingness to pay (WTP) varies at different times of the day. In such a case, the R50 for a fraction of a kilowatt hour (approximately 0.005 kWh) is perceived as valuable in the case of an emergency, travelling, outdoor adventures as marketed by the supplier. However, this perception of priority of phone charging is different when the user is at home and directly influences the willingness to pay for this energy service.

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Figure 8: Once-off phone charging service valued at R50

Table 7: The MEPI with dimensions and weights adapted from Nussbaumer (2013: 235)

Dimension	**Indicator (Weight)**	**Deprivation cut-off (poor if…)**
Cooking	Modern cooking fuel (0.2)	Use any fuel beside electricity, LPG, kerosene, natural gas or biogas
	Indoor pollution (0.2)	True
Lighting	Electricity access (0.2)	False
Services provided by means of household appliances	Household appliance ownership (0.13)	False
Entertainment/ education	Entertainment/education appliance ownership (0.13)	False
Communication	Telecommunication means (0.13)	False

To formulate a priority index of energy services, a number of end uses for the energy services of a household during the morning and evening for households of the eShushu hypothetical test case were identified as listed in Table 8.

Table 8: An example end-user value framework for a test case household

Energy Service	**Morning**	**Evening**
Lighting	Preparing for the day	• Family/social time • Study/homework • Relax/stay up working on an extra project or preparing for the next day • Safety/security?
Refrigeration	Fresh food	• Fresh food • Lunch for the next day • Medication
Cooking	Warm breakfast	• Warm home cooked meal • Possible family/social time
TV	Weather report/ morning news	• Exposure to current affairs • De-stress, something to do • Social/family time
Phone Charging	Communication – transport, employer, emergency, potential business	• Communication – transport, employer, emergency • Internet access – business, educational, potential for productivity
Space Heating	Warmth	• Warmth
Water Heating	Bath/Shower • Tea/Coffee	• Bath/Shower • Tea/Coffee

Weighting of multiple decisions is commonly used in multi-criteria decision making and is typically carried out by one of three approaches, namely weighting by ranking, weighting by rating or weighting by pairwise comparison (Laube & Rogers, 2013). Weighting by ranking ranks the criteria in ascending or descending order, and weighting by rating assigns a score to criteria according to relative importance (Laube & Rogers, 2013). Weighting by pairwise comparison compares two criteria at a time in the form of a matrix. Although easy to use, determining criteria weights by ranking and rating approaches are less statistically secure as the number of criteria options increase (Laube & Rogers, 2013). The downside of the pairwise comparison method is that it is time consuming as two criteria are compared at a time but allows one to monitor the consistency of the matrix (Løken, 2007).

Seeing that energy services are not mutually exclusive, the simple pairwise comparison method is selected to simulate the priority of energy services for this study. As a proxy for the type of household survey used by Zalengera, Blanchard and Eames (2015), energy services are compared to each other in a simple pairwise comparison matrix. The pairwise comparison process is carried out in two main steps, namely (1) constructing a pairwise comparison matrix and (2) calculating the vector of criteria weights (Laube & Rogers, 2013). To construct the pairwise matrix, two criteria are compared row (i) by row in the upper right half of the matrix based on the scale shown in Table 9 (Saaty, 2008).

The diagonal of the matrix is made up of values of 1 while the lower half of the matrix is filled with the corresponding fractions of the top half. To get a criteria weighting, the matrix is normalised ($\overline{a_{ij}}$) by dividing each matrix value by the sum of its columns (j). Finally, the weights (w_j) are given by the mean of the rows of the normalised matrix.

Table 9: Pairwise numerical scale ranking developed by Saaty (2008)

Value	Interpretation
1	i and j are equally important
3	i is slightly more important than j
5	i is more important than j
7	i is strongly more important than j
9	i is absolutely more important than j

The normalised matrix ($\overline{a_{ij}}$) entries and criteria weights (w_i) are given by

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_{i=1}^{m} a_j} \qquad (12)$$

$$w_i = \frac{\overline{a_{ij}}}{\frac{\sum_{i=1}^{m} a_i}{m}} \qquad (13)$$

Where m is the number of criteria being evaluated.

For the eShushu test case, the priority index of energy services categories include (i) cooking, (ii) lighting, (iii) water heating, (iv) services offered by other electrical appliances, (v) education and entertainment, and (vi) communication. An example of the comparison matrix is shown in Table 14 for a test case household. The rows (i) and columns (j) of the matrix represent the energy services. Once evaluated using the numerical scale in rows of the normalised matrix.

Table 10, the lower half of the matrix consists of corresponding fractions and each value is normalised by dividing through by the sum of the corresponding column.

The normalised values are used to formulate the matrix in Table 11 which is used to calculate the sum across each row to get a weighted index. For the test case, two periods in the day are identified with different priority indices for energy services as shown in Table 12.

Table 10: Pairwise Comparison Matrix

	Cooking	Lighting	Services by other appliances	Entertainment/ Education	Communication	Water heating
Cooking	1	1	7	5	7	7
Lighting	1	1	7	5	7	5
Services by other appliances	0.143	0.143	1	0.2	3	0.143
Entertainment/ Education	0.2	0.2	5	1	3	0.2
Communication	0.143	0.143	0.333	0.333	1	0.2
Water heating	0.143	0.2	7	5	5	1

Table 11: Normalised Pairwise Comparison Matrix

	Cooking	Lighting	Services by other appliances	Entertainment /Education	Communication	Water heating
Cooking	0.380	0.372	0.256	0.302	0.269	0.517
Lighting	0.380	0.372	0.256	0.302	0.269	0.369
Services by other appliances	0.054	0.053	0.037	0.012	0.115	0.011
Entertainment/ Education	0.076	0.074	0.183	0.060	0.115	0.015
Communication	0.054	0.053	0.012	0.020	0.038	0.015
Water heating	0.054	0.074	0.256	0.302	0.192	0.074

In reality the energy services are not mutually exclusive but have a differing priority of value that is unique for different households. However, for planning, there are some general shared trends of behaviour around energy usage (Saaty & Vargas, 1982).

Table 12 shows two priority indices 1 and 2 which represent two different time periods of the day. The indices result from constructing the matrices in Table 10 and Table 11. The differences in index 1 and 2 stem from the perception of relative importance of each of the energy services during the two periods of the day (for example during off-peak hours and peak hours of energy usage for this hypothetical community).

Table 12: Priority index weights for eShushu

Energy Service	Index 1	Index 2
Cooking (CG)	0.33	0.35
Lighting (LG)	0.33	0.32
Services provided by other appliances (AS)	0.05	0.05
Entertainment/Education (EE)	0.08	0.09
Communication (CN)	0.04	0.03
Water heating (WH)	0.16	0.16

4.2.4 Energy Service Usage

Energy service usage represents demand at each hour in terms of energy services. The household appliances used in the test case are grouped under one of the five main energy services (water heating, lighting, entertainment, cooking, communication and other appliances) defined for the multi-dimensional poverty index (MEPI) as defined in the previous section where the demand profile for the test case is defined. For this term, the user's demand at each hour of the day is made up of a distribution of energy services. Figure 9 shows an example of demand in terms of energy services on an hourly basis over 24 hours for each energy service category.

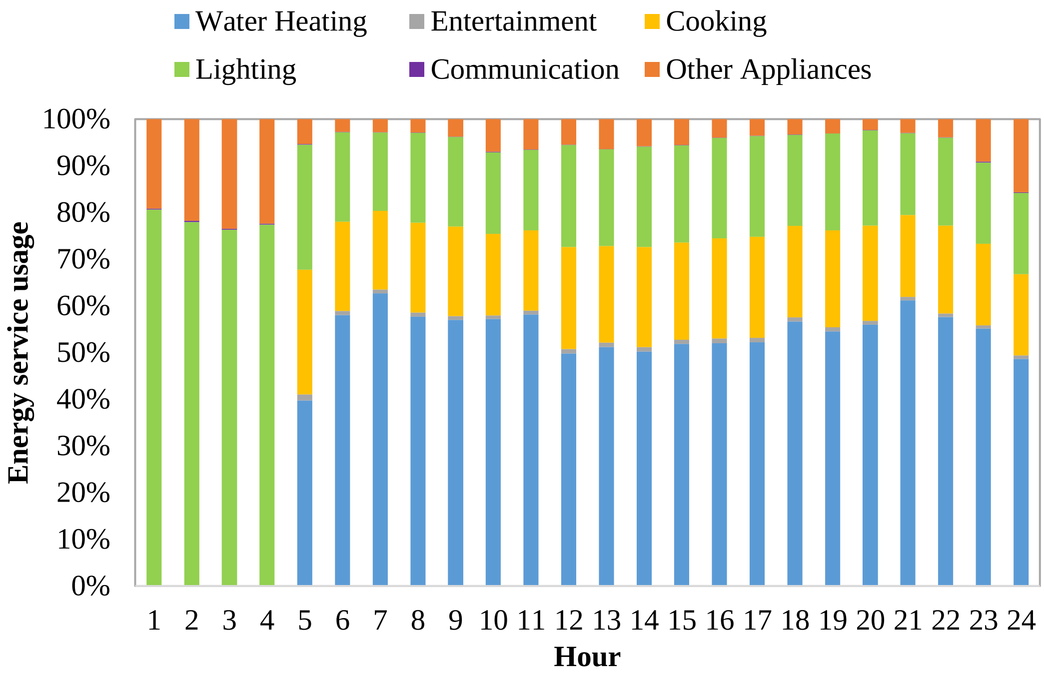


Figure 9: Hourly share of energy service usage over 24 hours

4.2.5 Demand Shortfall Ratio

The demand shortfall ratio is calculated as the annual ratio of demand shortfall to the total demand in equation (14).

$$\text{Demand shortfall ratio} = \frac{\text{Demand shortfall}}{\text{Total demand}} \tag{14}$$

From the supply side, each energy system based on a combination of unique supply technologies has a portion of the demand load which it was unable to meet for various reasons such as minimum levels of storage discharge, availability of weather resource, scheduled maintenance.

An example of the discomfort level per generator for a randomly selected day is shown in Figure 10.

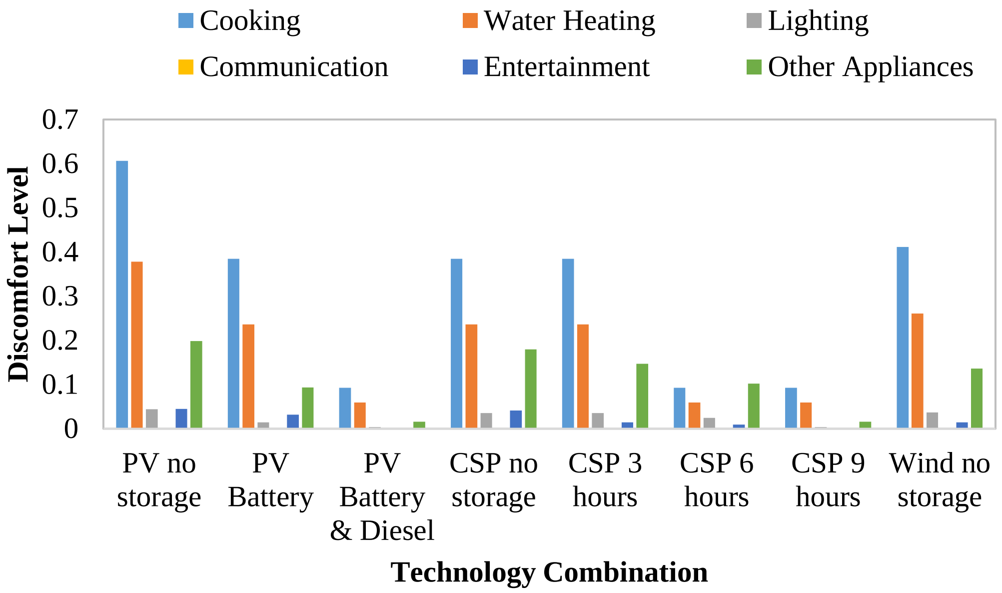


Figure 10: Discomfort Level for a randomly selected day

4.2.6 Integration of Discomfort Level into the Energy System

The discomfort level is measured on an hourly basis and is dependant on the (i) priority index of energy services as perceived by the user, (ii) energy service usage patterns of the user and (iii) the demand shortfall ratio measuring unmet demand by supply energy infrastructure as shown (highlighted in grey) in Figure 11.

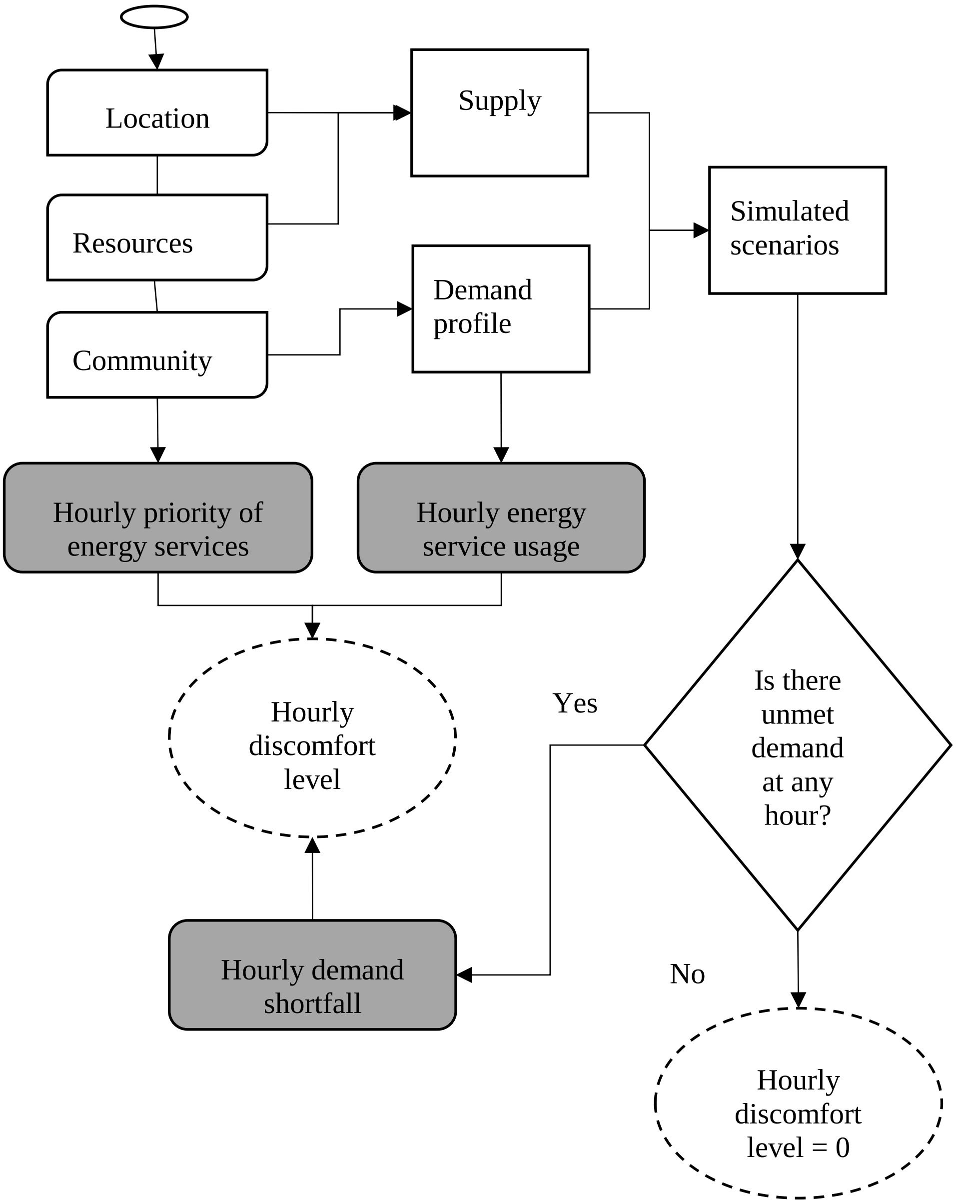


Figure 11: The proposed components of discomfort level

4.3 Chapter Conclusion

This chapter has outlined a framework for discomfort level as an end-user service indicator. This indicator provides a basis for comparing different technology combinations based on demand shortfall unique to supply generators and energy services unique to a community context. Although the framework defined in this chapter is conceptual, the user energy services can be altered according to appliance usage and the priority of energy services assigned unique indices as shown in the proceeding chapter with two real case studies. Seeing that the terms defining the metric have been defined, the proceeding model description will provide outputs required for the application of the discomfort level framework.

5 SIMULATION DESCRIPTION & TEST CASE

This chapter presents a detailed description of the simulation components, process and application to a test case needed to test the discomfort framework developed in the previous chapter. Figure 12 shows the building blocks of supply which include distributed energy generators; energy storage; and solar water heaters (SWHs). Demand was formulated from electricity and heat driven energy services determined by the community context. For each sub-model defined, it is directly applied to a hypothetical community to test the method and key concepts introduced in Chapter 2 are expanded where relevant.

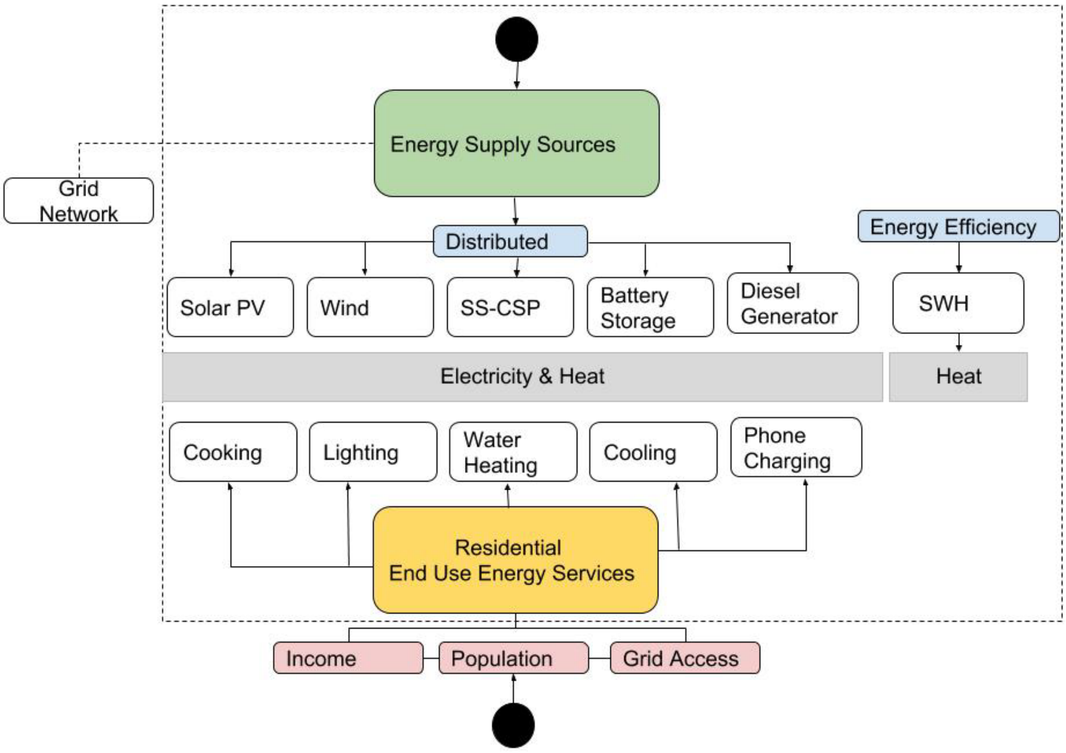


Figure 12: Model boundary of demand and supply building blocks

5.1 Conceptual Test Case: eShushu

The hypothetical community eShushu is made up of 100 households located far from the grid network. Therefore an autonomous off - grid energy system with a high penetration of renewable energy technologies was modelled including a selection of solar PV, wind, concentrating solar power (CSP), battery storage, diesel generators and solar water heaters (SWHs). The objective for this community's hypothetical energy planner is to compare the discomfort level stemming from demand shortfall to the levelised cost of electricity (LCOE) for the selected supply technology combinations. For the purpose of this study, demand shortfall refers to the demand unserved per time interval due to limited supply. The test case was modelled using solar and wind data over a full year (1st July 2015 until 30th June 2016) sourced from the HelioClim-3 Archive Database of Solar Irradiance and

Meteorological Data (SoDA, 2017). The location used is an arbitrary site in Namibia at a latitude and longitude of -21.487 and 16.031 degrees respectively.

5.2 Energy Demand Model

For this study's objectives, a suitable approach for modelling demand is one which (i) considers end-use energy services; (ii) is applicable to residential community scale; and (iii) does not require historical energy consumption data. For this reason, a simplified bottom-up demand profile formulated from electrical appliance proxy data for energy services was used. In this section several approaches using appliances to create a demand profile are considered. Finally, a 'time of use' approach is selected over a simplified Monte Carlo is used to formulate a profile for eShushu.

5.2.1 Appliances as Proxy

In reality, a single household is not representative of an entire community. To account for variations in end-user demand profiles, various simplifying approaches were considered. A brief overview of each is provided.

a) Coincident Factors

One of the ways that power utility companies account for the variability in demand of residential households is through the use of coincident factors. A coincident factor of power demand (C) is a ratio of the daily peak demand of an aggregated community to the combined daily cumulative sum of individual households in that community (Brooks, Manur & Venkataramanan, 2016). This method is most applicable in cases where historic demand data is available.

b) Central Limit Theorem

The central limit theorem from probability theory is commonly applied to aggregating the demand of a population because the individual loads are both stochastic and intermittent (Boait *et al.*, 2015). The central limit theorem states that for a population with mean m and standard deviation σ, taking "large random samples n with replacement, the distribution of the sample means will be approximately normally distributed" with a mean equal to m and a standard deviation of ${}^{\sigma}\!/_{\sqrt{n}}$ (LaMorte, 2016: 1).

c) Simplified Monte Carlo

A simple Monte Carlo model by Baur and Eisner (2017) was considered. For this method, the probability of each appliance being switched on or off is represented by a percentage which depending on the random numbers (0 or 1) generated for each minute simulates the appliance usage of a household (Baur & Eisner, 2017). The power consumed at each time interval is then used to create a time series demand profile. A Monte Carlo simulation offers flexibility because it accounts to some extent for the diverse energy consumption behaviour of a population (Baur & Eisner, 2017). However the downside of such an approach is that it requires that an iteration of each household forming part of the community be carried out to formulate an average demand profile for the community.

d) EscoBox Demand Forecasting Tool

Boait, Advani and Gammon (2015) developed a demand forecasting tool called the EscoBox using end-use appliances to derive a demand profile compatible with Homer software. The demand generated is founded on three factors, (i) population of each electricity device (N), (ii) load of each device (E) , and (iii) the probability of each device being in use at each given time (p) as shown in equation (15) (Boait *et al.*, 2015).

$$\mathrm{D} = \sum_{1}^{\mathrm{i}} \mathrm{E_i p_i N_i} \qquad (15)$$

Random numbers are generated to simulate the appliance being on or off. For this approach the total demand is given by the sum of all appliances per time interval (i). The EscoBox tool makes use of a binomial distribution for the probabilities. ESCoBox offers a simple method of constructing a load profile also based on end-use appliances but the resulting profile is only accessible with the use of Homer. Another disadvantage is that the same probability of use for each appliance is applied throughout the whole day instead of an hourly time series probability.

5.2.2 Comparison of Demand Modelling Approaches

This study makes use of a unique probability of the appliance being in operation at each hour of the day instead of a daily value as used by Boait, Advani and Gammon (2015). The proxies used for eShushu are based on the time of use of appliances by Kehrer (2008) in a survey of a South African informal settlement. A demand profile for each appliance is generated for the community of 100 households by assuming the number of appliances per household and the probability of use at each hour of the day. Random numbers are generated at each time step and from this 100 iterations are simulated and the mean used as the community profile. The minimum and maximum of the probability of an appliance being on or off are 0 and 100 respectively.

In Table 13, the typical household appliances used to formulate a demand profile for eShushu are listed including power rating. Each appliance is grouped under one of the five main energy services defined for the multi-dimensional poverty index (MEPI) described in *Chapter 2 (Literature Review).*

Table 13: Residential electrical appliance power ratings from Kehrer (2008)

Appliance	Power (W)	Number of Appliances	Energy Service
Electric heater	1500	1	Services provided by other appliances
Electric stove	1500	1	Cooking
Electric kettle	2000	1	Water heating
Refrigerator	225	1	Services provided by other appliances
Microwave	1500	1	Cooking
Stereo	110	1	Communication
Television	100	1	Education or entertainment
Light bulb	60	2	Lighting
Cell phone	5	3	Communication
Electric geyser	3000	1	Water heating

The demand profile defined for this study is only used as a proxy and is based on subjective inputs of probabilities of time of use for each minute of the day per appliance. Daily usage times are assumed to create a demand profile for a single household and aggregated to represent a community of households. Seeing that the demand to be used is not for a prescriptive design study and that the simulation is frozen over a single year, proxy data from a representative household is applied.

In order to generate a demand profile for eShushu two similar approaches are compared. Figure 13 and Figure 14 show the average daily demand for a typical eShushu household in winter and summer respectively. Seeing that eShushu is located in Namibia, there are two seasons namely winter or dry season from May to October and summer or wet season from November to April (Wu, Deshmukh, Ndhlukula, Radojicic & Reilly, 2015a). The 'simplified Monte Carlo' approach makes use of random numbers generated for each probability of appliances being on or off. The 'time of use' approach makes use of the same on or off probabilities but does not make use of random numbers to simulate the diverse usage behaviour of a household. In this case, probability is converted to a multiplier to act as a proxy.

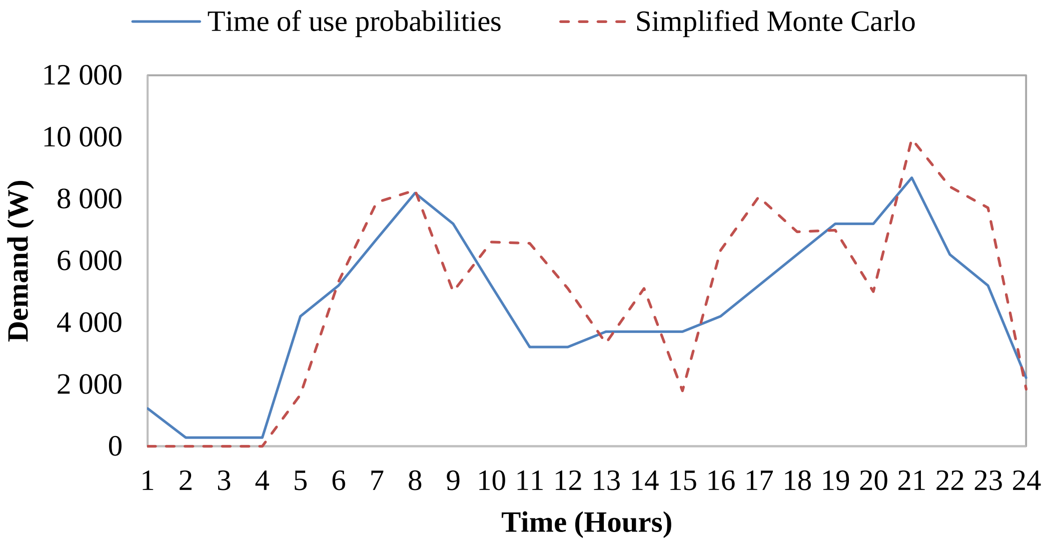


Figure 13: Average daily household demand (winter)

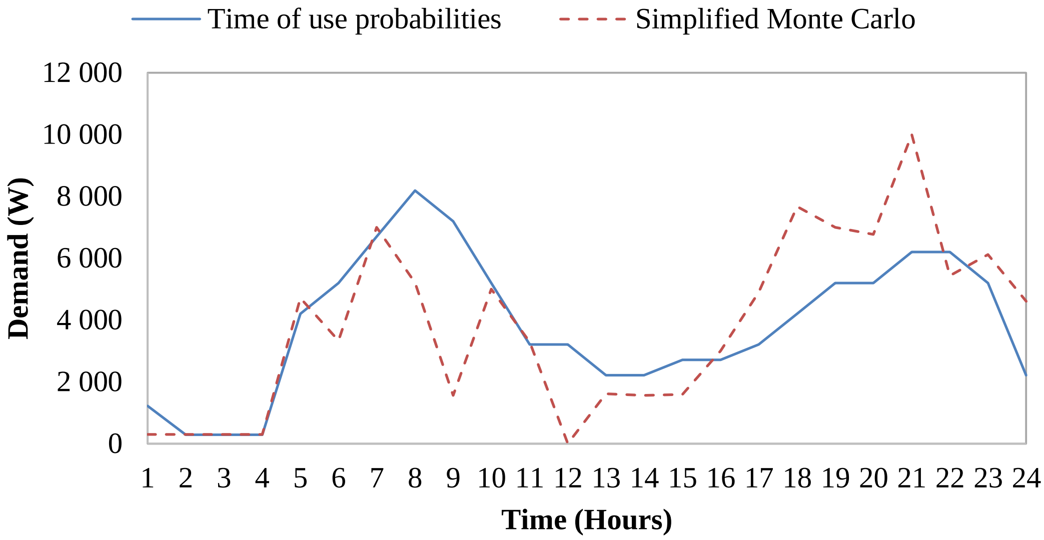


Figure 14: Average daily household demand (summer)

As highlighted by Mcloughlin, Duffy and Conlon (2010), it is evident from the demand profile that continuous appliances such as refrigerators keep the demand from reaching zero at any time interval. In addition to this, there is a reduction in demand during summer. The morning and evening peaks are also distinct between 6:00 to 8:00 and 17:00 to 21:00. It is evident from the comparison that the random number approach results in an erratic demand profile whilst the probabilities show a continuous profile. To generate a smoother continuous profile for a randomised Monte Carlo simulation at community level, a simulation would be necessary for each individual household as simply aggregating the erratic profile of a single household to 100 households would result in the same erratic profile. However the approach using probability multipliers also does not reflect the diversity of appliance usage.

The ‘time of use’ approach was used for final analysis. From the analysis, the average daily demand for each household is approximately 96 kWh per day or 2880 kWh per month. This is very high and is almost double that of the 1785 kWh average monthly consumption for the highest-consuming households in South Africa estimated by Eskom in 2012 (Dekenah, 2014). The high consumption for eShushu is as a result of the appliance assumptions made for the community. It is assumed that the average household in eShushu has access to many appliances. Although eShushu is only a conceptual community used for demonstration, this highlights the influence of the types of appliances used for modelling real residential demand. Of interest for this study is the unique time of use profiles shown in Figure 15 for each energy service which will be applied to the discomfort level defined in *Chapter 4 (Evaluation Framework)*.

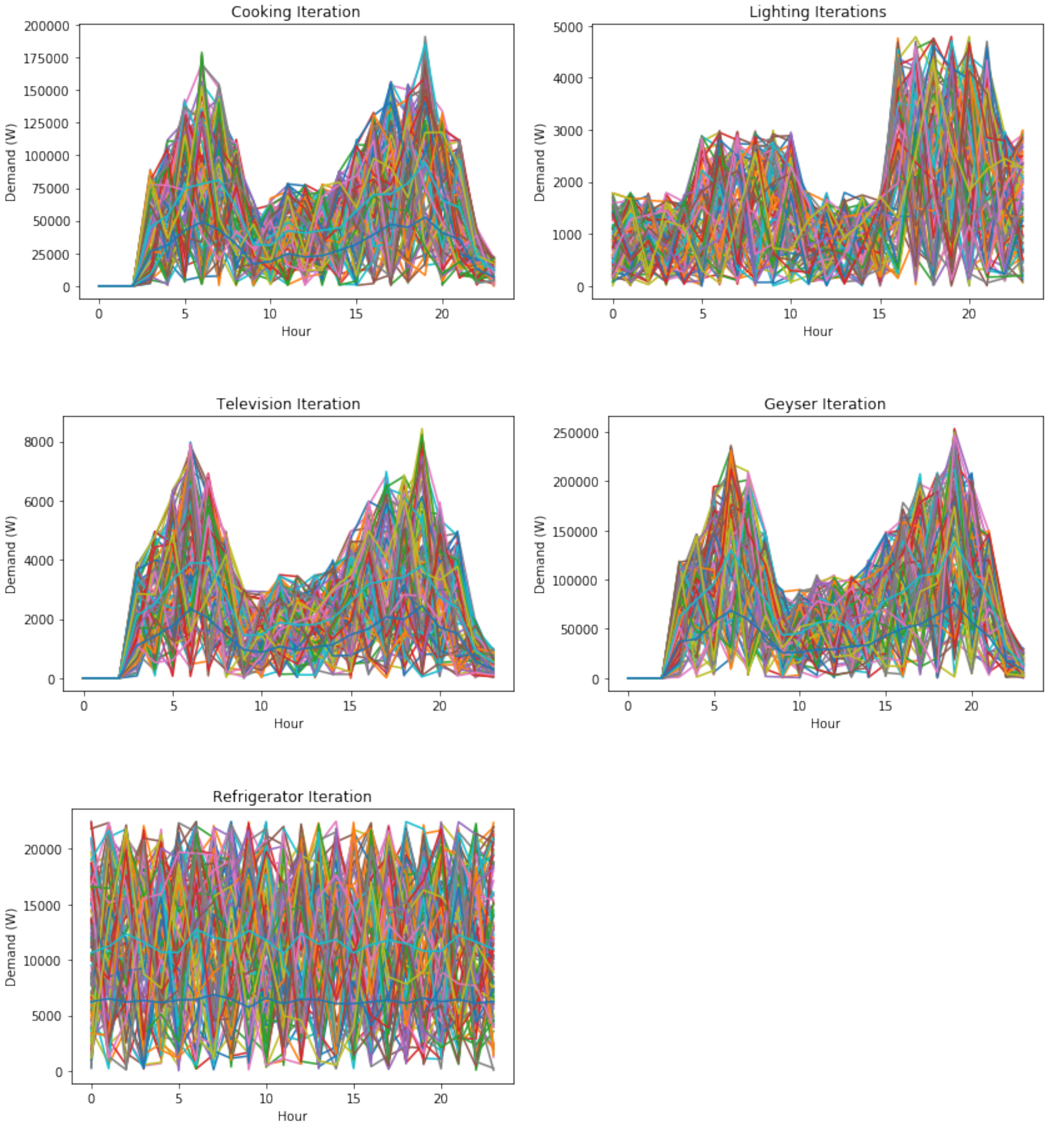


Figure 15: Energy service time of use profiles generated for eShushu

The mean (black dashed line) of the iterations for each appliance is used as the average profile as shown in Figure 16 for lighting, Figure 17 for cooking, Figure 18 for electric geysers, and Figure 19 for refrigerators. Finally, the profiles of all appliances (including phone charging, radio, etc) are aggregated to generate an hourly demand profile for the community of eShushu.

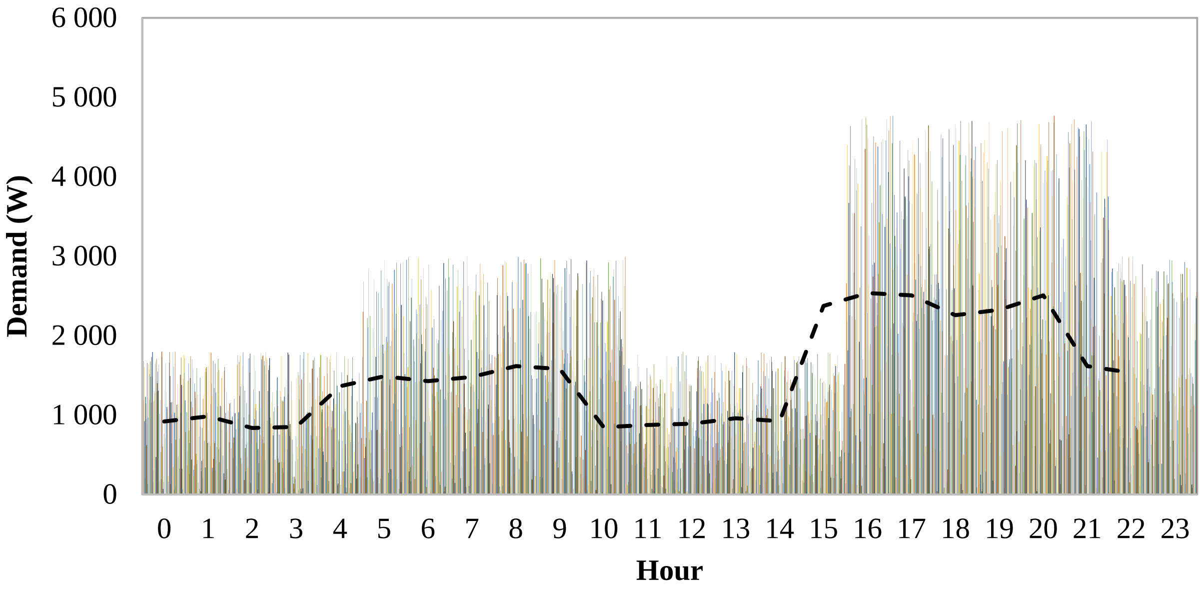


Figure 16: Community demand profile for lighting over 24 hours

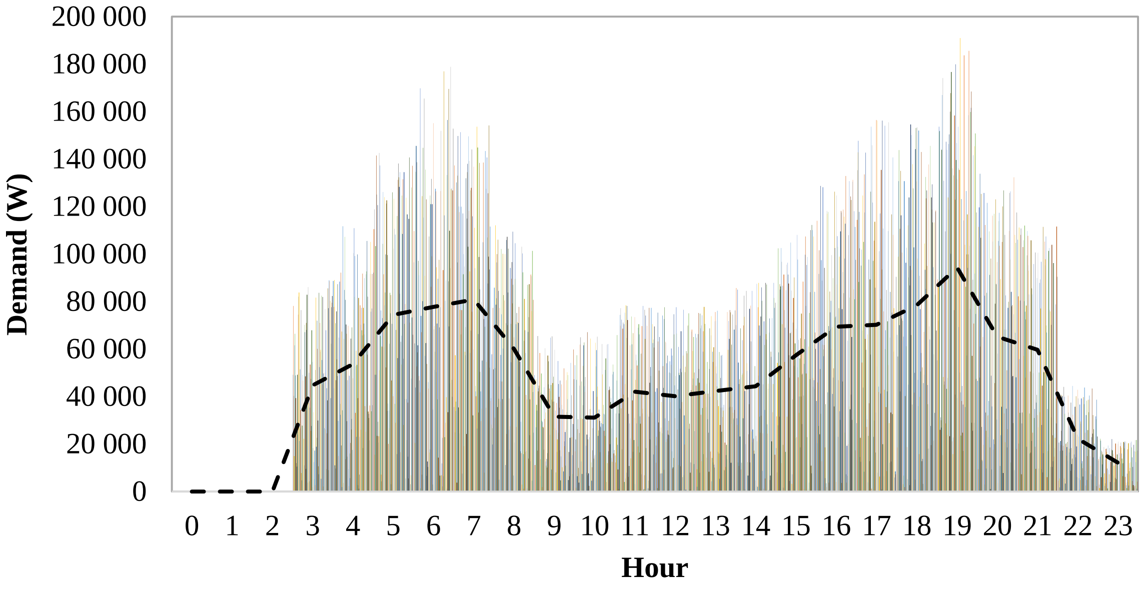


Figure 17: Community demand profile for cooking over 24 hours

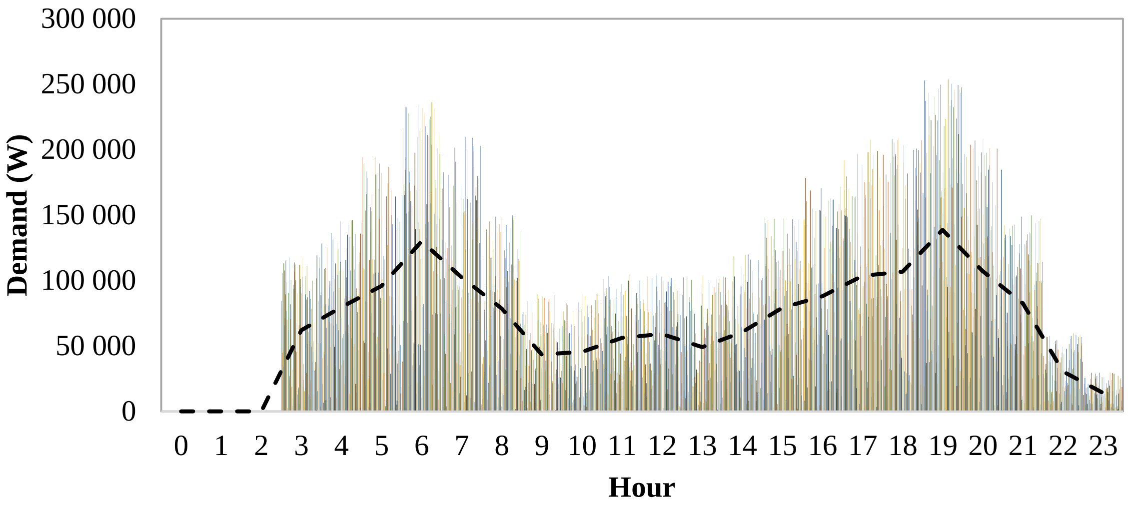


Figure 18: Community demand profile for electric geysers over 24 hours

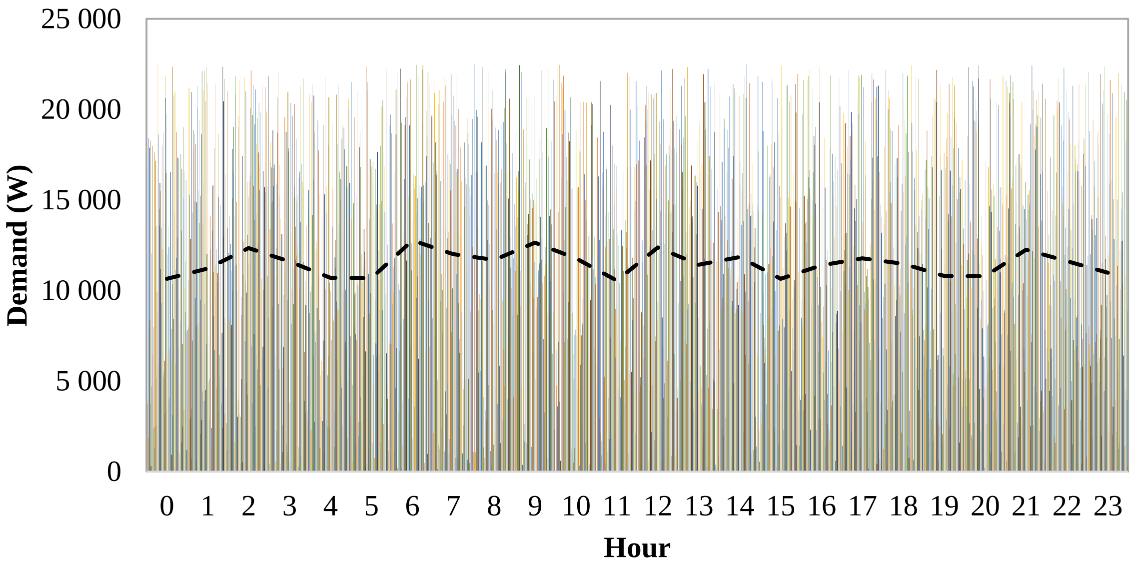


Figure 19: Community demand profile for refrigerators over 24 hours

5.3 Supply Generators

This section presents the (i) energy resource, (ii) the modelling equations, (iii) process flow and (iv) the validation for each supply generator as shown in Figure 20. The supply model consists of a generation mix of generic solar PV, wind power, battery storage, diesel generators, small scale CSP (SS-CSP) and solar water heaters (SWHs) as an energy efficiency technology.

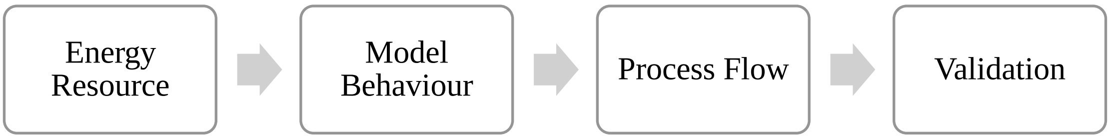


Figure 20: Supply generator sub-sections as presented in this section

A detailed description of the model behaviour of solar PV, wind and the S-CSP supply generators is provided in the Appendix.

5.3.1 Energy Resource: Wind and Solar Data

Solar resource data is acquired in one of two ways, namely using ground monitoring solar stations and satellite based measurements (Xu, Nthontho, *et al.*, 2016)**.** The direct normal irradiation (DNI) describes the amount of solar irradiation per unit area received by a surface positioned perpendicular to the Sun's rays (Wu *et al.*, 2015a). Diffuse horizontal irradiation (DHI) describes the amount of irradiation from the Sun that a surface receives scattered in different directions. The global horizontal irradiation (GHI) is the solar irradiation per unit area received by a surface positioned horizontal to the ground (Wu *et al.*, 2015a). The total irradiation with an irradiation angle (θ) received by a surface placed horizontal to the ground is given by equation (16).

$$\mathrm{GHI} = \mathrm{DNI}\cos\theta + \mathrm{DHI} \tag{16}$$

DNI is used to assess the quality of solar resource for concentrating solar power (CSP) and GHI is the metric used to assess the solar resource quality for non-concentrating solar technologies such as solar collectors and solar PV (Tiwari & Swapnil, 2010). Extracts of the GHI and DNI plots for the test case (eShushu) and the case studies (Thembelihle and Likoma Island) for this study are shown in Figure 21 and Figure 22 respectively for 3 winter days in July. The weather data for the test case was sourced from Gauché (2016).

The wind resource of a specific site is measured using an anemometer at a specified height above the ground (Mohammed, Mustafa, Bashir & Mokhtar, 2013). The power output of a wind turbine is a function of the speed at hub height and the rating of the turbine. For a wind turbine, the condition is that given that the actual wind speed is above the minimum and below or equal to the rated cut-off speed, the power output is simply the rotational kinetic power at that speed (RAE, 2009).

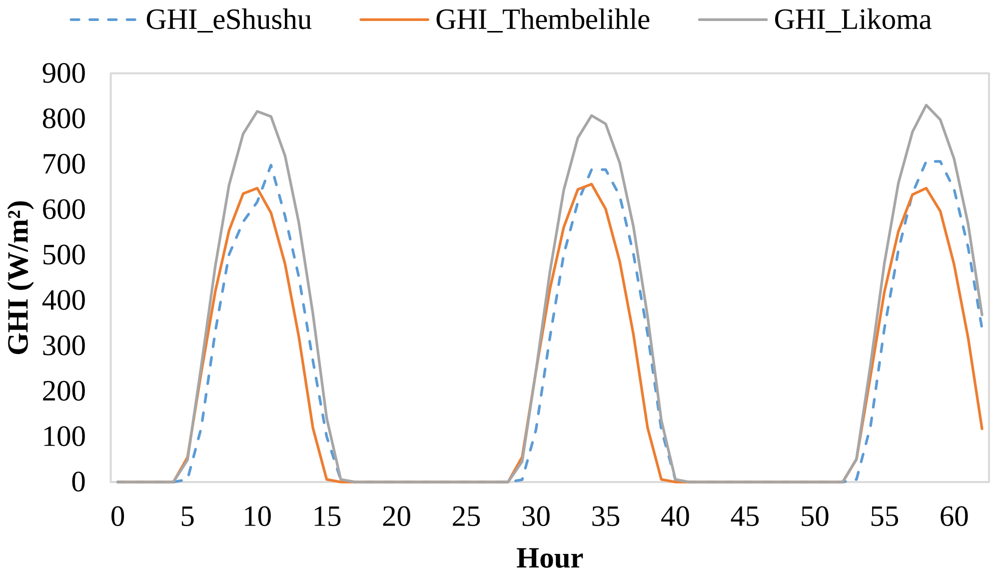


Figure 21: Solar GHI comparison (July)

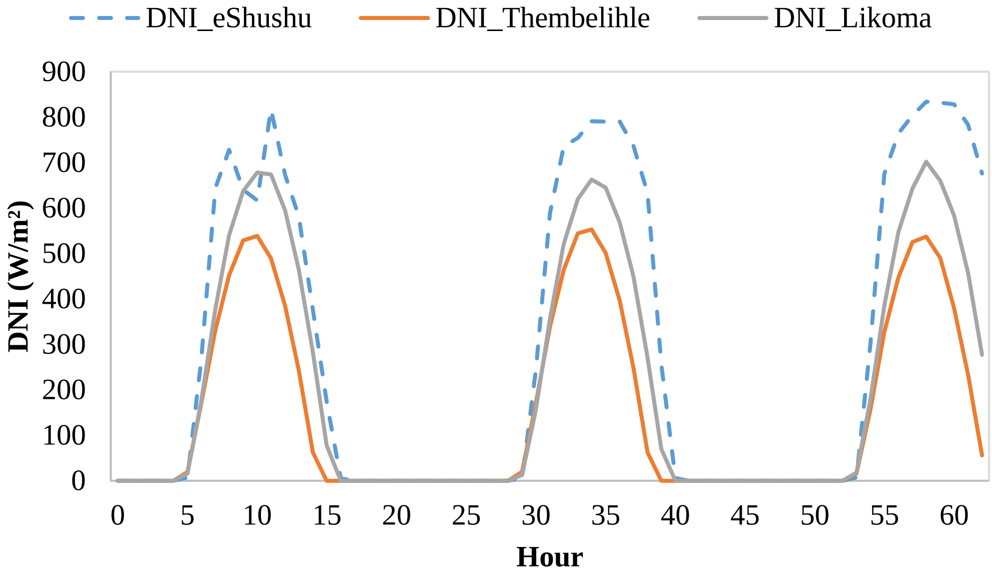


Figure 22: Solar DNI comparison (July)

5.3.2 Solar PV: Process Flow and Validation

For a 892 kW fixed tilt PV system arbitrarily sized for the purpose of verifying the output capacity factor of the test model to that of the model by Gauché (2016) is shown in Figure 23 for the first five days of July 2015 at a maximum GHI of 706 W/m^2.

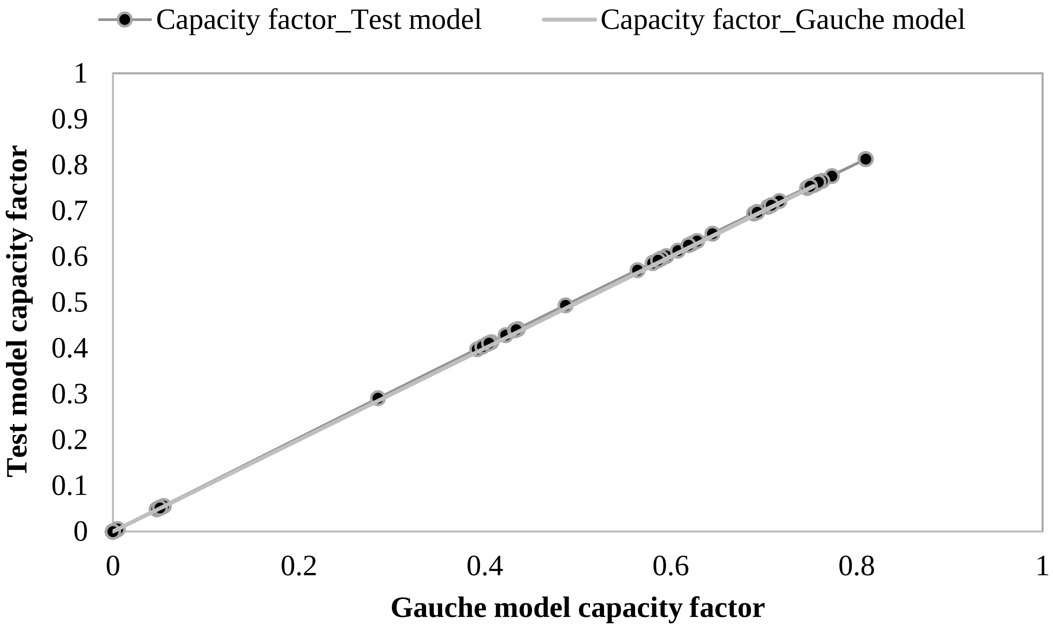


Figure 23: Plant output capacity factor verification

Figure 23 shows that there are no deviations in capacity factor in comparison to the PV model by Gauché (2016). This is also applicable to the annual capacity factor (22.1%) of this model which implies an acceptable simulated PV model. The best day had an hourly capacity factor of 91.7%. The flowchart in Figure 24 shows the process flow simulating a solar PV plant from solar resource collection to the final power output and capacity factor for an hourly time series.

For verification, this is compared to findings from a study conducted by IRENA (2015b) to identify opportunity areas for solar PV, CSP and wind energy in several African countries as part of the 'Clean Energy Corridor'. The opportunity areas are identified according to three factors namely, size, spatial proximity and resource quality (Wu *et al.*, 2015b). In order to estimate the average capacity factor ($CF_{solarPV}$) of solar PV for each zone, the approximation in equation (17) was used.

$$\mathrm{CF_{solarPV}} = \frac{(1-\eta_0)(1-\eta_i)r}{I} \tag{17}$$

Where η_0 , η_i , r and I are the outage rate, AC wiring and inverter efficiencies, resource quality and incident power density respectively.

Resource quality refers to the mean wind power density or solar irradiance of a site (Wu *et al.*, 2015b). Such an approximation is valuable for comparing a number of sites as done in the IRENA study (Wu *et al.*, 2015a). Applied to the eShushu site location in Namibia, which has an estimated solar PV outage rate of 4% (Wu *et al.*, 2015b), the average annual capacity factor is 24% compared to 22.1% calculated for this study.

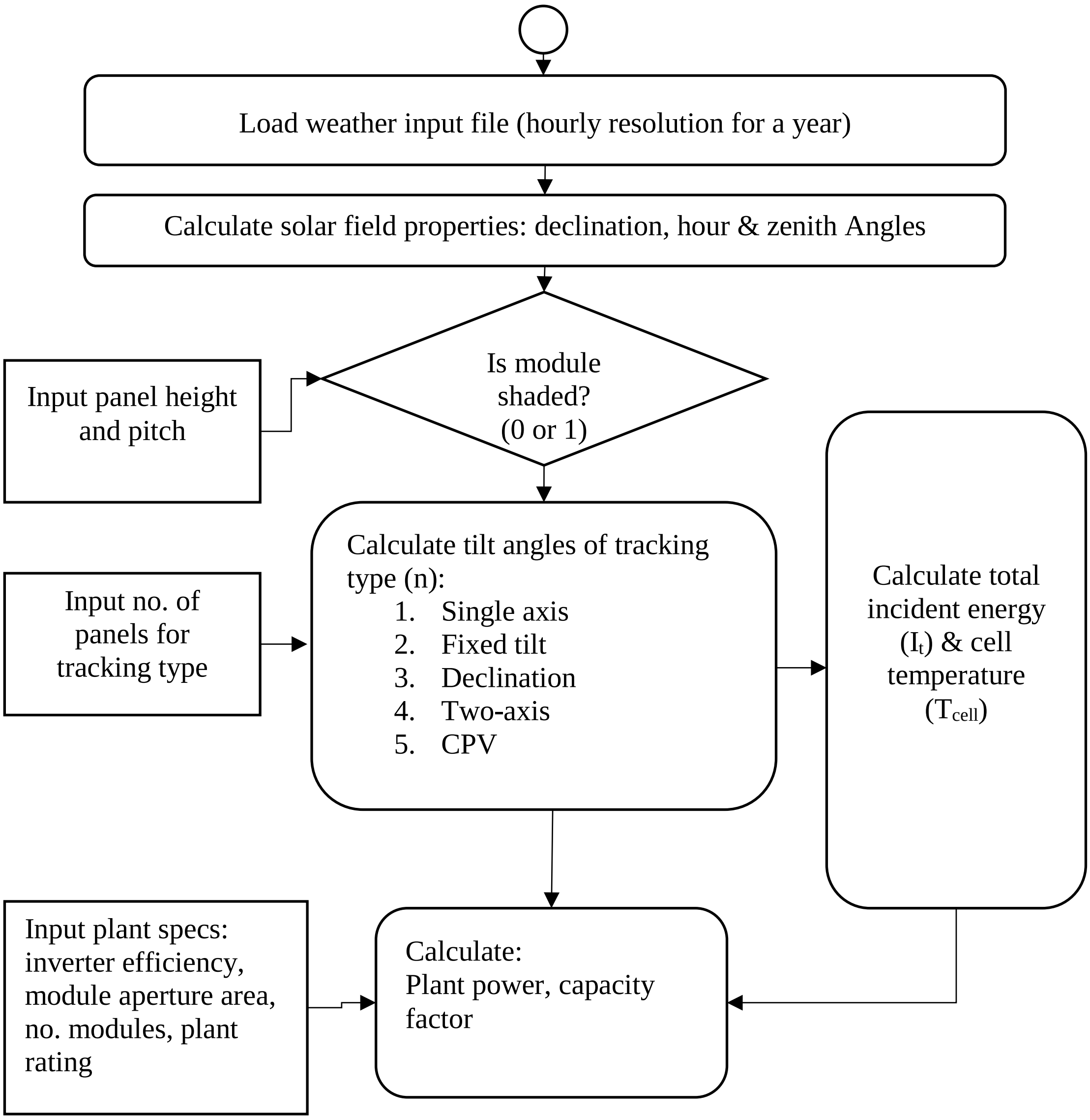


Figure 24: Solar PV plant model flowchart

5.3.3 Wind: Process Flow and Validation

The wind output model outlined in the process flow chart in Figure 25 simply checks whether the actual wind velocity (v) at each hour is above the minimum wind velocity (v_1) and below the maximum rated velocity (v_r) required to operate the turbine which is also at the maximum rated power (P_r). As validation, the same wind data series is compared to a Homer wind power curve as shown in Figure 26 for a 1.5 MW turbine at a cut-in wind velocity of 4 m/s at a hub height of 80 m. The power curve is useful for verifying the power output (P_{out}) of a specific turbine size depending on the incoming hub height wind speed. For verification, Homer software was selected because it is a widely published reference and makes use of hourly site location data. The cut-off speed of the turbine occurs at 25 m/s. According to IRENA (Wu *et al.*, 2015b), on-shore wind turbines are classified into three categories (the International Electrotechnical Commmission (IEC) classes) according to wind speed profiles. Class II and III are typically used for reference wind speeds up to 8.5 m/s and 7.5 m/s respectively while class I is above 8.5 m/s.

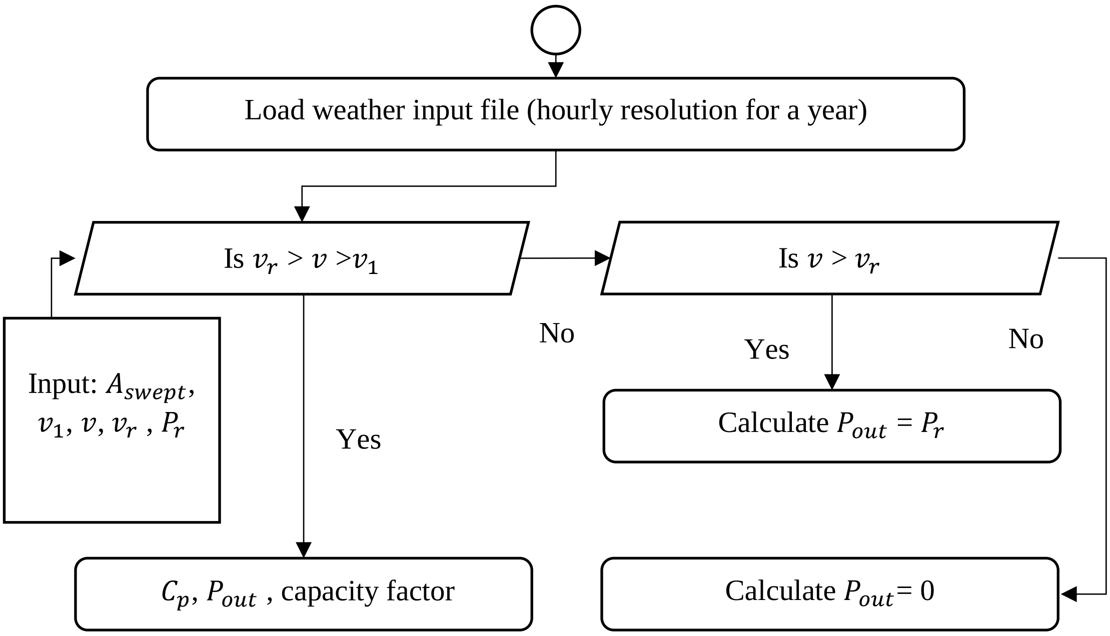


Figure 25: Wind turbine operation model flowchart

The power curve in Figure 26 shows a slight deviation from Homer at the low end when the turbine switches on and again between 9 and 12 m/s. This could be as a result of air densities of 1.16 kg/m^3 for the test model.

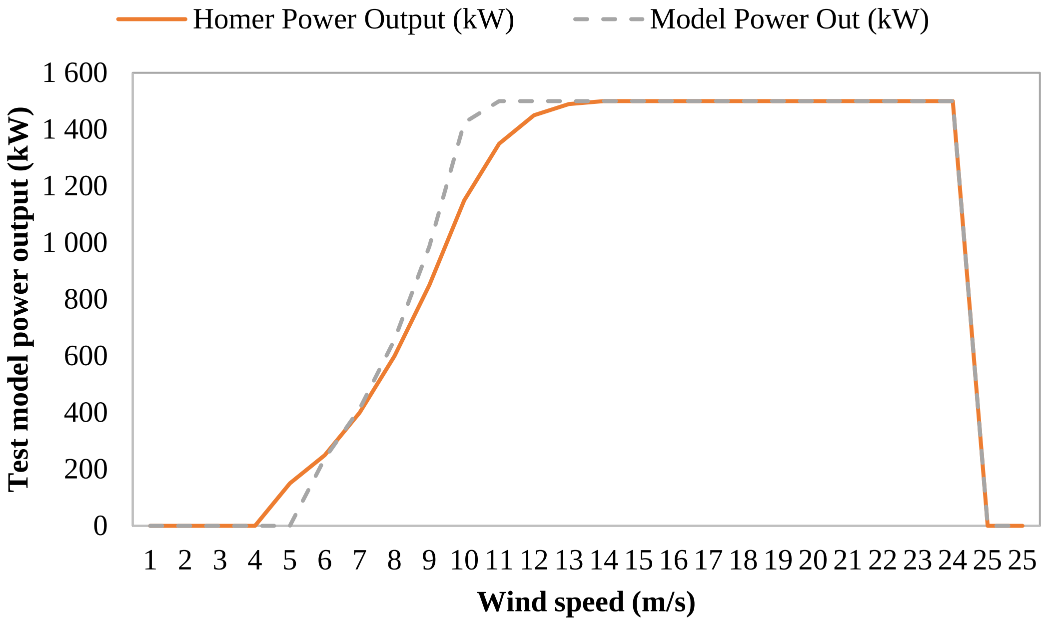


Figure 26: Validation of wind turbine hub speed model compared to Homer Pro

In addition to the power curve used for sizing, the annual capacity factor of a wind farm also provides an indicator for the performance of the wind turbines over a year. Typical annual capacity factors for wind turbine plants range between 30 to 40 % according to Gauche (2016). Although the capacity factor of a power plant is dependant on the unique site location, resource quality and demand such a range of anticipated capacity factors for wind turbine plants is helpful for comparison of sites. The annual average capacity factor for wind in the test model site region is between 20 and 31 percent (Wu *et al.*, 2015b). The wind turbine generators for eShushu show an annual capacity factor of 12.6 % at full load generation. However, in reality this will be much lower when the power plant is dispatched to meet demand. The aggregated effect on the performance of the wind turbines over a day versus over a year is more significant in comparison to solar PV because of the short term variability of wind resource.

5.3.4 SS-CSP: Process Flow and Validation

The model flowchart for a generic small scale CSP tower plant is outlined in Figure 27 as simulated in the test model. For validation in Figure 28, once again an arbitrarily sized 892 kW turbine rating is used to compare to the power output from a generic solar tower model simulated using the Power Systems Simulation (PSS) modelling tool (Landman & Gauché, 2017). One of the main challenges of CSP technology is the non-standard design configurations. This is relevant given that the low uptake of SS-CSP is attributed to low availability of optimised technologies, complexity of operation, low awareness, long payback periods, lack of confidence in the technology, scarcity of skills for installation and maintenance, and limited access to finance (Rawlins & Ashcroft, 2013).The solar tower design was selected for this study because the parabolic trough design is highly susceptible to seasonal variations. According to Franchini, Perdichizzi, Ravelli and Barigozzi (2013), the parabolic trough has a greater amount of incident radiation to intercept in the summer compared to heliostats. For this reason, the parabolic trough has a higher thermal efficiency during summer but it decays in winter whilst the solar tower on the other hand has a relatively constant amount of thermal energy collected during the year. The parabolic trough also has higher optical efficiency. The conversion efficiency from solar energy to electric energy of the parabolic trough is also lower than the central receiver (Franchini *et al.*, 2013).

Thermal storage for a CSP plant increases the capacity factor because of the increased electricity generation when the Sun is no longer shining. Wu et al. (2015a) highlights that the complex models and range of configurations of CSP plants make it difficult to approximate capacity factors. For this reason, the capacity factor of power plants are compared for different solar multiples and the hours of thermal storage. Power plants without thermal storage typically have solar multiples between 1.1 to 1.5 while plants with thermal storage can have solar multiples between 3 to 5 (Wu *et al.*, 2015b).

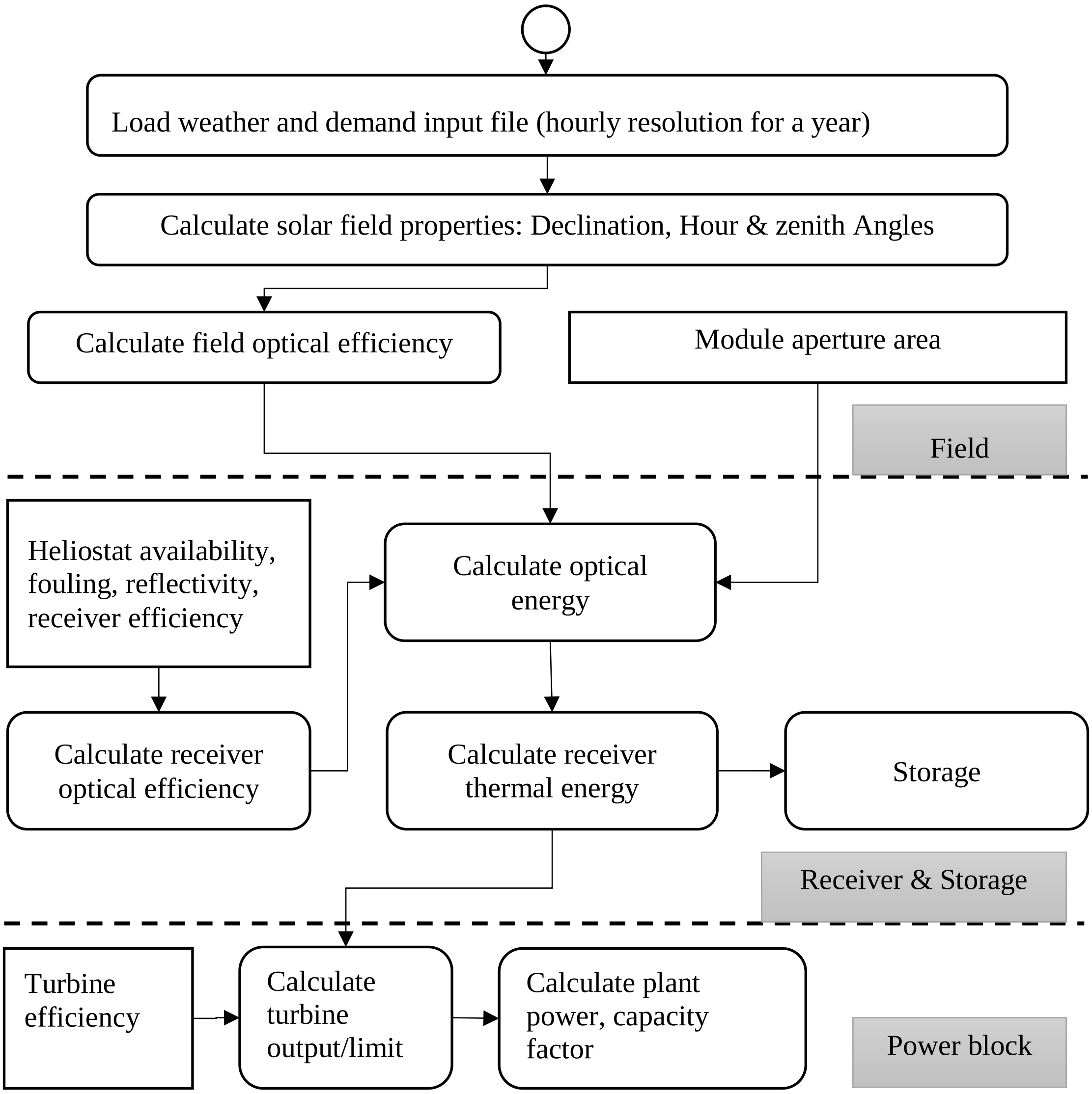


Figure 27: CSP tower operation model flowchart

The CSP tower plant used in the PSS tool is based on the design of the Gemasolar tower plant which has a solar multiple of 2.5 as a default but this can be changed. The PSS tool scales the optimum number of heliostats in order to calculate the field aperture area required for the reference hours of thermal storage. This 19.9 MW plant is located in Spain and delivers a 63% capacity factor with full load thermal storage of 15 hours (Xu, Vignarooban, Xu, Hsu & Kannan, 2016). Figure 28 shows the annual capacity factor for the CSP plant at varying hours of thermal storage. Given the small solar field as a result of lower solar multiples and increased thermal storage hours in the test model, the capacity factor remains unchanged from 6 hours to 9 hours of storage for solar multiples of 1.5 and 2 as shown in Figure 28.

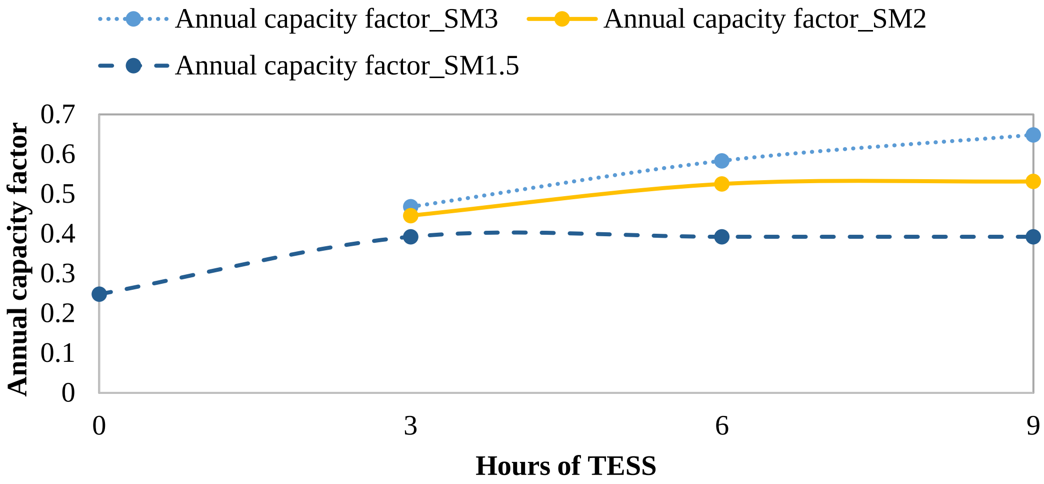


Figure 28: Comparison of SS-CSP capacity factors with and without TESS for a 1MW turbine

For a solar multiple of 3, the capacity factor shows a 10% increase from 6 hours to 9 hours. The implications of this for a CSP plant is that additional thermal storage at low solar multiples for a small scale plant results in extra costs and land.

5.3.5 Solar Water Heater Model

According to Weiss (2015), a solar water heater for a household is sized based on the type of dwelling, hot water demand per person and the amount of hot water demand in the kitchen. However for this study, a simple generic solar water heater is modelled similar to a battery charging and discharging in the form of thermal energy based on solar weather data. Dioro et al. (2014) suggest that theoretical thermal energy ($Q_{delivered}$) at the solar tank storage of a solar water heater is calculated from equation (18). For simplification it is assumed that thermal energy stored during daylight hours is retained in a storage tank and the thermal energy discharged based on demand is modelled.

$$\mathrm{Q_{delivered}} = \dot{\mathrm{m}}_{\mathrm{draw}}\mathrm{C_p}(\mathrm{T_{deliv}} - \mathrm{T_{mains}}) \tag{18}$$

However for a weather based representation the thermal energy at the solar tank storage is given by

$$\mathrm{Q_{delivered}} = \mathrm{C_A C_Y} \tag{19}$$

Where C_A and C_Y represent collector array area and collector yield respectively. The collector yield is given by

$$\mathrm{C_Y} = \mathrm{S_R}\eta_{\mathrm{c}}\eta_{\mathrm{sys}} \tag{20}$$

Where S_R represents global horizontal irradiation (GHI), η_c is the efficiency of the collector and $\eta_{sys}$is the efficiency of the system (including piping, storage, etc). Different solar collector designs have different efficiencies depending on the design and an efficiency curve is typically used (AEE - Institute for Sustainable Technologies, 2009: 43). A simplification of the thermal energy provided from the storage tank heated by an electric element is represented by

$$\mathrm{Q_{storage}(t) = Q_{delivered}\,(t) - Q_{demand}(t) + Q_{storage}(t-1)} \tag{21}$$

Which is only applicable when storage is not depleted expressed by $Q_{delivered}\ (t) + Q_{storage}(t)\ > Q_{demand}(t)$. Should this not apply, demand shortfall is given by

$$\mathrm{Demand\ shortfall\ (t) = Q_{demand}\ (t) - Q_{delivered}(t)} \tag{22}$$

For eShushu, a typical water usage profile developed by Ijumba and Sebitosi (2010) is applied. This profile shows the average fraction of daily energy consumption for water heating in South Africa as shown in

Figure 29.

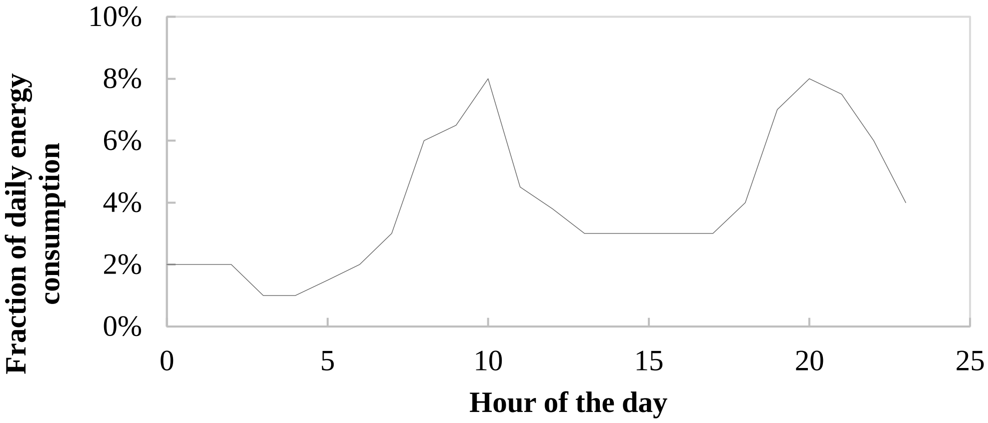


Figure 29: Average hot water profile adapted from Ijumba and Sebitosi (2010)

For eShushu, the assumptions of the solar water heating model are provided in section *5.6 System Simulation*. For this study, solar water heaters are treated as an energy efficiency technology used to reduce thermal demand. For this reason, it is assumed that solar water heaters are only applicable to the water heating energy service.

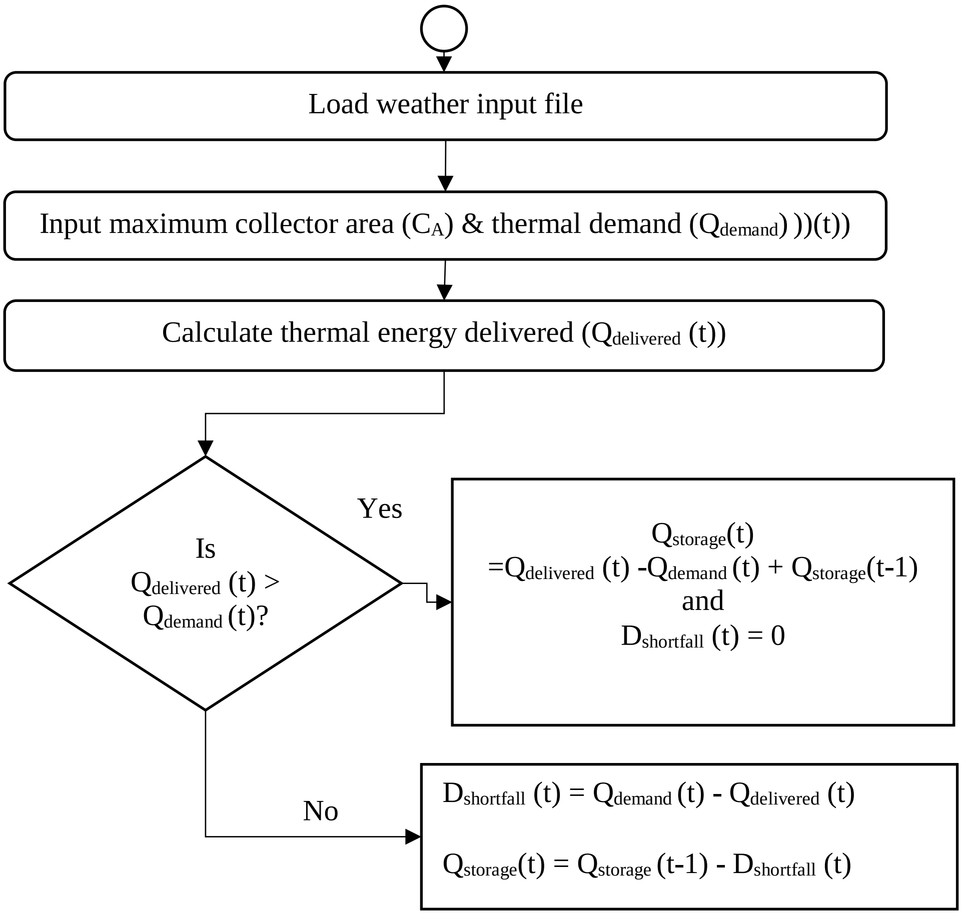


Figure 30: Solar water heater process flow

5.3.6 Battery Storage Model

Energy storage is necessary in an energy system with renewable energy technologies to store excess power for use at times when solar or wind resource is not sufficient to meet the load. The capacity of the battery should be sized to run the daily load under normal conditions (Hove & Tazvinga, 2012).The conditions for sizing of energy storage in HOMER and also generally applicable include the (i) battery type, (ii) size, (iii) daily load requirements, (iv) number of autonomy days, (v) maximum depth of discharge, (vi) system voltage and, (vii) the battery's cycles to failure at the specified depth (Xu, Nthontho, *et al.*, 2016).

With reference to sizing of battery systems, there are several methods, with optimization being a typical example. However, Ashok (2007) simply sizes the battery bank for a hybrid PV-diesel-battery system as the difference between the positive and negative peaks of the load. Homer also allows for optimization in battery bank sizing. There are however standard generic capacities for the Li-ion battery bank, including 1 kWh, 100 kWh and 1 MWh. A generic storage battery is modelled as an idealized storage model adapted from Homer Energy (2017a). The following parameters are specified for the idealized battery, (1) nominal capacity,

(2) maximum charge rate and the (3) maximum state of discharge. The lifetime of the battery is not calculated because the model is frozen in a single year.

The useable capacity (P_u) of the battery is limited by the minimum depth of discharge (D_d) and the capacity of the battery (P_c)as shown in equation (23).

$$\mathrm{P_u = D_d P_c} \tag{23}$$

The maximum depth of discharge (R) of the battery is given by the maximum charge rate (R_{max}) over the efficiency (η_{batt}) of the battery (Elszasz, 2014)

$$\mathrm{R} = \frac{\mathrm{R_{max}}}{\eta_{\mathrm{batt}}} \tag{24}$$

When calculating the battery marginal cost of generation, Homer gives this as the sum of the battery wear cost and the battery energy cost. Where the battery wear cost is defined as the cost of cycling through the battery until it needs replacement. The battery energy cost is the cost of charging the battery at each time step. However, seeing that the battery storage in this case discharges based on the energy balance in such a way that it follows demand and only charges from solar PV and wind, the energy cost is zero. Therefore only the wear cost (C_{bw}) of the battery is considered given by

$$\mathrm{C_{bw}} = \frac{\mathrm{C_{rep,batt}}}{\mathrm{N_{batt} Q_{lifetime}} \sqrt{\eta_{\mathrm{rt}}}} \tag{25}$$

Where N_{batt}, $C_{rep,batt}$, $Q_{lifetime}$ and η_{rt} represent the number of batteries in a battery bank, the replacement cost of the battery, the lifetime throughput of a single battery and the round-trip efficiency respectively.

5.3.7 Battery Storage: Process Flow

The generic process flow for battery storage modelled with the option of charging from solar PV, wind and the grid is illustrated in Figure 31. The battery storage state of charge is limited by the maximum state of charge, peak or off-peak period and excess generation from supply generators. The grid in this case may be treated as an external source and is not considered.

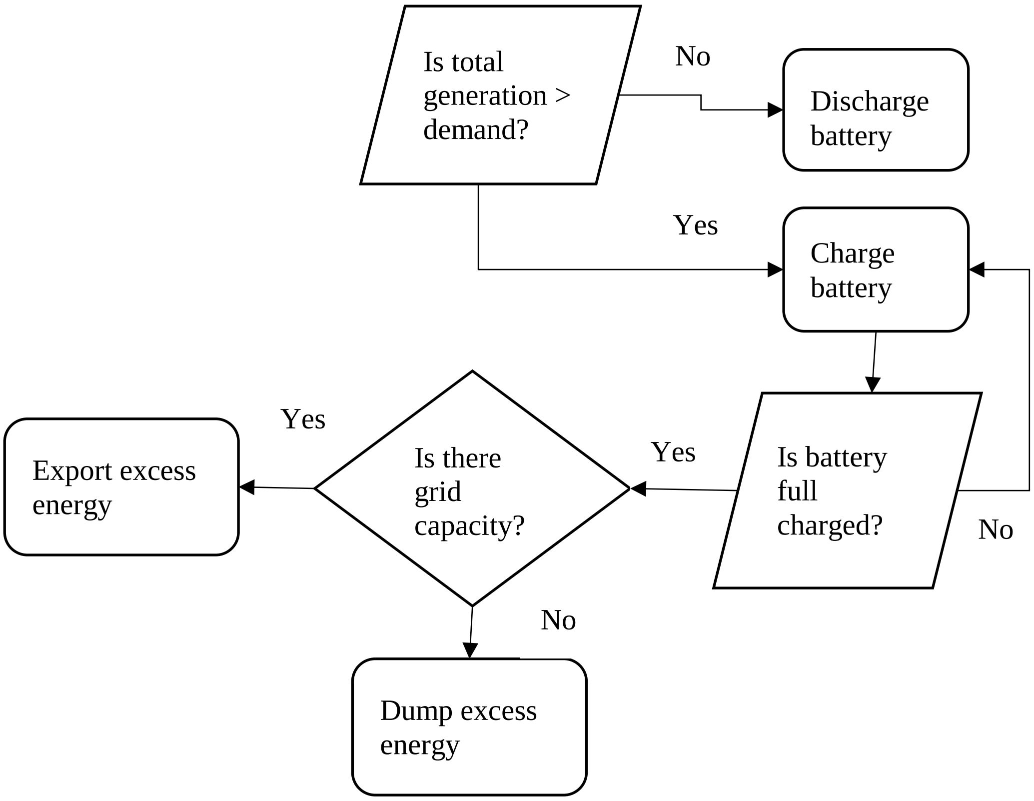


Figure 31: Battery storage model process flow chart

5.3.8 Diesel Generator Model

For a generic diesel generator, a simple efficiency model is defined based on the rated power and efficiency of the generator. The main aim of the diesel generator is to ensure that there is continuity in supply and therefore improves reliability and availability of the system. This is possible because the generator can be dispatched or turned on and off when needed. For this reason, it is typically used for peaking applications (Hove & Tazvinga, 2012). Homer Energy (2017b) defines the generator efficiency as the electrical energy output divided by the chemical energy of the fuel as input shown in equation (26).

$$\eta_{DG} = \frac{3.6\ P_G}{\dot{m}\ LHV_{fuel}} \tag{26}$$

5.4 Levelised Cost of Electricity Assumptions

The generator technology cost assumptions applied to this case are taken from LAZARD (2016a,b) and are listed in Table 14. For solar water heaters, Nielsen (2004) recommends a conversion factor of 0.7 kW_{th}/m^2 from collector area to specific nominal capacity of solar thermal collectors. These include including fixed operations and maintenance (FOM) and variable operations and maintenance (VOM) costs. All costs are reported for 2016 and are expressed in US Dollars. However, a discount rate of 8% used is the same as that used in the Integrated

Resources Plan (IRP) 2016 (DoE, 2016). Levelised cost of electricity (LCOE) is calculated using a US dollar (USD) to South African Rand (ZAR) average exchange rate of R13.5 (Investing.com, 2017) for December 2016 because the costs are also applicable to this time period. South Africa's consumer price index (CPI) was not included because the original costs are in US financial terms. For solar water heaters, Nielsen (2004) recommends a conversion factor of 0.7 kW_{th}/m^2 from collector area to specific nominal capacity of solar thermal collectors.

Table 14: Technology cost assumptions used to calculate LCOE

Technology	**Net Discount Rate**	**Plant Life (Yrs)**	**CAPEX ($/kW)**	**CAPEX ($/kWh)**	**FOM ($/kW-yr)**	**VOM ($/MWh)**	**Fuel Cost ($/GJ)**
Solar PV (LAZARD, 2016a)	0.08	25	2000 - 2800	0	12-16	0	0
Wind (LAZARD, 2016a)	0.08	20	1250 - 1700	0	35-40	0	0
Battery (Li-Ion) (LAZARD, 2016a)	0.08	10		440-1045		1.0-1.1% of Capex	
CSP (Tower with Storage) (LAZARD, 2016a)	0.08	25	10000 - 10300	0	80-115	0	0
Diesel Generator (LAZARD, 2016a)	0.08	20	500-800		15	0.015	17.26

5.5 Energy Balance and Dispatch Strategy

The hourly energy balance of the energy system is such that the total output from the supply generators constrained by availability and the generation capacity is dispatched in response to demand at each time step (hourly). The system balance (E_{system}) was simplified to a single node where the combination of supply technologies results in a system energy balance between demand and supply (Pfenninger, 2015). Based on the node concept adapted from Pfenninger (2015), supply technologies act as sources while demand and the battery storage charging cycle function as sinks to the system. The logic is illustrated in Figure 32 and equation (27) where the total system energy balance is a sum of supply energy from each generator (G_x), discharge energy from storage, the storage charging cycle (S_c) and demand (D).

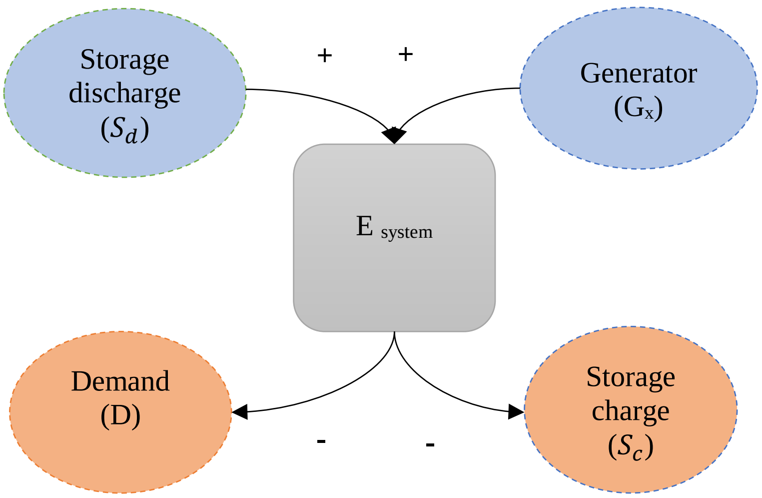


Figure 32: Schematic of the system energy balance logic

$$E_{system}(t) = \sum_{i}^{x} G_x(t) + S_d(t) - S_c(t) - D(t) \qquad (27)$$

The metrics used to compare each system simulation include (i) the demand shortfall, which occurs when the system energy balance is negative as a result of demand exceeding supply per time step, (ii) the annual generation output and (iii) the LCOE of each system. The demand shortfall ratio is calculated as the ratio of demand shortfall to the total demand in equation (28) where *t* represents each time step.

$$\text{Demand shortfall ratio}_t = \frac{\text{Demand shortfall}_t}{\text{Demand}_t} \qquad (28)$$

Initially, the supply from all generators at each hour is added up. The total supply should first serve demand. In the case that there is excess supply, the excess is used to charge battery storage given that the battery is not full. In the case that the battery is fully charged, the excess is curtailed if there is no grid and fed to the grid if one exists. However, in the case that the total supply from renewables is insufficient to serve demand, the grid, battery storage and diesel generators are dispatched depending on the availability of each technology determined per scenario.

To test that a system energy balance is achieved, a base case is simulated using the Power Systems Simulation (PSS) tool. An example of a system simulation of solar PV, wind, battery and diesel combinations is shown in Figure 33. for six representative days in winter (top) and summer (bottom) given the demand for eShushu. Shown here is the average as a sum of power generated to satisfy the demand (in dotted line) at an hourly resolution over 2 days in the month of July. The total supply as a sum of the total contribution from generation and storage is also shown. The battery storage charged from excess total supply is shown as negative generation. It is observed that wind is highly variable at least for the short term in comparison to solar PV which maintains a distinct profile. At hour zero or midnight of the first day shown in Figure 33, demand is supplied by wind generation and battery storage. At sunrise (approximately 6 am), diesel generators supplement solar PV as solar irradiation gradually peaks. Intermittent wind resource and diesel generators continue to supplement generation throughout the day. Battery discharge takes place before sunrise and after sunset while battery charging takes place during the day when there is excess generation. The following day experiences a significant increase in wind resource and therefore excess generation is available to charge battery storage while less diesel generation takes place.

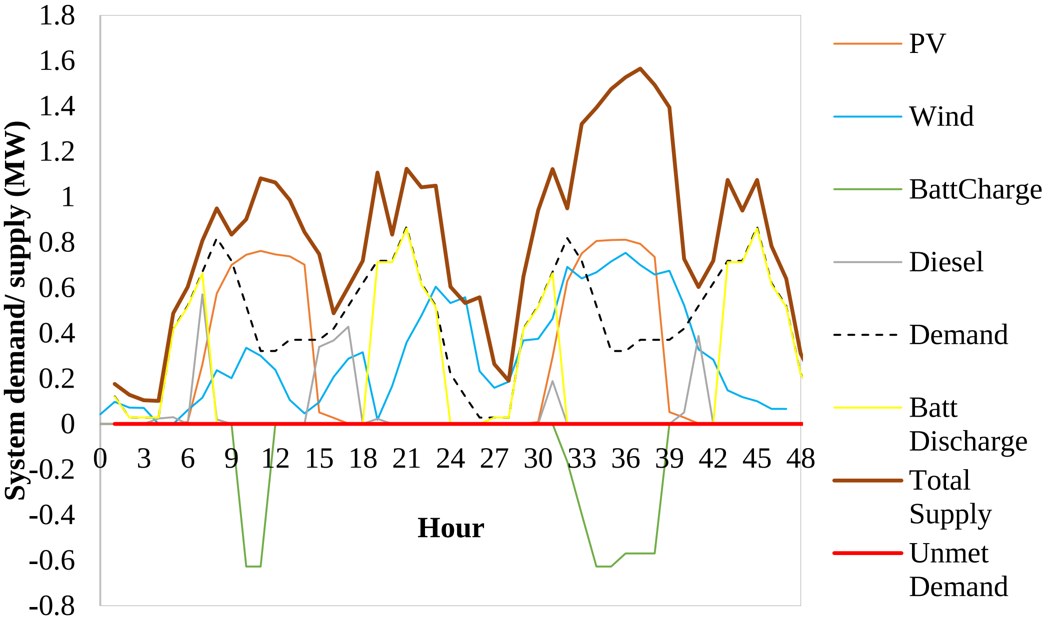


Figure 33: July 48 hour non-constrained simulation

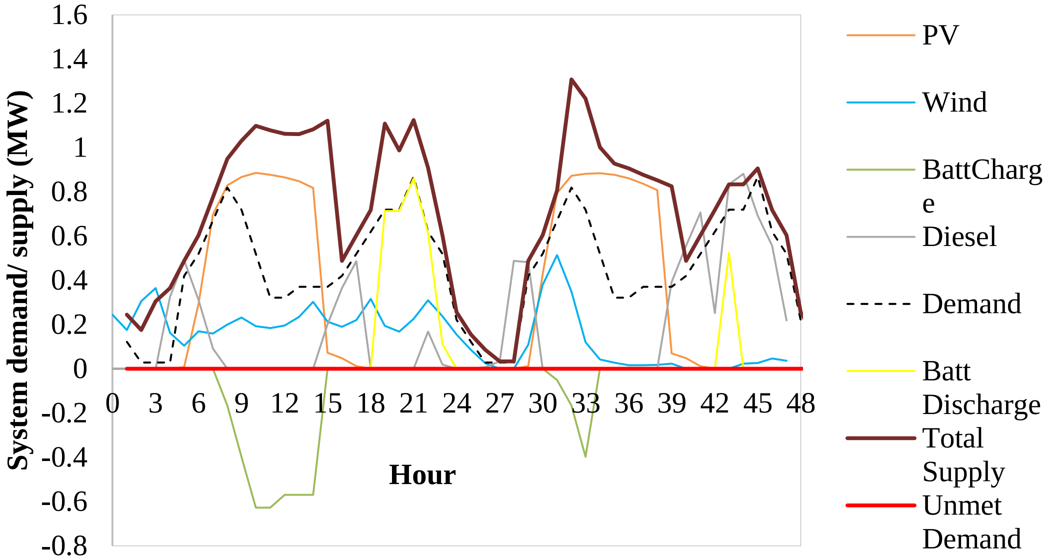


Figure 34: October 48 hour simulation

For two days of the month of October shown in Figure 34, sunrise has shifted earlier by an hour to 5am. This shows an improved alignment between the solar PV profile and the demand morning peak. In contrast to the two days in July, it is also evident that battery storage is not discharged in the morning as a result of increased generation from solar PV earlier in the day. There is zero unmet demand for both cases. The highest demand shortfall in both winter and summer occurs between 16:00 in the afternoon and 7:00 in the morning. Solar PV generation is consistent throughout winter and summer with a defined profile from the morning until the Sun sets. There is a clear need for energy supply between the late afternoon and early morning. For this reason, energy storage and diesel generation are observed to fill up the gaps when solar generation is not available. In this model, solar PV and wind are not curtailed by demand but system size. However, in reality the conversion system would control the dispatch of solar PV to the system either by limiting output or storing the energy for later use, solar PV is seen to overshoot demand for this reason. Excess energy from the solar PV and wind system is stored in the batteries while CSP with and without thermal storage is curtailed according to demand. The annual capacity factor for solar PV is 22.1% compared to 21.6% from Homer. Wind has a capacity factor of 12.6% compared to 6.8% from Homer and CSP with zero hours of thermal storage has a capacity factor of 19.7%.

5.6 System Simulation

A hybrid energy system has the potential to increase energy output but also reduce system fluctuations caused by weather dependant renewable energy supply (Ashok, 2007). To test the discomfort framework, the proxies required for the demand shortfall and supply simulation is unmet demand at an hourly resolution. In order to have a demand shortfall this implies a system imbalance because demand exceeds supply. Although the objective of a standard design of any energy system is to optimise the reliability of supply, this study is not aimed at designing a system but rather simulating the conditions of low reliability in order to interpret the implication for comfort from an end-user perspective and thus also providing a metric for interpreting the improvement in satisfied energy services (discomfort level) as a direct result of supply technology combinations. To achieve this, an optimisation model with unmet demand as an objective function could be used. For simplicity, a sensitivity analysis was done for the system sizing of several generator combinations, comparing the demand shortfall required as input for the discomfort level which is finally compared to LCOE of the scenarios selected as shown in Figure 35. The constraint on the energy mix is the availability of each technology. Solar and wind are weather dependant while battery storage is dependant on the excess power from these. Demand shortfall and LCOE are selected as the sizing requirements simply for the reason that the system should satisfy system demand at the lowest cost for the given technology.

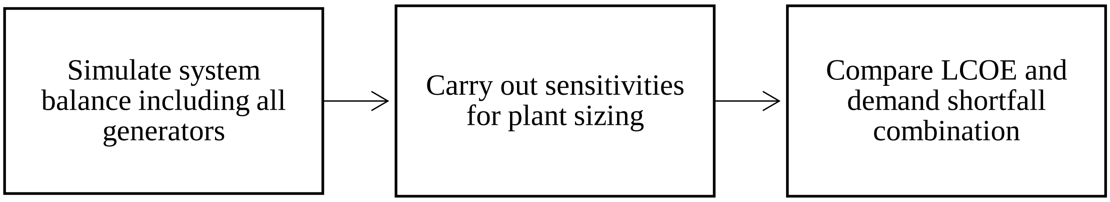


Figure 35: System simulation and analysis process flow

5.6.1 Hybrid Scenario

The hybrid scenario includes solar PV, wind, battery storage and diesel generators. Sensitivities are carried out for the capacity of wind energy. To create different scenarios the objective was to compare different technology combinations to demonstrate how unmet demand changes (resulting in a change in the demand shortfall). For each run, the PV system size is kept constant and wind capacity is varied in 0.5 MW intervals. Figure 36 illustrates an example of a sensitivity for a 0.5 MW and 1 MW solar PV system while Figure 37 shows that of a 1.5 MW and 2MW solar PV system. Annual generation of wind energy shows a linear distribution because solar PV and wind are not curtailed.

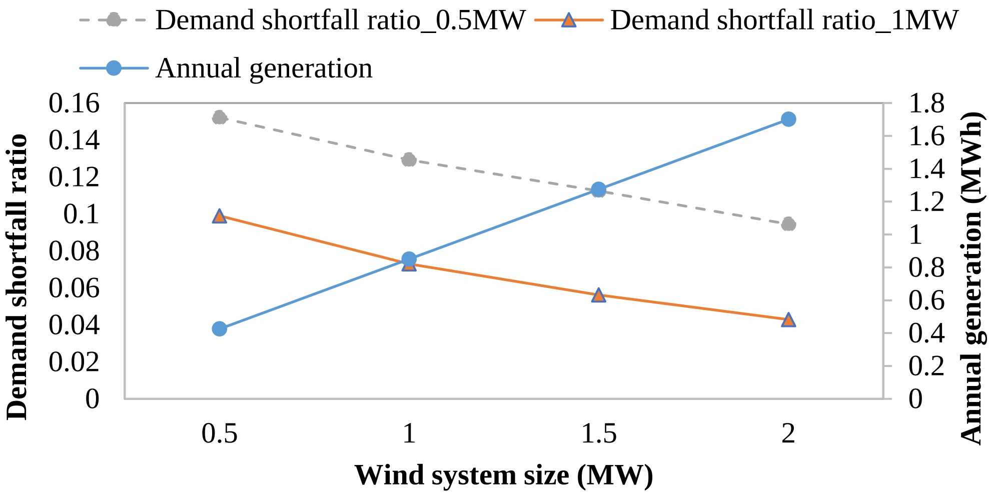


Figure 36: Wind size sensitivity for a PV array size of 0.5 and 1 MW

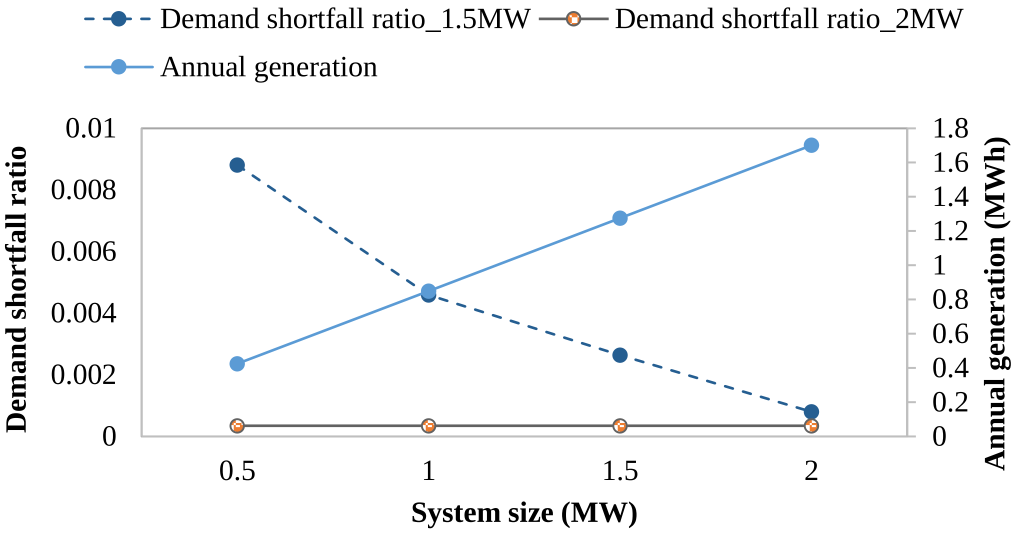


Figure 37: Wind size sensitivity for a PV size of 1.5 and 2 MW

The challenge with scenario selection is in determining which level of demand shortfall is desired. For example in this case, a solar PV system of size 1MW and above results in a demand shortfall ratio below 0.1. Table 15 shows the annual generation, demand shortfall ratio and LCOE for each case of a 1 MW PV system. For comparison, a Homer simulation was carried out. To constrain the scenarios, the availability of battery storage discharge was limited to the evening while charging could only happen during the day. Diesel was only made unavailable during hours of sunshine.

Table 15: Indicators of selected scenarios

	PV-Battery	PV-Battery-Diesel	PV-Wind-Battery	PV-Wind-Battery-Diesel
Annual Generation (MWh)	2298	4167	4899	5181
Demand Shortfall Ratio	0.57	0.1	0.28	0.09
LCOE (R/kWh)	1.14	3.74	3	5.6

The objective of the battery storage is to have a battery size that can tolerate the capacity of the excess PV and wind energy at each hour. The battery discharge cycle for three days is shown for the solar PV and wind system in Figure 38.

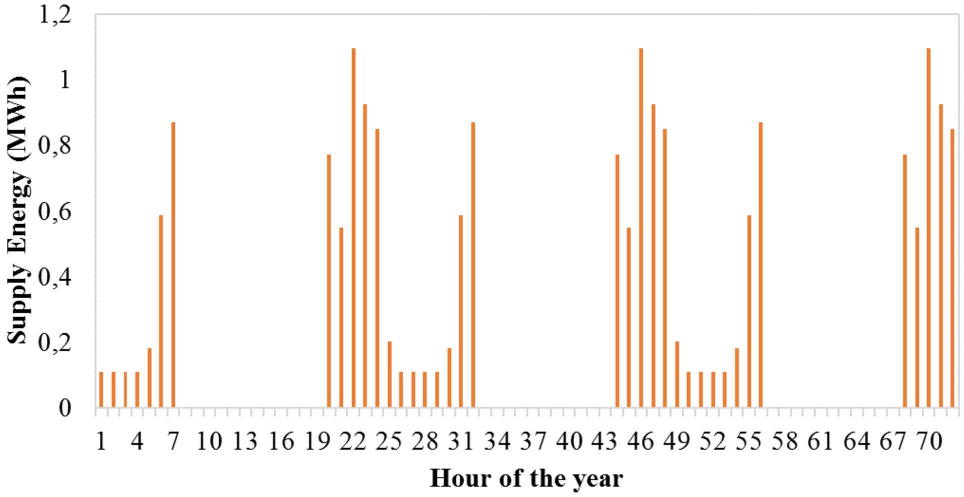


Figure 38: Battery charge and discharge cycle over three days

The LCOE for PV was calculated at R1.14 compared to R1.60 from Homer – the slight difference could be as a result of the lower capacity factor used in Homer for solar PV. On the other hand, the LCOE of wind was much lower (R1.86) in comparison to that used in Homer (R3.26) which can also be attributed to almost a

50% less capacity factor of 6.81 % reported in Homer compared to the PSS model at 12.6%. Figure 39 shows the annual generation and LCOE for each of the cases.

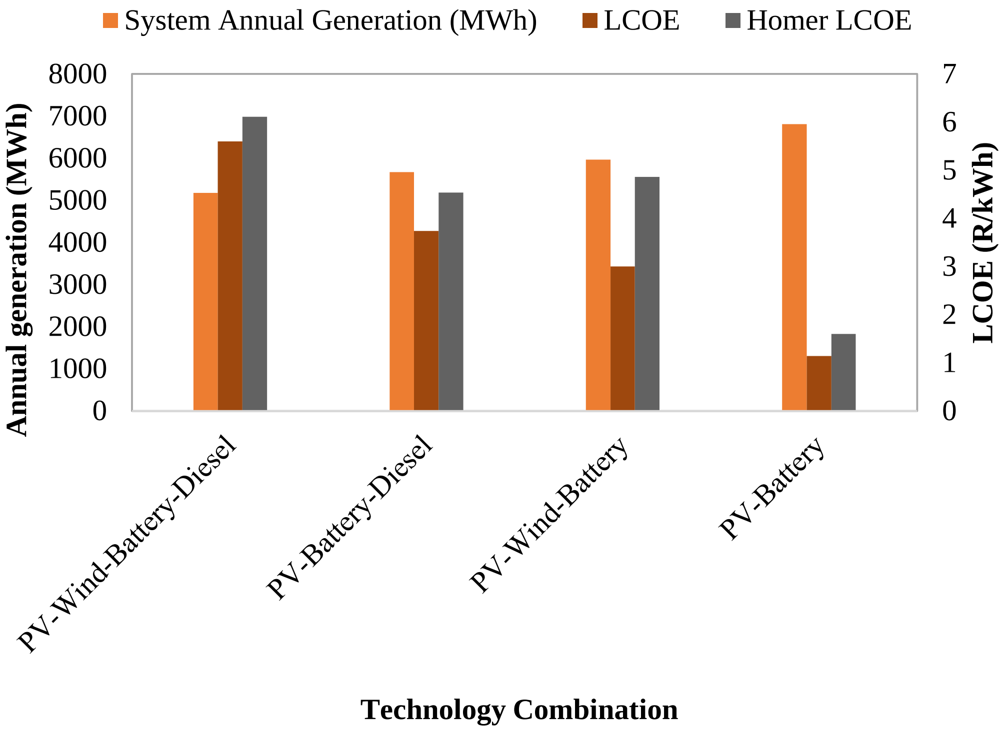


Figure 39: Annual generation versus LCOE

Figure 40 shows how the system sizing of components affects the size of battery storage required. The largest battery capacity (8.8 MWh) is that of the wind and PV with storage while the smallest battery capacity (1.1 MWh) required is the case where the load is shared amongst all the generators.

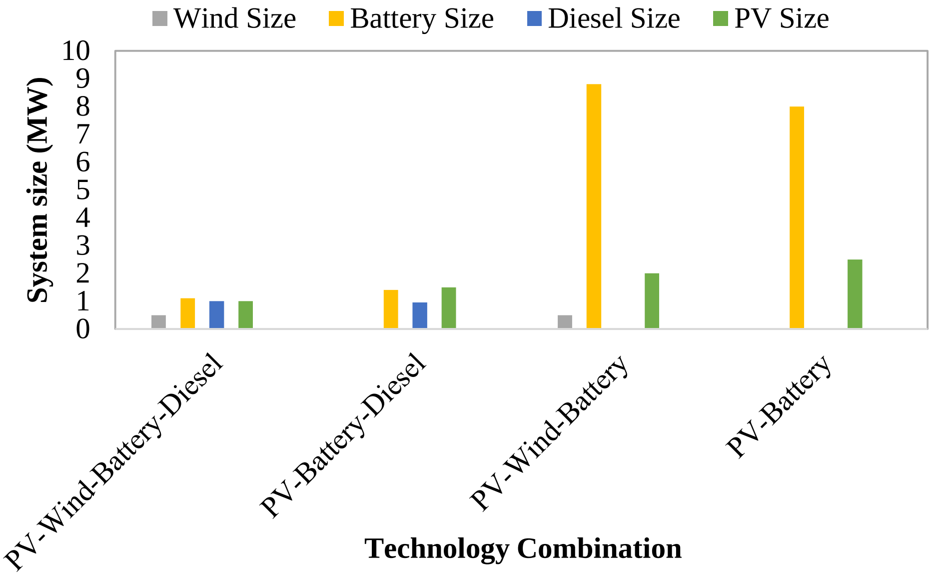


Figure 40: System size per technology combination

5.6.2 CSP Scenario

For CSP, a sensitivity analysis was carried out at varying hours of thermal storage (0, 3, 6 and 9 hours) shown in Figure 41. The annual generation plot is not linear in the cases where the annual generation is higher than demand because generation from the CSP plant is curtailed. A zero demand shortfall ratio is reached for CSP plants of 1MW and above for both 6 and 9 hours of storage.

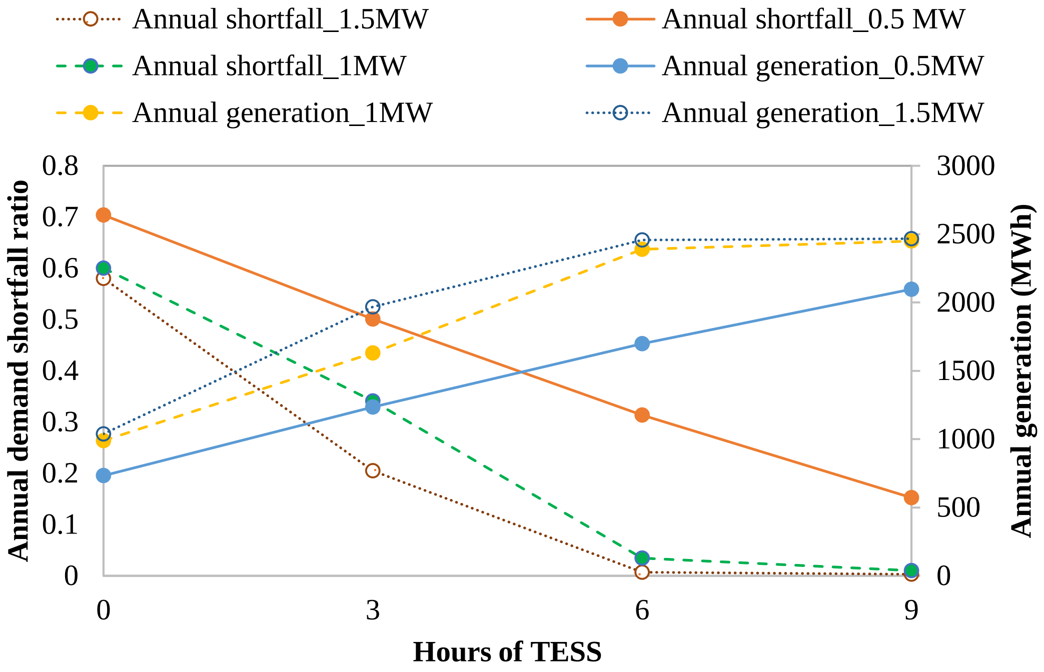


Figure 41: Sensitivity of CSP capacity at varying hours of thermal storage

The capacity factors of each of the plants are also compared in Figure 42.

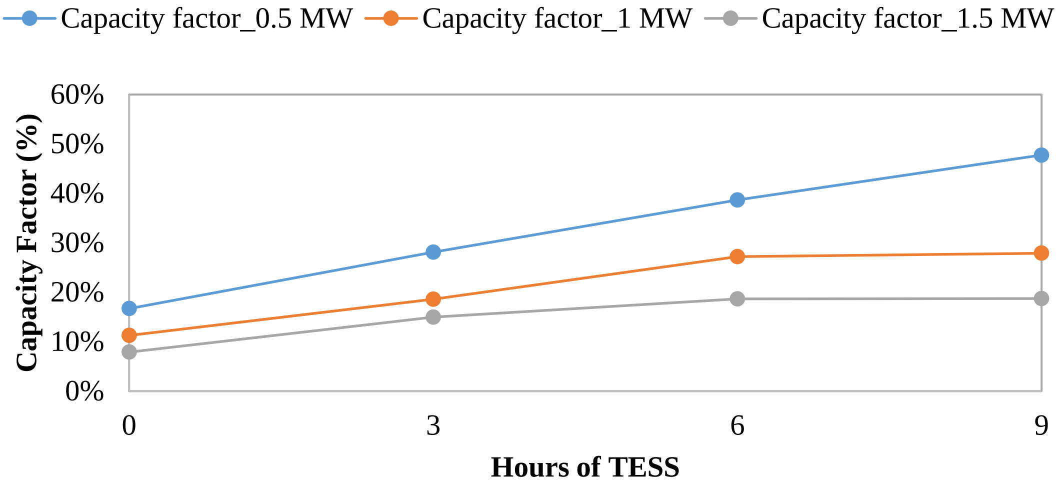


Figure 42: Comparison of CSP capacity factors

Capacity factors for all plants without storage are between 10 and 20%. The additional thermal storage increases this dramatically for the 0.5 MW plant to approximately 48%. However, the larger plants do not increase as dramatically most likely because the plants are oversized in relation to demand. The 0.5 MW plant with 9 hours of storage yields the lowest LCOE at R 3.38/kWh while the 1.5 MW plant with zero storage comes with an LCOE of R20/kWh. There is a significant reduction in LCOE with added TESS. Between 0 hours and 9 hours of storage there is a reduction of approximately 35%, 39% and 42% in LCOE for the 0.5, 1 and 1.5 MW plants respectively. LCOE for CSP with storage is more responsive to demand as the capacity factor includes the availability of storage.

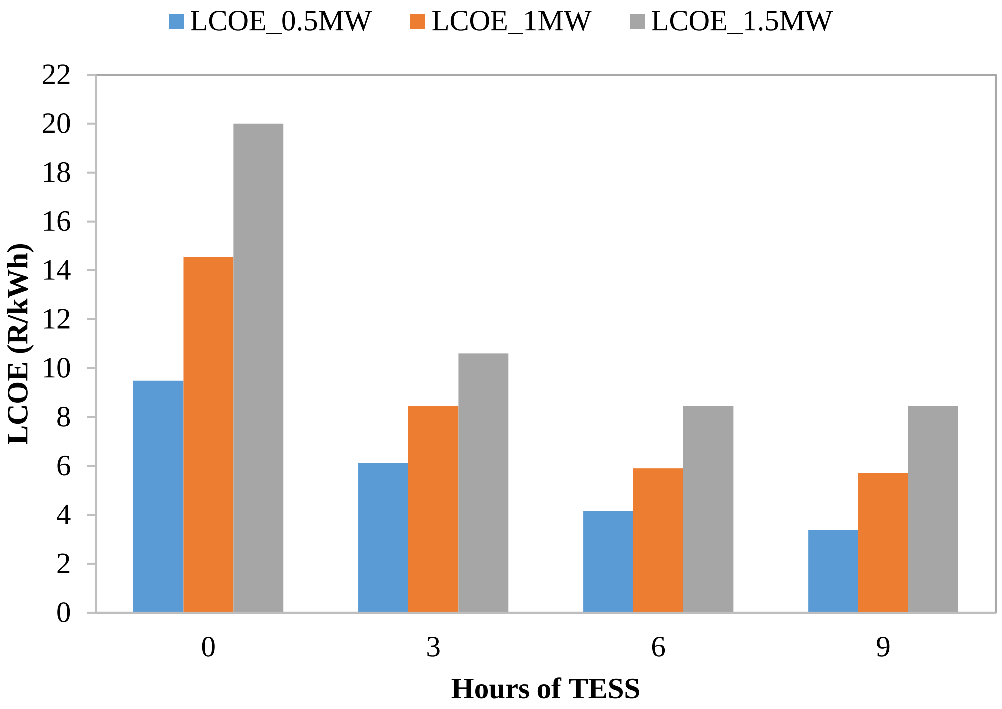


Figure 43: LCOE of CSP at varying hours of TESS

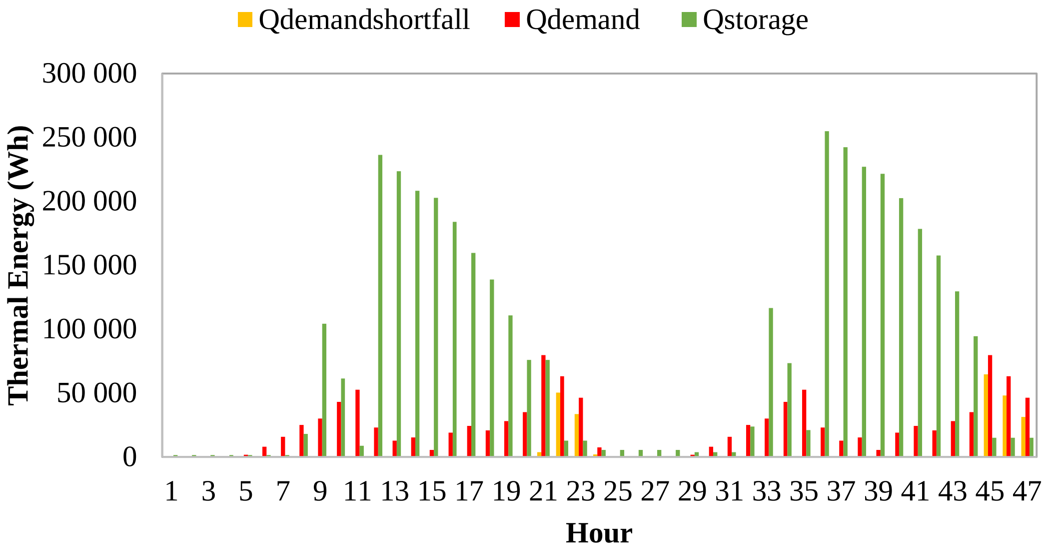
5.6.3 Solar Water Heater Analysis

To model solar water heaters, it is assumed that solar water heaters are only able to service water heating in this model. The demand profile for eShushu is reduced to a thermal load profile using the average hourly hot water usage profile proposed by Ijumba and Sebitosi (2010) and described in Figure 29. From the solar irradiation data (global horizontal irradiation), an hourly thermal energy output for each household is aggregated. Each household is assumed to have the same collector area as shown in Table 16. This results in a levelised cost of thermal energy of R 0.5/kWh.

Table 16: Solar water heater specifications

Parameter	Units	Value
Collector area per roof	m^2	3
Number of households	households	100
Tilt angle	degrees	25

Figure 44 shows the thermal energy flow of the solar water heater model, the stored energy varies daily but results in a lower demand shortfall during the summer.



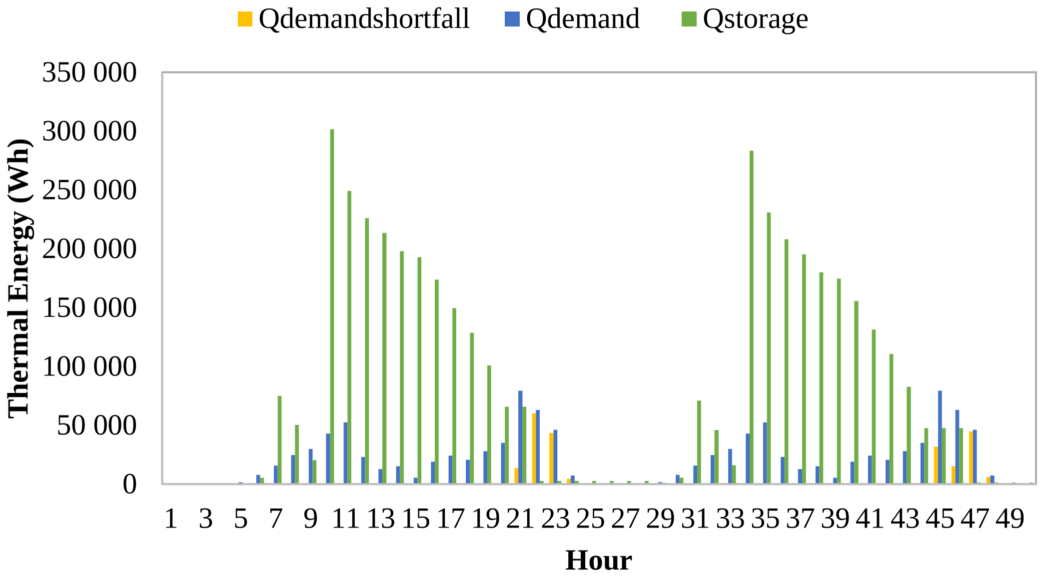


Figure 44: Solar water heater mode - winter (top) and summer (bottom)

The solar water heater simulation is similar to that of battery storage, since the charging is dependant on the hourly solar resource and discharges from storage when the sun is no longer shining. Only the thermal energy stored during daylight hours is kept warm to be dispatched later. For the solar water heating, the discomfort is calculated as all the other generators except that only the thermal demand is considered. Figure 45 shows the demand shortfall comparison for winter and summer over three days.

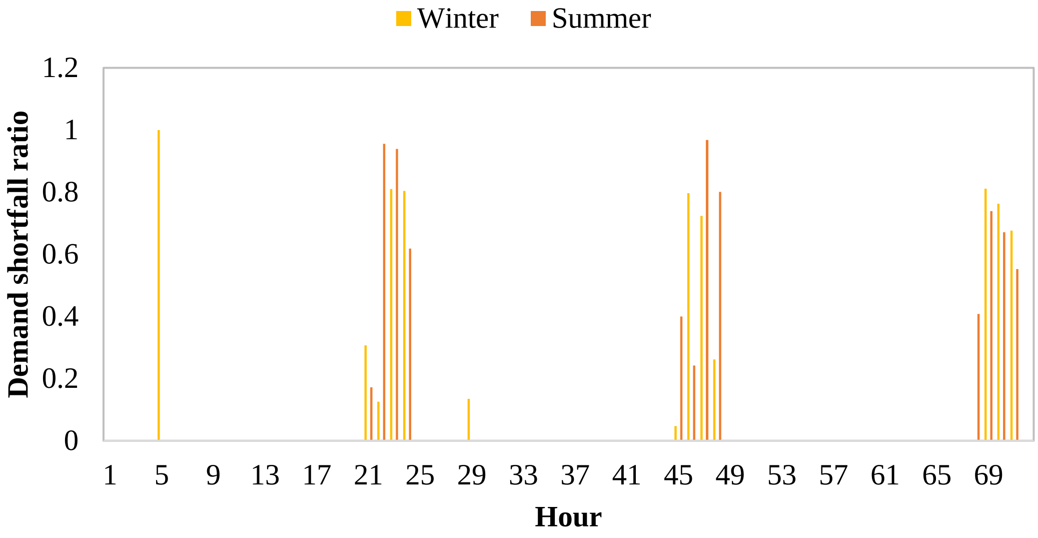


Figure 45: Example of the demand shortfall - three days (winter & summer)

5.7 Comparison of Discomfort Levels: Application to Test Case

From the solar water heater analysis, Figure 46 shows an example of discomfort for two days in both winter and summer. From this it is evident that the battery struggles to keep up with demand in the early morning and late evening.

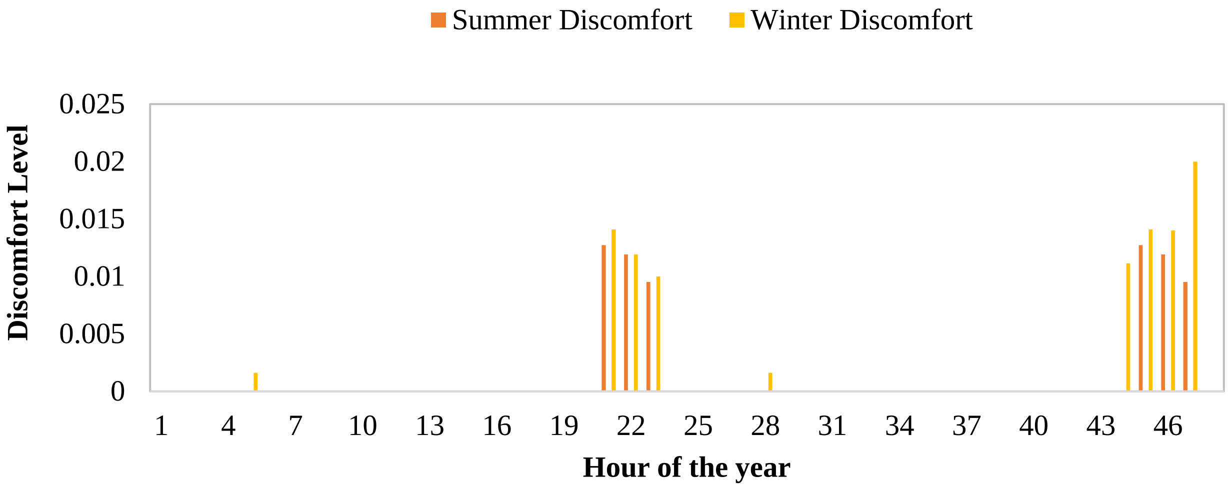


Figure 46: Example of discomfort level profile for two days (winter & summer)

5.7.1 Discomfort Level versus LCOE

From the priority index of energy services, energy service usage and demand shortfall ratio the resulting total discomfort levels for eShushu per technology combination are shown in Figure 47. The scenarios with the lowest discomfort levels include (i) solar PV with battery storage and diesel generation, (ii) CSP with 9 hours of storage and (iii) solar PV with wind generation and battery storage. Unlike LCOE in the scenario comparisons, the LCOE reported here includes the battery wear cost.

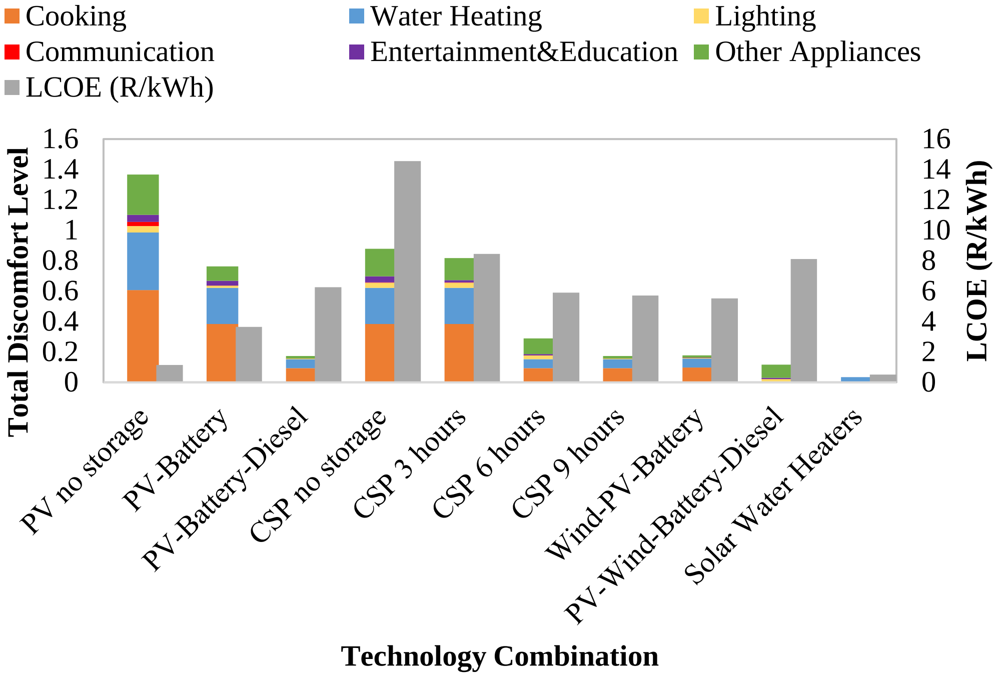


Figure 47: Total discomfort levels vs LCOE for eShushu

From the discomfort levels versus LCOE, the results in Figure 47 show that:

- The wind generation case has highly variable discomfort levels because of the varying wind resource. Cooking and water heating contribute the highest share of energy services unsatisfied. Wind, when combined with solar PV and batteries shows a significant increase in cost and a reduction in discomfort levels comparable to that of CSP with 9 hours of storage and solar PV with batteries and diesel.

- The marginal value of adding battery storage and diesel to solar PV is evident in terms of an improvement in satisfying water heating and cooking energy services but this comes at double the cost in terms of LCOE.

- For CSP, the 9 hours of storage do not come at an increased cost compared to the 6 hour storage case and shows a reduction in LCOE from the 3 hour case. This is a demonstration of the value of storage to the overall cost and the reduction in discomfort levels.

5.7.2 Significance of Discomfort Level

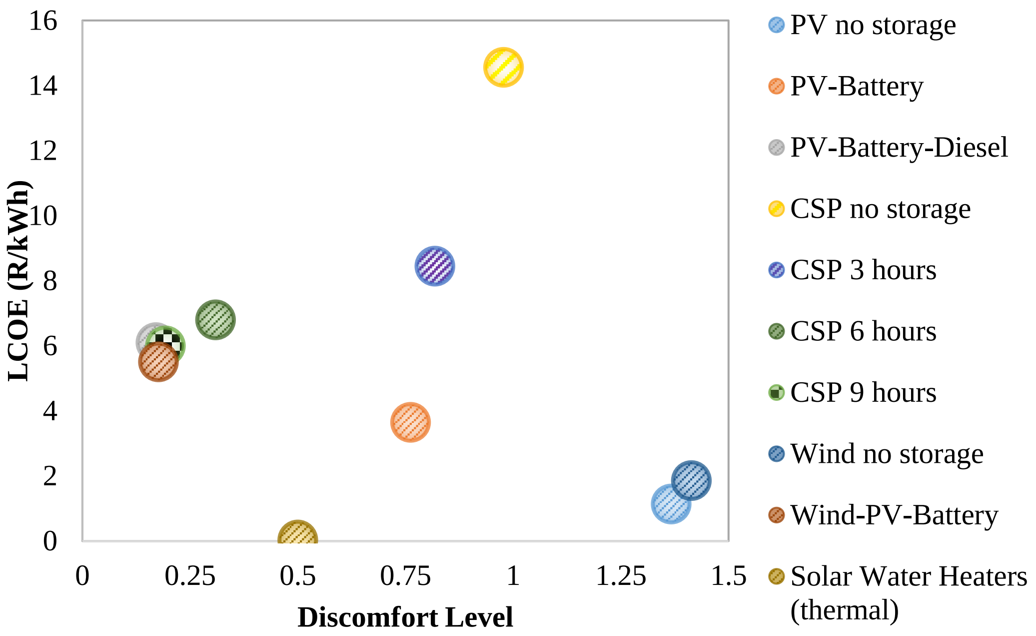


Figure 48: Discomfort level vs LCOE case comparison

Seeing that the discomfort level taken is the hourly average over a year, a discomfort level above 1 indicates a high average demand shortfall ratio as shown in Figure 48. A discomfort level below 1 indicates a low demand shortfall ratio. However the discomfort level term is proportional not only to the demand shortfall but also the energy service usage and priority index. The priority index and energy service usage are also changing variables dependant on the hour. On the discomfort scale one is also able to perceive which energy services are critical. For example, cooking and water heating are most prominent on the discomfort level scale not only because these have a high demand shortfall ratio, but also because these are considered important by the end-users and that the appliances used to deliver these energy services have a relatively high power rating. This is clear because even though lighting is generally an energy service in use for longer periods of time compared to cooking, cooking still results in a higher discomfort level. It is also evident that technologies without storage have an average discomfort level above 1. For eShushu, there are three distinct discomfort level (DL) categories, namely (i) high discomfort level (DL >=1); (ii) mid-range discomfort level (0.5<DL<1) and (iii) low discomfort level (DL<0.25). For this community technologies without storage and CSP with thermal storage hours below 6 hours are not viable options.

5.8 Chapter Conclusion

This chapter provided the building blocks of an energy system simulation for a test case with which to test an evaluation framework. The same approach will be applied in the proceeding chapter to two different cases.

6 APPLICATION TO CASES

This chapter presents the application of the supply-demand model and discomfort framework to two case studies that serve as examples of unique residential communities in Sub-Saharan Africa. The two literature-based cases are Thembelihle, an urban informal settlement in South Africa and Likoma Island in Malawi. A case description is provided and followed by a side-by side comparison of results for both cases.

6.1 Case Description: Thembelihle

Thembelihle is an informal settlement located in Lenasia, Johannesburg with approximately 7 306 residential dwellings which fall under City Power's service areas (Lembede & Vermeulen, 2016). City Power is an independent municipal energy utility owned by the City of Johannesburg (City Power, 2017). The section considered for this study includes 243 households. City Power (Lembede & Vermeulen, 2016: 12) has identified that, "Grid electricity supply is not sufficient to cover peak demand, due to limited capacity on the municipal bulk network". Although parts of the informal settlement has access to the grid network, the city is unable to provide reliable electricity supply during the morning and evening peaks. As a result, City Power has proposed a grid-tied solar PV system with battery storage to serve the community's electricity needs (City Power, 2011). Thembelihle is characterised by high population density of 2900 people per square kilometre and poor service delivery (City Power, 2011).

Figure 49: Thembelihle informal settlement in Johannesburg (AfriGIS, 2018)

6.2 Case Description: Likoma Island

Likoma Island is located near Lake Malawi and has a population of approximately 1 500 households with a total of 10 500 people (Zalengera *et al.*, 2015). Zalengera, Blanchard and Eames (2015) carried out an end-user energy survey of a section on the island with a population of 202 households also used for this study. The island is reliant on diesel generators feeding an independent grid-system used only for the island and it is reported that the high cost of diesel has resulted in electricity supply to residents at times being limited to 14 hours per day (Zalengera *et al.*, 2015). In contrast to Thembelihle, Likoma Island has a lower population density of 580 people per square kilometre.

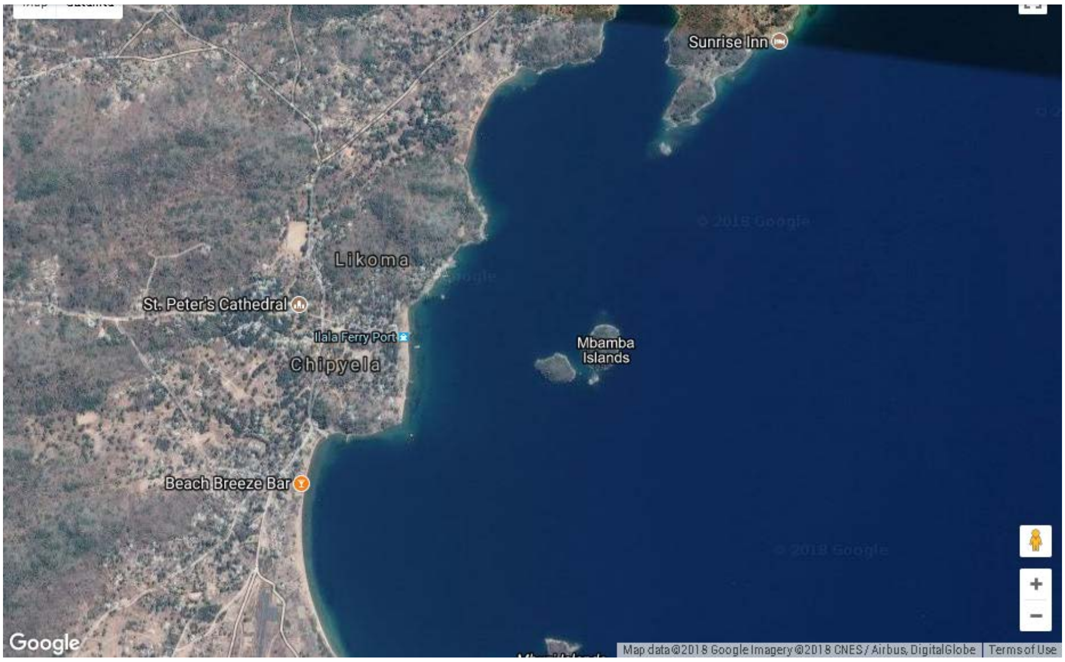


Figure 50: Likoma Island in Malawi (AfriGIS, 2018)

6.3 Energy Demand in Informal Settlements

Part of the challenge of planning an energy system for communities such as Thembelihle is that the historical data is not a reflection of the future energy demand. For example, Lloyd (2014) in a survey of 150 households in the Samora Machel informal settlement near Cape Town found that only 20% of homes had refrigerators, kerosene also known as paraffin was the main source of energy for cooking, water heating, space heating and even lighting whilst electricity was only used for low power energy requirements such as charging cellphones and radios. Only 38% of homes in the community had electricity access (Lloyd, 2014). The survey also sought out to find out the perception of alternative fuels amongst the residents and findings show that even though paraffin dominates at above 45%, only 22% of people were satisfied with using it while others only used it because of the perception that it was cheap (10%) and some cases where users reported health problems.

Another significant finding is that energy costs made up more than 25% of the monthly household income (Lloyd, 2014). Fuelwood is also commonly used for space heating (18%) and candles for lighting (24%) after paraffin (Lloyd, 2014). Makonese carried out a similar study in Tembisa, Johannesburg. In this case, coal was the dominant fuel source during winter months because of the dual function of providing cooking and space heating energy services. Kerosene for cooking and heating was dominant during summer months (Makonese, Masekameni & Annegarn, 2016). Coal is readily available in Johannesburg compared to the Westerm Cape because of the transportation distances from the coal fields (Makonese *et al.*, 2016). Makonese advocates that energy interventions should be less supply driven because households in these areas make use of multiple energy fuels. LP gas in both cases is perceived to be unsafe and is therefore only used occasionally (Makonese *et al.*, 2016).

6.4 Simulation Description

The energy model for both cases runs over a period of one year and follows the process defined in *Chapter 4 (Model Description)* and *Chapter 5 (Discomfort Framework)*. To begin with, base case scenarios without storage for solar PV, SS-CSP and wind were simulated for system sizing using sensitivity analysis. From the selected sizes, battery storage and/or diesel generators are added to reduce the demand shortfall considering total annual electricity generation, levelised cost of electricity (LCOE) and capacity factor for each technology combination. In the case where test case results are presented for a day(s), the days selected are taken for the same day from the high demand season in July using real weather series data for the location. Hourly solar and wind data for both Thembelihle and Likoma Island is obtained from HelioClim-3 Archive Database of Solar Irradiance and Meteorological Data (SoDA, 2017) for a year from 2005/07/01 to 2006/06/30 at a solar PV tilt angle of 25 degrees. Table 17 shows site details at a wind measurement height of 10 metres.

Table 17: Case study weather data details

Case Study	Latitude	Longitude
Thembelihle	-26.334	27.866
Likoma Island	-12.058	34.735

6.5 Demand Profile

To simulate time of use, probabilities are applied for each appliance at each hour in-line with the method outlined for the test case. Proxies used to determine probabilities for Thembelihle is based on the demand profile modelling (DPM) tool developed for Eskom for South Africa (Heunis & Dekenah, 2010) and later updated in 2014. The tool predicts the demand profile of a region based on the number of people and the income level.

A side by side comparison for different energy services is shown based on time of use for Thembelihle and Likoma Island. The probabilities for time of use for Thembelihle are derived from the energy demand profile generated from the demand profile while the Likoma probabilities are based on the survey results on the appliances and time of use patterns.

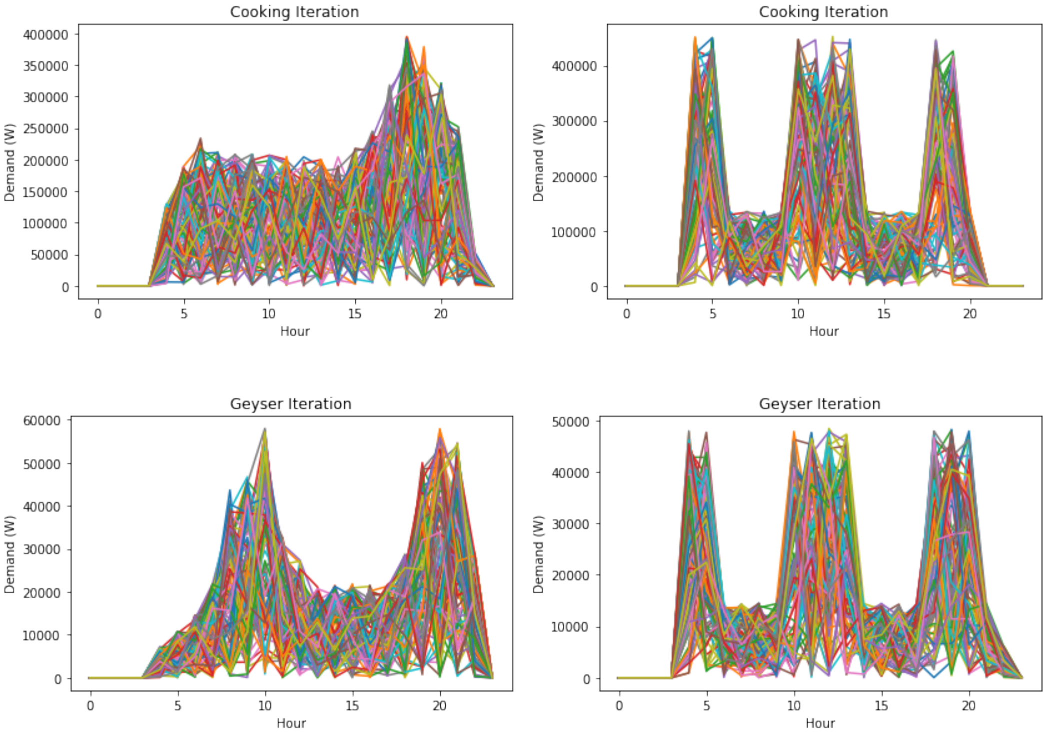


Figure 51: Time of use profiles: Thembelihle (left) and Likoma (right)

The same demand modelling approach used for the test case is applied for both Thembelihle and Likoma Island. For Thembelihle, the appliances used are obtained from Kehrer (2008) who carried out a survey for the types of household appliances used in informal settlements. For all modelling assumptions related to Likoma Island, the household survey data carried out by Zalengera, Blanchard and Eames (2015) for 202 households living on a section of the island is used. An example of the resulting average demand profile for both cases is shown in Figure 52 for 24 hours.

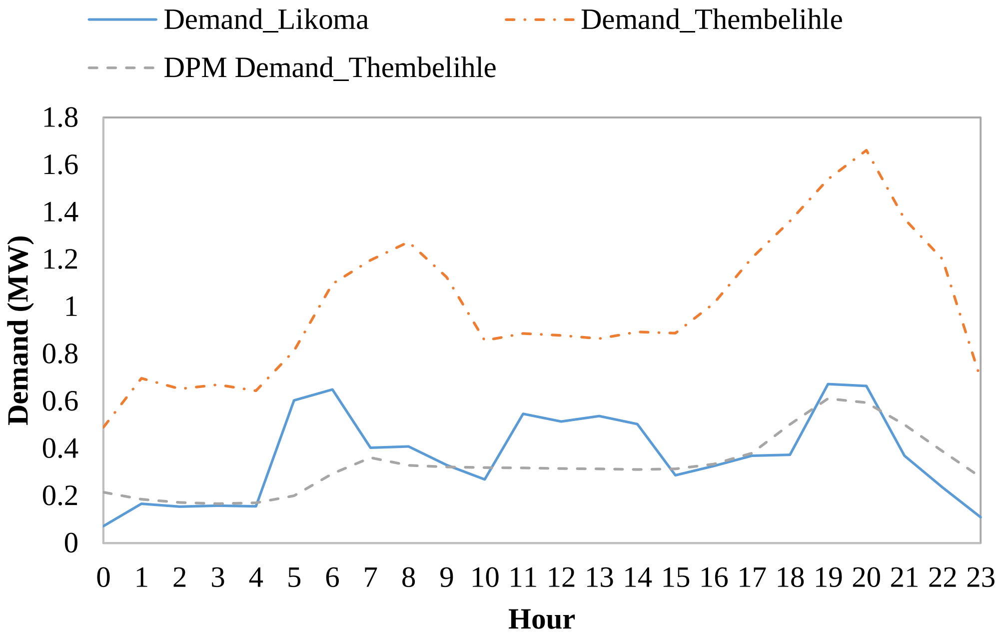


Figure 52: Average demand of Thembelihle and Likoma Island

Part of the challenge of forecasting demand for a place such as Thembelihle is that the historical consumption does not reflect the future reality. The DPM estimation is well below that of the model developed in this study. This is mainly because the reality in an informal settlement such as Thembelihle, there might not be hot water geysers or microwaves. It is also clear from this graph that the informal settlement as shown in the map might have a higher energy consumption per household due to the number of people making up a household.

From Figure 52, Thembelihle's average demand shows two distinct peak periods in the early morning and evening. On the other hand, Likoma Island shows peaks in the early morning, afternoon and evening. The daily, peak and annual load figures are listed in Table 18.

Table 18: Average demand profile daily, peak and annual results

Parameter	Units	Thembelihle	Likoma Island
Daily Energy Demand	kWh	23972	8876
Daily Peak Demand	kW	1662	672
Annual Demand	MWh	8750	3240

6.6 Hybrid Scenarios

This section presents a side-by-side comparison for both cases. Similar to Chapter 5 availability assumptions, diesel generation and battery storage are constrained not to contribute to supply during the day (when solar resource is available). The demand shortfall ratio versus total annual electricity generation for the hybrid scenarios of each case are shown in Figure 53 and Figure 54.

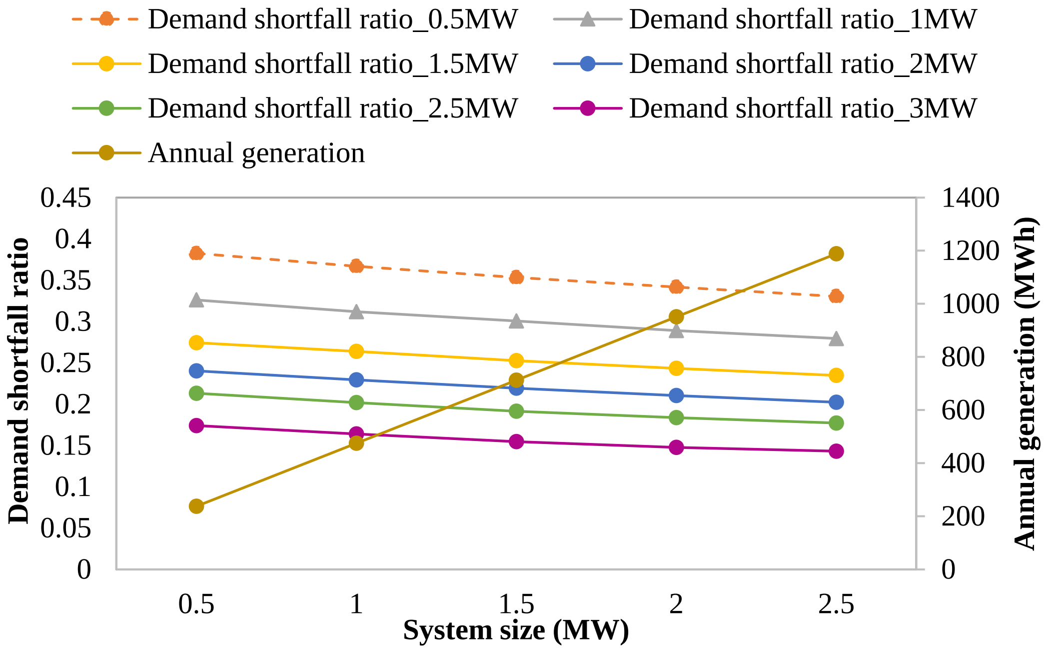


Figure 53: Wind size sensitivity for Thembelihle PV array (0.5 – 3 MW)

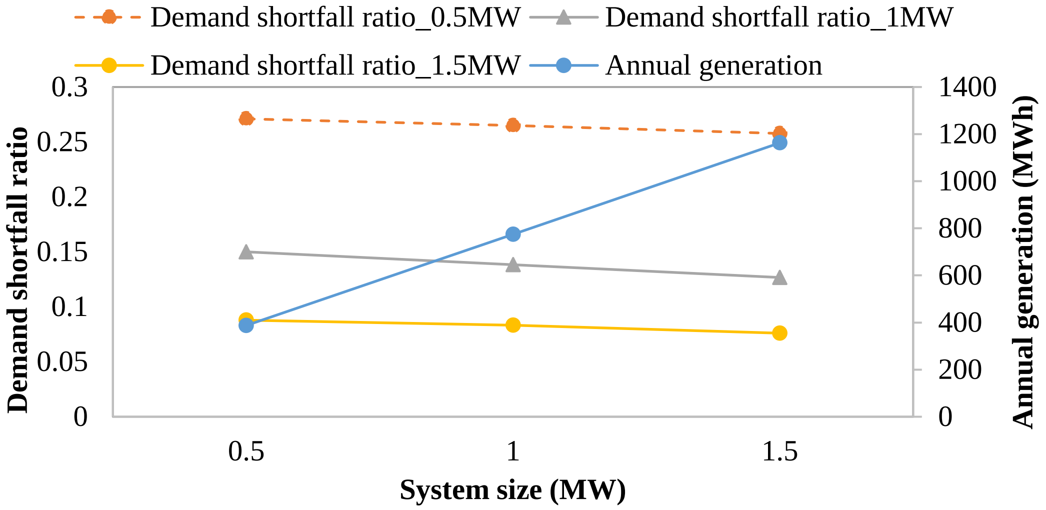


Figure 54: Wind size sensitivity for Likoma PV array (0.5 – 1.5 MW)

The capacity factor for solar PV is 15.1 % which is below the capacity factor from Homer (19.8%) for Thembelihle. For Likoma, a solar PV capacity factor of 22% compared to Homer (18.2%). The wind capacity factors are relatively low at 5.4% (very similar to 5.5% from Homer) and 8.8 % (10% from Homer) for Thembelihle and Likoma respectively. The LCOE compared to that calculated by Homer for each generator is shown in Figure 55 for each case.

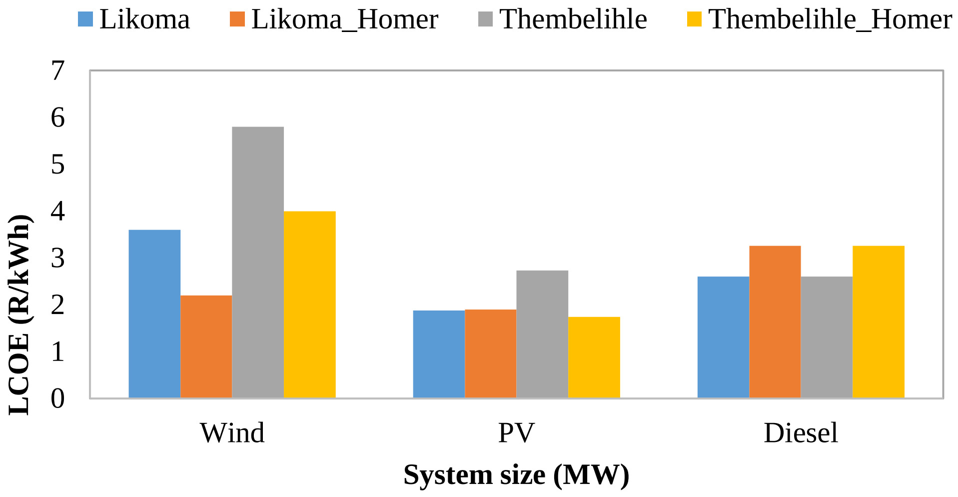


Figure 55: LCOE of hybrid generators

The results of hybrid scenarios created by adding battery storage and diesel using the system sizes selected in the previous section are presented for Thembelihle and Likoma Island in Table 19. For comparison, a 1 MW system for both Likoma and Thembelihle is shown in Table 19.

Table 19: Hybrid Comparison: Thembelihle and Likoma Island

	Demand Shortfall (%)		LCOE (R/kWh)	
Scenario	**Thembelihle**	**Likoma**	**Thembelihle**	**Likoma**
PV-battery	0.46	0.46	2.7	1.88
Wind-PV-battery	0.48	0.45	8.5	5.48
PV-battery-diesel	0.24	0.17	5.3	4.48
PV-wind-battery-diesel	0.2	0.1	11	8

In terms of diesel generation, Figure 56 and Figure 57 show the annual generation for both Likoma and Thembelihle respectively.

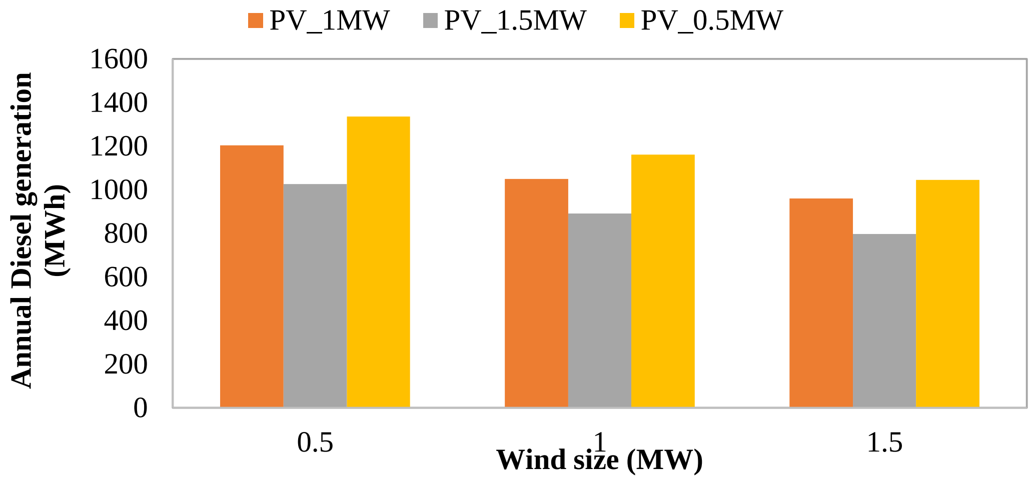


Figure 56: Annual generation from diesel generators: Likoma

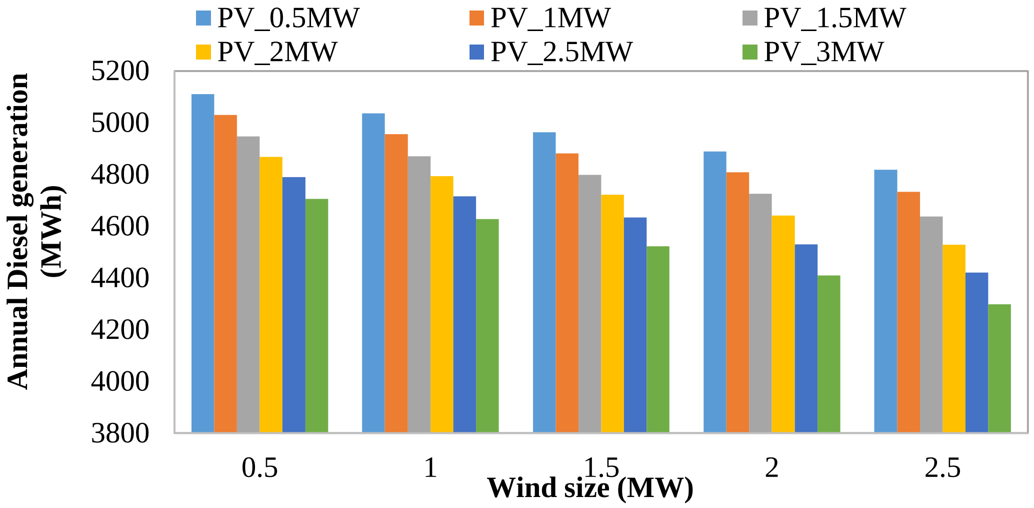


Figure 57: Annual generation from diesel generators: Thembelihle

A 100 kWh Li-ion battery type from the eShushu test case is used to size a battery bank with autonomy of 30 hours, system voltage of 600 V, nominal current of 167 Ah and a minimum depth of discharge of 20 percent for both cases. The smallest battery bank capacity for Likoma Island is 0.9 MWh for the PV, battery, diesel and wind scenario. For Thembelihle, the same scenario results in a 2.3 MWh battery bank. The largest battery bank is 13 MWh for Thembelihle with a 3 MW solar PV and battery storage scenario.

6.7 CSP Simulation

The following section presents side by side sensitivities for CSP system size considering thermal storage from zero to nine hours.

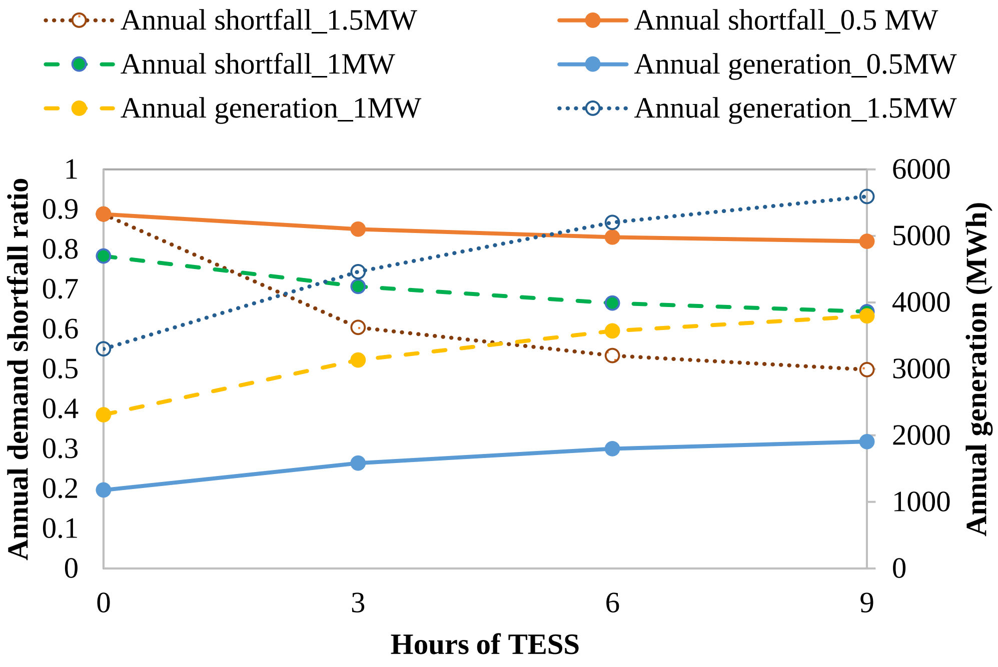


Figure 58: Sensitivity for CSP capacity: Thembelihle

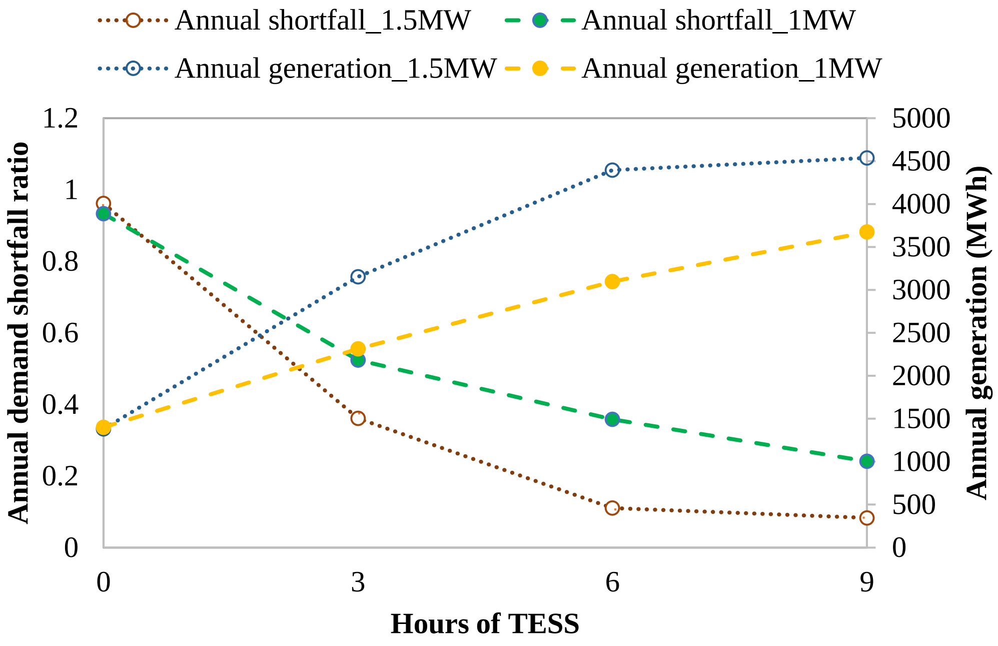


Figure 59: Sensitivity for CSP capacity: Likoma

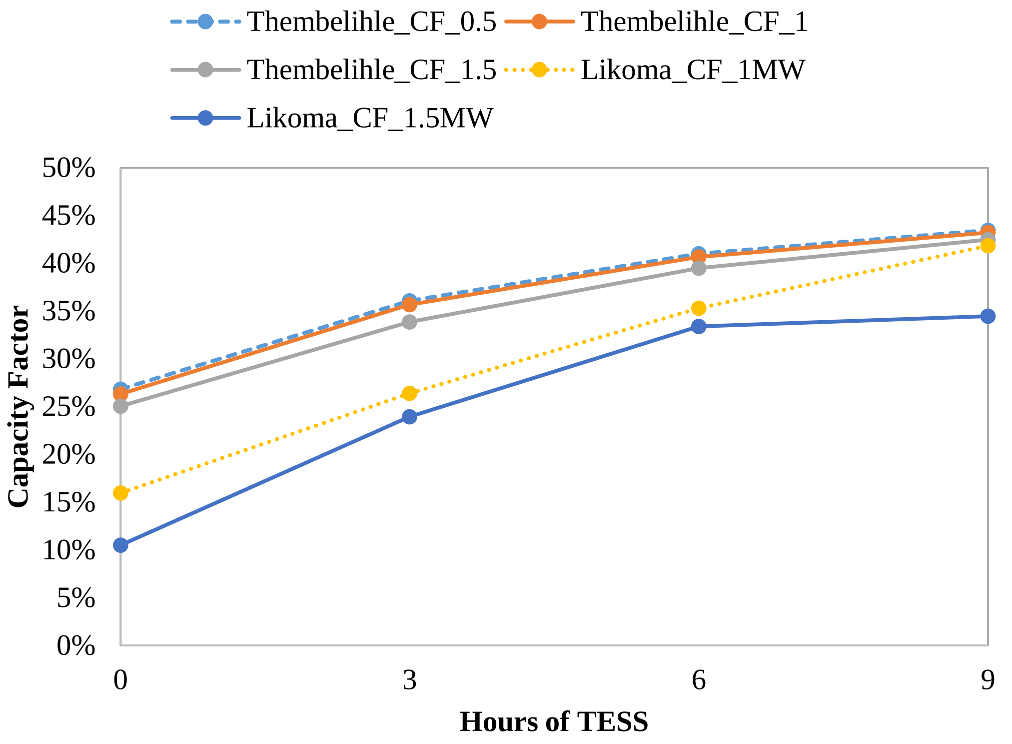


Figure 60: CSP capacity factors for varying hours of thermal storage

The capacity factors above show that in Thembelihle, the capacity factor is almost insensitive of plant size and thermal storage hours because of the low irradiation.

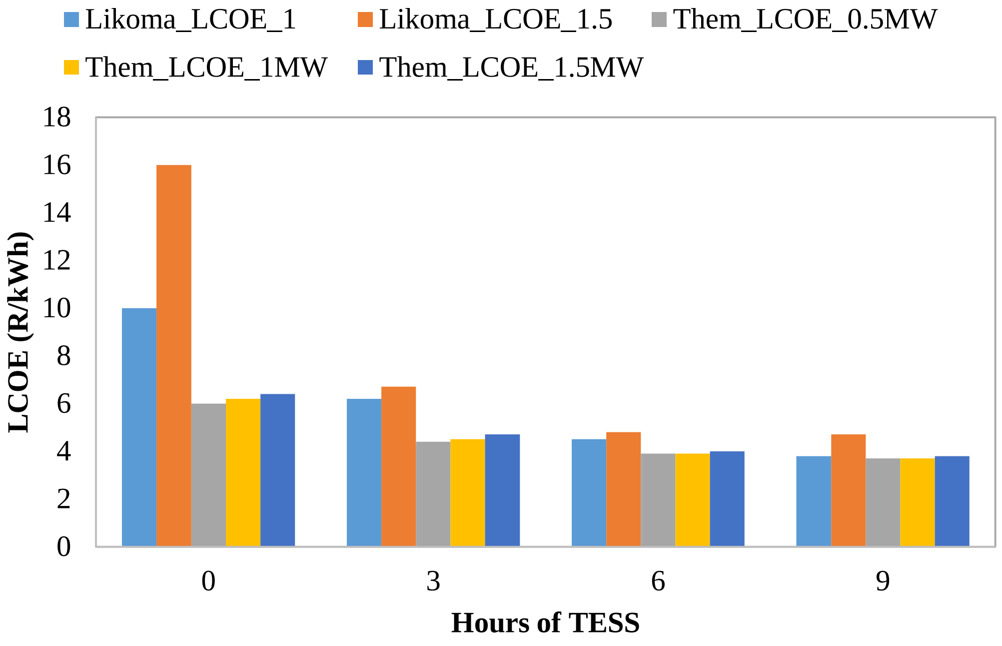


Figure 61: LCOE for varying hours of thermal storage

6.8 Discomfort Level Assumptions

In this section, the assumptions used to formulate a priority index of energy services for both cases are presented. To calculate discomfort a sample from the sensitivities carried out was selected. To maintain consistency, a hybrid system with 1 MW PV and 0.5 MW wind was selected simply for comparison across both cases. This is not necessarily the cases with the lowest demand shortfall. For Thembelihle, this is a system with a 30% demand shortfall and 15% for Likoma.

6.8.1 Priority Index of Energy Services: Thembelihle

The priority index weights for this case were adapted from the multi-energy poverty index (MEPI) (Nussbaumer *et al.*, 2013) as a proxy because literature for the specific case outlining this could not be found. Seeing that the access to energy problem for this case study is during the morning and evening peak when the grid is constrained, a priority weighting index was assigned for these two periods during winter and summer. Three distinct periods were selected for calculating a priority weighting for each energy service for Thembelihle, namely (i) the morning and evening peak during winter, (ii) morning summer peak and (iii) an evening summer peak. Here it was assumed that the morning and evening peaks of the winter season share the same priority weighting because the weather is similar. However for summer, a distinction was made between the morning and evening peak periods as shown in Table 20.

Table 20: Comparison of Thembelihle priority indices to MEPI indices

Energy Service	Morning & Evening Winter Peak	Evening Summer Peak	Morning Summer Peak
Cooking	0.305	0.323	0.306
Lighting	0.305	0.323	0.306
Services provided by other appliances	0.04	0.043	0.040
Entertainment/Education	0.084	0.089	0.084
Communication	0.032	0.039	0.032
Water heating	0.231	0.183	0.231

6.8.2 Priority Index of Energy Services: Likoma Island

The priority of energy services for Likoma Island are based on the results from a survey conducted by Zalengera, Blanchard and Eames (2015) where households ranked energy services according to their perceived importance as shown in Table 21 throughout the day. Table 21 shows the normalised rank of energy services as derived from the survey and the normalised priority weighting used as a proxy for the priority index of energy services.

The normalised rankings are used as a proxy for the priority index for each energy service. For this community, a distinction was not made between the morning and evening peaks as the average daily demand profile in Figure 52 is distributed throughout the day with peaks in the morning, afternoon and evening.

Table 21: Priority indices used for Likoma Island

	Normalised Rank	Normalised Weighted Priority
Cooking	0.85	0.216
Lighting	0.89	0.226
Water Heating	0.72	0.183
Communication	0.72	0.183
Education/ Entertainment	0.75	0.191

6.9 Evaluation: Discomfort and LCOE

This section shows the resulting discomfort levels versus LCOE for the different scenario combinations considered for Thembelihle and Likoma Island. The discomfort level provides a quality measure whilst the LCOE is an economic indicator.

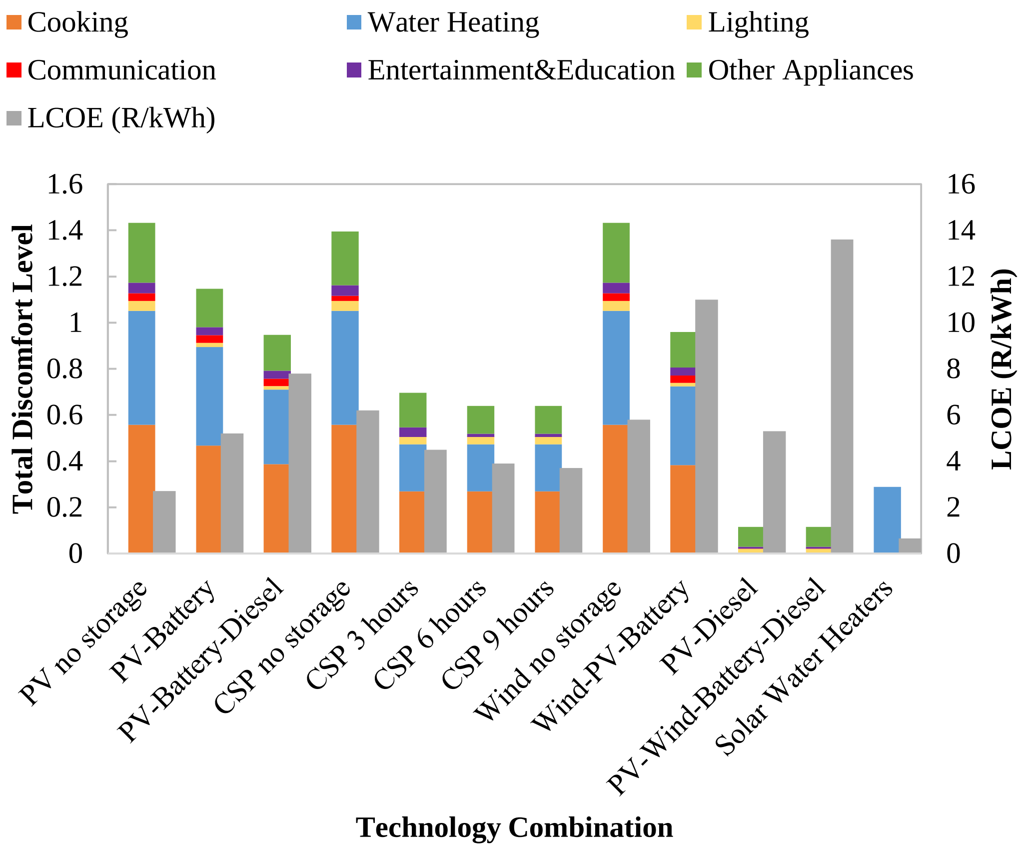


Figure 62: Discomfort versus LCOE evaluation: Thembelihle

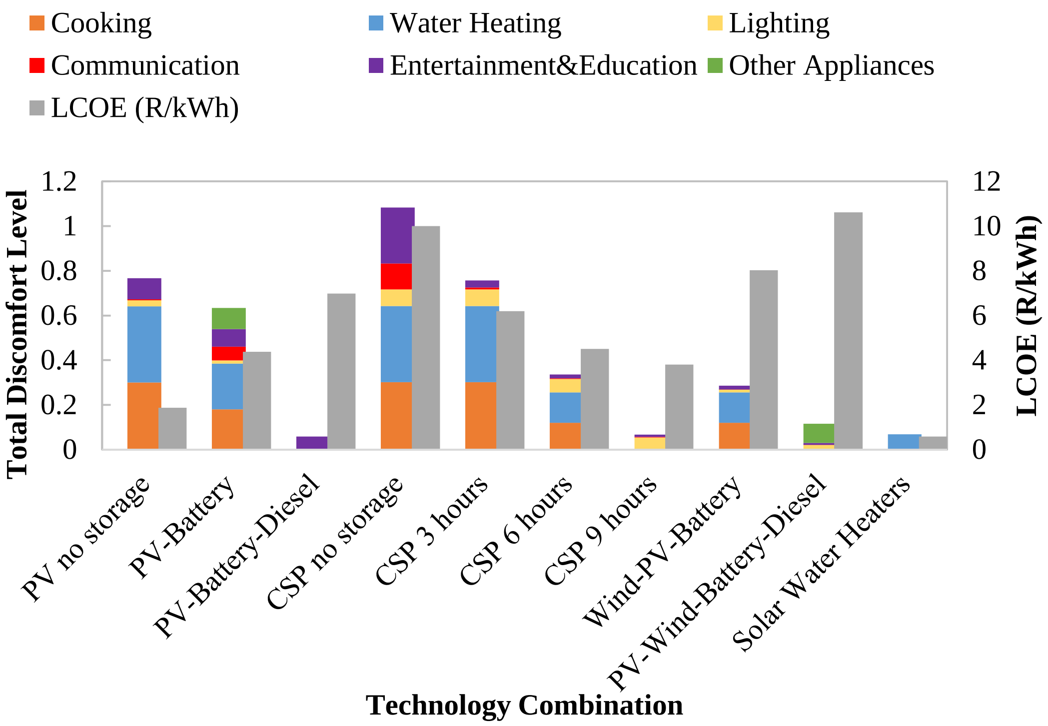


Figure 63: Discomfort versus LCOE evaluation: Likoma Island

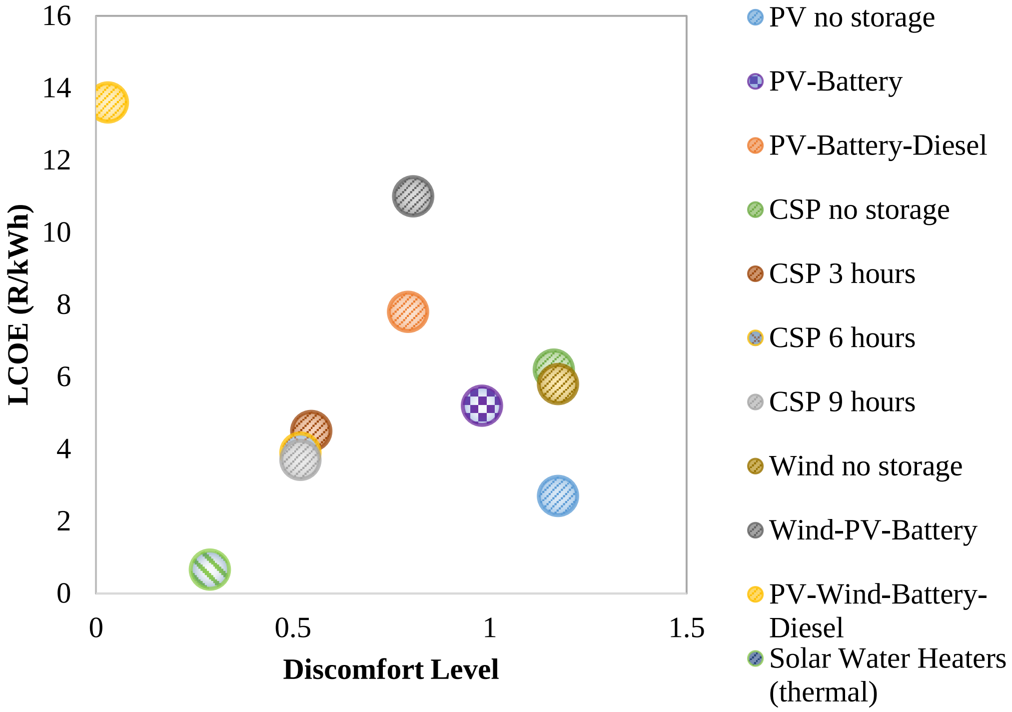


Figure 64: Discomfort vs LCOE: Thembelihle

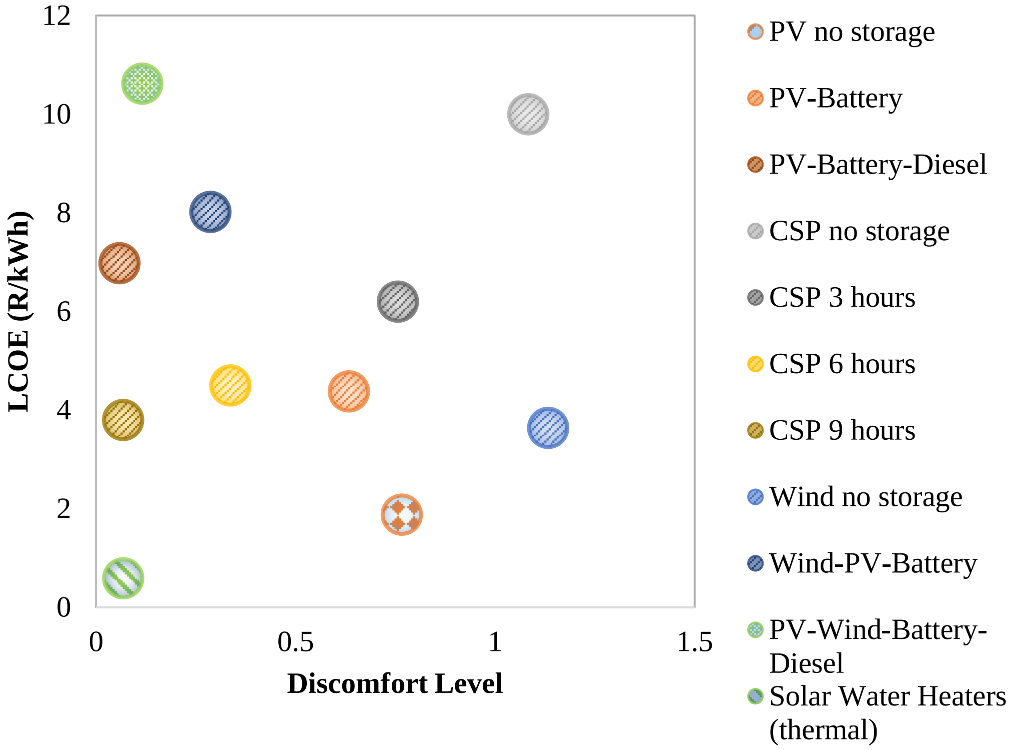


Figure 65: Discomfort vs LCOE: Likoma

6.10 Interpretation of Simulation Results

From Figure 62, Figure 63, Figure 64 and Figure 65 showing the discomfort levels against LCOE for Thembelihle and Likoma Island respectively it is evident that each community has unique discomfort levels for the same supply technologies. There is a trade-off between cost and discomfort level for each case. For Thembelihle, the lowest cost is given by the ‘PV-battery’ case while the lowest discomfort is achieved with the ‘PV-battery-diesel’ energy mix as shown in Figure 62. However for Likoma Island, the lowest discomfort level is given by the ‘PV-battery-diesel’ case and CSP with 9 hours. The lowest cost and lowest combination is also CSP with 9 hours of TESS shown in Figure 63.

- **Finding 1: CSP and solar PV offer better value to Likoma Island regardless of storage because of the demand profile throughout the day.**

Likoma Island has the lowest discomfort levels compared to Thembelihle and eShushu. This can be attributed to the average demand profile of Likoma Island which has peaks in the early morning, afternoon and evening whereas the other two communities do not have high demand when the solar resource is at its best during the day as shown in Figure 52. The test case (eShushu) has the best solar resource but not when it is needed during the early morning and evening. This is evident in the comparison in discomfort levels for CSP with 6 hours of storage which for Likoma Island has a discomfort level below 0.4 which is comparable to CSP with 9 hours of storage for Thembelihle. Wind is highly variable in the short term for all three cases which without storage results in the highest discomfort levels. However, this comes at double the cost of only solar PV with batteries for Likoma Island and three times the cost for Thembelihle.

- **Finding 2: The priority of energy services is distinct in the discomfort levels of each case but lighting, water heating and cooking are consistent across cases.**

Lighting, water heating and cooking represent the highest discomfort levels across both cases shown in Figure 62 and Figure 63. Water heating and cooking remain the two main energy services with the highest demand and the least satisfaction mainly because these energy services are required during peak times when solar resource is poor and consumption is at its highest. Figure 63 also shows that communication and education/entertainment are highly valued in Likoma Island. This is because the survey by Zalengera used to formulate the demand profile shows that the community uses less appliances and thus energy services such as communication have a higher energy share.

- **Finding 3: Solar water heaters result in reduced discomfort levels for thermal energy across all three cases.**

Thembelihle has a greater population and has a defined morning and evening peak which results in a higher discomfort level for water heating in comparison to Likoma Island. Once again, this can be attributed to Likoma Island’s demand profile being distributed across the day with three peaks. This also shows that behavioural patterns in hot water usage throughout the day are a key factor in the discomfort level associated with each technology. Seeing that the results show a dominance of water heating and cooking requiring thermal energy, diesel generation can potentially be replaced with energy efficiency technologies.

- **Finding 4: A high spatial and temporal data resolution is not only beneficial for the integration of renewable energy technologies but also emphasizes the value of storage and peaking technologies.**

In terms of the energy resource potential specifically for wind and solar, a high spatial and temporal resolution is as Pfenninger, Hawkes and Keirstead (2014) suggest essential in integrating renewable energy technologies given their distinct weather dependant behaviour. In addition to this, a high spatial temporal resolution of resource data has proven as expected key for the modelling assumptions of storage and peaking technologies, in this case batteries and diesel generators. The value of these technologies is evident in the reduction of discomfort levels across all cases.

- **Finding 5: Specifying exactly which energy services are unsatisfied by different supply technologies provides an opportunity for complimentary energy storage and energy efficiency technologies to form part of the energy system.**

The selection of technologies demonstrated that modelling an energy system only in terms of electricity and LCOE limits the type and scale of technologies which can be used. Thus an electricity-only system is unable to tap into the unique consumption patterns within a community context and the opportunity to integrate energy efficiency technologies like SWHs.

6.11 Chapter Conclusion

From the case studies explored, a number of unique challenges have emerged, namely (i) the reliability of the grid and (ii) the use of mixed distributed generation technologies to meet the demand load. A comparison of discomfort levels and LCOE was carried out for each case and the results analysed. The relevance of these results to the objective of the study is discussed in the next chapter.

7 DISCUSSION

“Transforming the urban energy system is not a question of simply replacing one form of energy with another, but of rethinking the entire energy system with all the related interactions and uses”

IRENA, *Renewable Energy in Cities*, 2016

The study at hand has created an energy system model based on three main building blocks, namely (i) spatial and temporal energy resource data, (ii) a suite of energy supply technologies and an (iii) energy demand profile based on energy services. This section provides interpretation of the results from the energy simulation and discusses findings, challenges, implications and areas for improvement in relation to the research question.

As a reminder, the research question being:

What are the approaches of quantitatively evaluating community scale energy systems such that the choice of technology combinations offers an improvement in terms of (i) satisfying the end-user’s energy service needs, and (ii) representing a high penetration of distributed and renewable energy supply technologies in a developing country context?

7.1 Interpretation of Literature and Findings

This section is arranged in sections addressing the sub-question stated in *Chapter 1 (Introduction)*. Each sub-question is addressed from two perspectives where relevant, namely insight from literature and insight from the model results.

7.1.1 Unique Energy Needs of Developing Countries

The unique energy needs of developing countries that have emerged from literature in this study are identified in a number of forms, namely (i) the type of project (rural vs urban vs informal); (ii) the scale of project (community, building, town, etc); (iii) the types and priority of end-user energy services unique to a community; and (iv) the extrinsic value of energy services to the end-user. In terms of project scale, it ranges from building, community and municipality scales. The types of distributed energy systems found in literature are a reflection of some of the energy needs. For example, rural electrification projects are dominant in South Africa and neighbouring countries (Mabaso & Gauché, 2018). However, demand in a developing country context is harder to rigidly define and forecast because the end-user’s demand is adaptable to the nature of supply. This ‘elastic’ nature of demand is demonstrated in the case of Thembelihle where the community has access to the grid but receives an unreliable service.

7.1.2 Unique Energy Modelling Approaches

Software tools such as Homer, DER-CAM and urban network models such as Urbs designed for modelling of micro-grids are emerging (Mabaso *et al.*, 2018). There is also an increase in the number of tools modelling energy types other than electricity, including thermal energy, combined heat and power (CHP) and cooling. There are also tools such as Temoa and Calliope which are aimed at representing a high penetration of renewable energy features but are designed for utility scale systems. Overall, the models considered focused on a least cost modelling approach or at least offered the option. However, simulation tools such as the Power Systems Simulation (PSS) tool dispatch supply generators based only on availability and hierarchy as determined by the user (Mabaso *et al.*, 2018). In general, there is minimal interaction between end-user energy services as defined in this study and energy supply infrastructure except for microgrid software such as Homer and DER-CAM but these are still geared towards the context of the countries where they were designed (predominantly developed countries) with the assumption of the availability of demand profile data. In terms of energy modelling, centralised models are more common at national scale. However, in South Africa for example, there is evidence of growing interest in decentralised energy projects at a municipality scale but published modelling studies were not found at the time of this study.

Apart from modelling tools, there exists indices measuring energy poverty but not directly attached to the operational features of energy infrastructure. For example although the multi-criteria energy poverty indicator (MEPI) considers isolated technologies, it does not reflect the technical performance of technologies in combination with one another or the unique site weather resource. Another missed opportunity is that there are various studies which explore the sustainability and project acceptance of distributed energy systems but these are compiled in hindsight and there is no evidence found where outcomes were incorporated into the planning phase of energy infrastructure projects or in techno-economic models. Various examples of these types of studies were found (Brent & Rogers, 2010; Buchana & Ustun, 2015; Musango & Brent, 2011; Urban, 2009).

7.1.3 Effects of Increasing Availability and Affordability of Renewable Energy

Unique small scale projects for rural and urban electrification including the Solar Turtle (van der Walt *et al.*, 2015), iShack (Keller, 2012) and Jabula Microgrid (Zonke Energy, 2017) are examples of the effects of increasing availability and affordability of renewable energy technologies (Mabaso & Gauché, 2018). The unique nature of these projects is largely focused on the business models that align with the buying power of customers in the rural and informal settlement sectors. This is largely in the form of mobile phone pay as you go payments (ACORE, 2015). In South Africa, the reduction in the cost of solar PV and wind technologies is comparable to that of grid tariffs on an LCOE basis (GreenCape, 2017). By modelling battery storage, diesel generators and energy efficiency technologies as done in this study, the complimentary supply combinations offering reduced discomfort levels at low cost are apparent. For example, a community such as Likoma Island which experiences high discomfort levels because of a reliance on expensive diesel can benefit from a CSP plant with 6 hours of storage or reduce the reliance on diesel and supplement this with solar PV and batteries for a lower discomfort level as shown in Figure 63. Therefore another opportunity of the increasing affordability and availability of renewables is that unique communities can tailor a generation mix suited for the resources available in that area. In addition to this, seperating demand into electricity and thermal energy flows provides opportunities for energy efficiency policies such as solar water heaters.

7.2 Relevance of Results

The study at hand has formulated discomfort levels for different combinations of distributed technologies. Overall, the results are not surprising but offer insight into the types of end-user energy services which are unmet at an hourly rate.

The simulation modelling method applied for this study has proven to be both applicable and relevant in determining

- Which technologies are well suited for a context,
- Which energy services each combination of technologies is able to supply,
- The gaps which could potentially be filled with energy efficiency technologies
- The energy services of focus within a local context
- Ways of reducing the pressure on the energy system during peak hours

Firstly, the type of energy service most unmet across technology types is cooking followed by water heating. The implication of this is that there is an opportunity for energy policy directed at energy efficiency (solar water heaters) and gas technologies satisfying thermal energy services.

Secondly the comparison of technology combinations reveals the marginal value added to renewable energy by battery storage. This same storage can be substituted by a network grid and diesel generators. A community that seeks to address specific energy services such as water heating is able to see the value of energy efficiency with such an approach compared to a cost comparison. A cost comparison does not allow one to see the complimentary offering of energy efficiency as a compliment to distributed energy technologies. In addition to this it means that technologies which don’t necessarily have the lowest discomfort levels or LCOE can still be considered with a combination of energy efficiency technologies such as solar water heaters and LPG.

Finally, technologies which are not directly comparable to one another can be compared in an intuitive manner. For example, the unique features of CSP with storage make it a challenging technology to compare to others specifically at small scale. In the test case study, three systems with equivalent total discomfort include

(i) PV-battery-diesel; (ii) CSP with 9 hours of storage; and (iii) wind with solar PV and battery storage.

7.3 General Discussion

The following section discusses general factors relevant to the study.

7.3.1 Subjective Nature of Weighting

By virtue of the process, each weighting assigned for the priority of energy services is subjective. Ideally, the priority of energy services should be attained from surveys as done for the Likoma case study. The challenge is in ensuring that the subjectivity in decision making does not ignore or isolate other stakeholders within the system because different households perceive the priority of energy services differently throughout the day. The value of the evaluation of scenarios is that each parameter applies to different users and they will have a completely different list of priorities. This is why the lowest cost optimisation method, although helpful is not always applicable. The cost of electricity for a mine that has been paying high prices for diesel and are subject to fluctuations in cost and availability is not the same as the cost of electricity for a residential user who is dependant on the network grid limited to certain times of the day. For the first, reliability and availability is critical to the running of their business. For the latter, the availability or duration of the service is also critical but these are not the same.

7.3.2 The Scale of Projects is Influenced by the Type of Sector

From this process, the following issues emerged related to informal urban settlements in comparison to the rural or island residential sector.

7.3.2.1 Urban informal settlement sector

There are many unknowns with this scale of modelling an energy system. The main issue that emerged here is that even though it may be argued that this scale contains some of the richest contextual challenges in South Africa's residential sector, these are very difficult to quantify. Observations include:

- The challenge with modelling energy demand for Thembelihle and Likoma Island is that these places are still undergoing shifts in income, political and economic structures.
- Socio-economic issues such as safety, operations, illegal connections, wide range of income distribution and the rapid and often unpredictable growth of informal communities make it difficult to not only model but also put in place tariffs and maintenance of the systems.
- Energy efficiency devices such as solar water heaters, heat pumps, solar street lights and LED lights are convenient for directly supplying the energy services needed for residents in informal settlements. This is also supported by the City of Cape Town (Gaunt, Salida, Macfarlane, Maboda, Reddy &

Borchers, 2012) in a project to improve access to energy for informal settlements.

- The modelling of an energy system in itself is a formal process based on the assumption that the infrastructure at the point of delivery is adequate. This is not the case with informal settlements as the dwelling conditions vary, energy needs vary per household and the type of dweller and income varies.
- Informal settlements are typically located in urban settings not far from the national grid.

7.3.2.2 Rural residential sector

Rural energy modelling has already been undertaken by Howells et al. (2002) in an attempt to electrify these areas. This type of community although complex has higher predictability. There is a wealth of knowledge around rural areas in South Africa and the model by Howells et al. (2002) is an example of this. Observations include:

- The abundance of land in these communities allows for energy infrastructure needed for a micro-grid. There is also scope for the expansion of local businesses – specifically in agriculture and manufacturing for example (Accenture, 2016).
- The SolarTurtle (van der Walt *et al.*, 2015) is an example of the level of flexibility required in both informal and to some extent rural communities because there isn't a guaranteed uptake of the electricity supplied.

7.4 Limitations of the Study

- The study provided a simplified energy system model but did not account for a grid comparison or the growth in demand.
- For a community such as Thembelihle which is located in an urban setting, there is uncertainty with regards to future expansion of the network grid.
- The priority index of energy services used in this study assumed that the person or people rating the preferences are objective and consistent.
- The discomfort framework is data intensive.
- There is not a qualitative explanation for each discomfort level (ie. a 0.4 versus a 1.2)

7.5 Chapter Conclusion

The discussion provided an overview of the literature and model results in light of the study objectives. The next chapter summarises the main study findings.

8 CONCLUSIONS & RECOMMENDATIONS

This section is a summary of the discussion and provides conclusions, recommendations and contributions of this study.

8.1 Summary of Findings

From the simulation of cases in eShushu, Thembelihle and on Likoma Island, the findings show that

1) *By modelling an energy system in terms of end-user energy services is one of the approaches of evaluating whether the choice of technology combinations offers the highest comfort levels in terms of (i) satisfying the end-user's energy service needs, and (ii) representing a high penetration of distributed and renewable energy supply technologies in a developing country context.*

The energy demand profile in terms of energy services as opposed to simply electricity has demonstrated the unique energy needs of a developing country context from an end-user perspective. It has also become apparent that the definition of the demand profile in terms of energy services is a lever for determining the types of supply generators to be modelled and also provides an opportunity for integrating complimentary energy storage and energy efficiency technologies. Making use of an end-user service approach provides a link between the user's energy services, supply generators and energy efficiency technologies that an approach where demand is specified only in terms of kWhs falls short. Although the extrinsic value that energy services provide for the end-user is not quantified in this simulation, it is clear which energy services remain unsatisfied at different time intervals.

2) *Supply technologies without storage are not viable in terms of discomfort level*

Although the LCOE of technologies without storage resulted in lower cost, the discomfort level of these regardless of technology was high (in some cases above 1).

3) *CSP generation with thermal storage below 6 hours for all three cases is not viable in terms of LCOE and discomfort level*

For Thembelihle, CSP is not a viable technology at all given the solar irradiation. For eShushu, only at 9 hours and above are the discomfort level and LCOE reduced.

4) *A comparison between discomfort level and levelised cost of electricity (LCOE) shows that the cheapest option does not always offer the lowest discomfort levels in terms of satisfying the end user's unique energy services and vice versa.*

From the cases tested in this study, the LCOE and discomfort levels are both dependant on the demand profile, the weather resource and supply generators.

However, low LCOE does not guarantee low discomfort levels or vice versa and is often a trade-off. For example, Likoma Island showed the lowest discomfort levels mainly because the average demand profile of the community showed high demand at three distinct times during the day including when solar resource is at its highest availability. This is not the case for the urban informal settlement Thembelihle in Johannesburg because the average demand profile for this community has the lowest demand during the day when solar resource availability is at its highest. It is however evident that lower discomfort levels come at a higher cost specifically for solar PV and wind because of added storage and diesel generators. For CSP, the added storage results in a reduction in LCOE and discomfort levels. However for a site such as Thembelihle, the solar resource would require a much larger plant size (1.5 MW) with more hours of storage (9 hours) compared to a site such as Likoma Island which only requires a 1MW CSP plant with 6 hours of storage. In general, the capital costs of CSP are much higher in comparison to the other technologies. CSP capital costs used for this study are based on utility scale studies as small scale community CSP is still an amateur technology.

5) Solar water heaters result in an improvement in thermal energy services satisfied

All three cases show that the thermal demand required for water heating results in discomfort levels below midrange (< 0.5) when supplied by solar water heaters. At the lowest LCOE, these energy efficiency technologies clearly result in an improvement in satisfied thermal energy services.

8.2 Conclusions

From an orthogonal view of discomfort level vs LCOE, this study presented a framework to make energy systems analysis more relevant in a developing country context. The reason for this is that energy discomfort in the developing country context remains high.

In general, the following conclusions are drawn from carrying out this study:

- There does not exist a single best modelling approach applicable to the unique context of developing countries. A combination of methods is useful, such as LCOE and discomfort levels but often requires a trade-off for the energy planner.
- Data and time resources are limiting factors for end-user indicators such as the discomfort level. Proxies proved helpful for this study but are not precise.
- Renewables paired with distributed technologies such as diesel and battery storage offer value to the energy system by lowering the discomfort levels.
- It was also observed that seperating energy flows into thermal and electrical loads not only reduces the electricity supply load but also shows the potential value of energy efficiency technologies such as solar water heaters for an energy system.

8.3 Recommendations

Recommendations for future improvement stemming from the study limitations include:

- There is a high amount of excess solar PV that could either be sold back to the grid or transferred to storage. For this reason, modelling of the grid with a financial model should be further explored.
- The proxies used for test cases, including priority of energy services and demand profile should be tested against real data for validation.
- The potential for a simple program with a drag and drop user interface used to simulate the discomfort framework should be further explored.
- For follow-up work it would be valuable to carry out a survey or interview type of methodology to find out how the elasticity of demand in developing countries can be captured in an energy system.
- There is scope for modelling of other energy efficiency technologies such as liquefied petroleum gas (LPG) for thermal energy demand.

8.4 Contributions

The contribution of this study are two-fold. Firstly, it acknowledges how technology systems are embedded within a complex social context but also highlights the value of integrating a user-end based approach with a supply technology approach to inform energy systems modelling. The following contributions in the form of papers yet to be submitted for publication have been made through this study:

1. Mabaso, M., Gauche, P., van Niekerk, J.L. & Pfenninger, S. 2018. Addressing energy challenges in newly industrialised economies with freely available modelling tools: the example of South Africa. 1–16.
2. Mabaso, M. & Gauché, P. 2017. A systematic literature review of hybrid renewable energy micro-grids: South Africa & Surrounding Countries. In Centre for Renewable and Sustainable Energy Studies (CRSES) Renewable Energy Postgraduate Symposium (REPS) 2017.

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APPENDIX

This section includes further details of the body of the report, namely (i) the review of modelling tools and (ii) the modelling equations for the solar PV, wind and SS-CSP generators in the PSS tool.

A1 A Review of Modelling Tools

This section is a review of twenty five tools found in literature and does not account for all existing tools. Relevant studies identified relating to energy modelling were reviewed to answer questions in two layers. The objective of this review is to find out, among energy modelling tools which are freely available, those which are applicable to newly industrialised economies in particular. The context is that of an increasing decentralisation of energy supply and its increasing variability, in the context of countries which have not yet achieved full electrification and have rapidly changing economies. The focus is on freely available tools because researchers are able to easily access these tools. Seeing that energy models are used to inform energy policy, open source tools have the advantage of transparency and allow for adaption to local context.

A1.1 Description of Tools

This section provides a review of tools which are free to use, offer a free academic license or free and open source. All of the tools included in this review are explorative tools, that is, tools with the general purpose of exploring different aspects of energy scenarios. A short description of each model is followed by a detailed characterisation in Table 22.

BALMOREL is a partial equilibrium tool designed for electricity and district heating. An example of a partial equilibrium tool is one that only focuses on the equilibrium between demand and supply because it only focuses on specific parts or equilibria of the economy (Van Beeck, 1999).

BCHP Screening tool carries out the assessment of the savings potential of combined cooling, heating and power systems specifically for commercial buildings (EnergyPLAN, 2016a).

Calliope is a relatively new multi-scale energy systems (MUSES) modelling framework designed for high shares of renewable energy and other variable generation technologies. The model is structured such that the model code and data are separated. This open-source Python-based tool is referred to as an example of new generation modelling because it incorporates spatial-temporal detail and decision-making allows for operational constraints (Pfenninger, 2015).

COMPOSE provides a techno-economic assessment of energy projects. The tool is designed to combine operational simulation models with energy system scenario models for a realistic assessment. It also includes Monte Carlo risk assessments (EnergyPLAN, 2016b).

CP3T (Clean Power Plan Planning Tool) is an Excel based spreadsheet tool which provides open source evaluation of scenarios of electricity generation (Synapse Energy Economics, 2015).

DER-CAM is a decision support tool for decentralised energy systems developed by the Lawrence Berkeley National Laboratory. It is an optimization tool with the objective function being the lowest cost energy suite for electricity, cooling, heating and natural gas specifically aimed at micro-grid systems (Stadler, 2016).

EnergyPLAN is a deterministic input/output tool which provides a simulation of the entire energy system. It is also based on analytical programming and system components are aggregated which makes it able to perform faster compared to tools using advanced mathematical programming and individual components (EnergyPLAN, 2016b).

ETEM (Energy Technology Environment Model) provides an evaluation of policy for the lowest energy, technology and production cost. This tool accounts for demand response and is also compatible with DET2STO (ORDECSYS, 2016).

FreeGreenius is a performance model for CSP (Concentrating Solar Power) and other renewable grid-connected power projects (DLR, 2016).

GCAM (Global Change Assessment Model) previously known as MiniCAM is an integrated assessment tool designed to examine long-term, large scale changes in global and regional energy, land and water systems linked to a climate model. It covers energy markets, energy supply and generation technologies on a global scale over a long term (JGCRI, n.d.).

Invert is a tool aimed at designing efficient promotion schemes for renewable and efficient energy technologies (Connolly *et al.*, 2010).

LEAP (Long-range Energy Alternatives Planning) is described as a bottom-up supply and top-down demand model that explores the impacts of energy consumption, production and resource extraction in all sectors of economy. This means that the supply is based on optimisation methods and an econometric or macro-economic approach is used for demand. The license for this tool is free for developing countries (EnergyPLAN, 2016b).

ORCED (Oak Ridge Competitive Electricity Dispatch) is an equilibrium dispatching tool for power plants to meet electricity demand at any given year up to 2030 (EnergyPLAN, 2016b).

OSeMOSYS (Open Source Energy Modeling System) performs linear optimisation of energy systems for medium to long term energy planning. It includes all energy sectors and is able to integrate with LEAP (Howells, Rogner, Strachan, Heaps, Huntington, Kypreos, Hughes, Silveira, DeCarolis & Bazillian, 2011).

PLEXOS is a commercial tool with a free license accessible to academic institutions. It performs simulation and least cost optimisation for integrated electricity power systems for the short, medium and long term. The tool includes mixed-integer linear programming (Examplar, 2016). PLEXOS also has a Southern African Power Pool (SAPP) dataset with country-level granularity.

Power Systems Simulation (PSS) Tool is an energy modelling tool developed by the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University. The tool simulates various generation technologies to meet system demand and does not include cost optimisation.

ReEDS (Regional Energy Deployment System) is a long-term capacity-expansion model for the deployment of electric power generation technologies and transmission infrastructure designed for the US. The tool is based on a deterministic optimisation model and a least cost strategy (NREL, 2014).

RETScreen is an Excel spreadsheet toolbox designed as a decision support tool for the financial evaluation of renewable energy and energy efficient technologies (EnergyPLAN, 2016b).

SAM (System Advisor Model) previously known as Solar Advisory Model is a performance and financial model that makes performance predictions and cost of energy estimates for grid-connected renewable energy power projects (NREL, 2010).

STREAM is a bottom-up energy modelling tool in the form of Excel spreadsheets. The tool was developed for the purpose of modelling different energy mixes for Europe, countries and regions in Europe. STREAM does not have economic optimisation capabilities but includes three sub-models that flow into each other namely, (1) an energy savings model; (2) a duration curve model; and lastly (3) an energy flow model (Ea Energy Analyses, 2017).

SWITCH (Solar and wind energy integrated with transmission and conventional sources) combines top-down and bottom-up approaches to address the optimal design and operation of power systems with large amounts of renewable energy. The model is based on stochastic linear optimisation tool incorporates electricity capacity expansion planning and a least cost strategy (Fripp, 2016).

Temoa (Tools for Energy Model Optimization and Assessment) is an open source tool with a technology explicit energy economy optimization model. It is similar in structure to MARKAL/TIMES, OSeMOSYS and MESSAGE. The tool is designed to satisfy exogenously specified end-use demand at minimum present cost of energy supply using energy technologies and commodities over time. Temoa allows for third party verification which means that model source and code can be publicly archived (DeCarolis, 2015).

TEMPO (Techno-Economic Mini-Grid Planning and Optimization) is an open source modelling tool developed in Python by the Energy research Centre (ERC) at UCT. The tool was designed for hybrid mini-grids for rural electrification at an hourly resolution but it applicable to any scale. The tool makes use of a particle swarm least cost optimization approach and currently only models electricity generation and storage.

Urbs is a least cost linear programming open source energy modelling tool developed in Python by the Technical University of Munich (TUM) (Dorfner, 2017). The unique feature of this tool is that it offers multiple energy commodities in addition to electricity at hourly time-steps (Dorfner, 2017).

A1.2 Classification of Tools

In this section each tool is classified in

Table 22 according to (i) project scale, (ii) simulation, optimization or scenario based approaches, (iv) bottom-up , (v) time resolution and (vi) sectoral focus.

Table 22: Classification of modelling tools

Tool	Organisation	Project Scale	S, O or Sc	Bottom-up	Time res.	Sectors
BALMOREL	Collaborating Institutions	International	S[1], O[2]	Yes	H	EG, ES, CHP
BCHP Screening Tool	Oak Ridge National Laboratory	Local community/single project	S, O	Yes	H	CHP
Calliope	ETH Zürich	Multi-scale	O	Yes	H[3], M	EG
COMPOSE	Aalborg University	Local / single project	O	Yes	H	EG, ES, CHP, T, Co
CP3T	Synapse Energy Economics, Inc	Multi-scale	Sc[4]	Yes		EG
DER-CAM	Lawrence Berkeley National Laboratory	Multi-scale	O	Yes	H, M	EG, ES, CHP
EnergyPLAN	Aalborg University	National/state/regional	S, O	Yes	H	EG, CHP, T, E

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[1] S (Simulation)

[2] O (Optimisation)

[3] H (Hour) and M (Minute)

[4] Sc (Scenario Analysis)

Tool	**Organisation**	**Project Scale**	**S, O or Sc**	**Bottom-up**	**Time res.**	**Sectors**
ENPEP-BALANCE	Argonne National Laboratory	National/state/ regional	S, Sc	Yes	Y	EG, ES, CHP, T
ETEM	ORDECSYS	Local/ single project	S, O	Yes		EG, H
FreeGreenius	The German Aerospace Center	User dependant	S, O	Yes	H	EG, CHP
GCAM (previously MiniCAM)	Pacific Northwest National Laboratory	Global/ international	S, O	Yes	Y[5]	EM, EG,
Invert	Vienna University of Technology/EEG	National/state/ regional	S, Sc	Yes	Y	EG, H, T
LEAP	Stockholm Environment Institute	National/state/ regional	S, Sc	Yes	Y	E
ORCED	Oak Ridge National Laboratory	National/state/ regional	S, Sc, O	Yes	H	EG, H, T, ES
OSeMOSYS	Collaborating Institutions	National/state/ regional	S, O	Yes	D[6]	E
PLEXOS	Energy Exemplar	National/state/ regional	S, O	Yes	H,M	EG, ES
PSS	CRSES	User dependant	S	Yes	H	EG
ReEDS	NREL	National/state/ regional	S, O	Yes	Y[7]**	E, ES
RETScreen	Natural Resources Canada	Multi-scale	S, IO	Yes	M	EG, H
SAM	NREL	User dependant	S, O	Yes	H	RE
SIVAEL	Danish TSO Energinet.dk	National/state/ regional		No	H	EG, CHP
STREAM	Energy Analyses (Ea)	National/ regional	S	Yes	H	E
SWITCH	UC Berkeley	National/state/ regional	S, O	Yes	H	EG, ES

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[5] Y (Year)

[6] D (Day)

[7] 17 annual time steps

Tool	Organisation	Project Scale	S, O or Sc	Bottom-up	Time res.	Sectors
Temoa	North Carolina State University	Single Region	O	Yes	Y***[8]	E
TEMPO	Energy Research Centre (ERC)	Multi-scale	O	Yes	H	EG, ES
Urbs	Technical University of Munich (TUM)	Multi-scale	O	Yes	H	E

Sectors: EG (electricity generation), ES (electricity storage), CHP (cooling and heating power systems), H (heating), E (all energy sectors), T (transport), Co (cogeneration), EM (energy markets), RE (renewable energy sectors)

A2 Modelling Equations

This section details the mathematical models for solar PV, CSP and wind generators applied to Chapter 5.

A2.1 Solar PV Model

A solar PV panel is tilted at an angle to the Sun's position that maximises solar irradiation incident on the solar panel which increases the panel's optimal power output (Xu, Nthontho, *et al.*, 2016). Gauché (2016) explains that the Sun's position is specified by a zenith angle(ϑ_z) which is the angle of the Sun with the vertical (or zenith) as reference. However to account for the variations in the Sun's position with time and seasons a declination angle and hour angle are measured. The declination angle (δ) specifies the angle of the zenith or vertical relative to the equator and the hour angle (ω) converts the solar time to an angle. Equations modelling the behaviour of solar PV are applied from Gauché (2016) and Stine and Geyer (2001).

Total incident irradiation for a non-concentrating solar collector positioned at a fixed tilt angle (α) is given by:

$$\mathrm{I_t} = \mathrm{I_b}\cos\theta + \left[\mathrm{I_d}\left(\frac{1+\cos\alpha}{2}\right) + \rho\mathrm{I_g}\left(\frac{1-\cos\alpha}{2}\right)\right] \tag{29}$$

The total incident irradiation equation above is dependant on the direct normal irradiation (I_b), scattered or diffuse horizontal irradiation (I_d) and the total global horizontal irradiation (I_g). Ground reflectance (ρ) accounts for the type of

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[8] Multi-year

buildings, terrain, vegetation, natural and man-made objects that influence the PV panel design.

Gauché (2016) defines five solar PV tracking types including fixed tilt, declination angle tilt, single-axis tracking , two-axis tracking and concentrated PV. For this test case, only the fixed tilt set to latitude is modelled. For an angle of incidence fixed to the latitude angle (L) for a non-shaded PV panel, $cos\theta$ is dependant on the zenith angle (ϑ_z), the fixed tilt angle (α) and solar azimuth (φ) angles as follows

$$\cos\theta = \cos\vartheta_z\cos\alpha + \sin\vartheta_z\sin\alpha\cos(\varphi - \alpha) \tag{30}$$

Where the zenith and solar azimuth angles are given by equations (30) and (31) respectively.

$$\vartheta_z = \cos^{-1}(\sin\delta\sin L + \cos\delta\cos L\cos\omega) \tag{31}$$

$$\varphi = y\cos^{-1}(\cos\vartheta_z\sin L - \left(\frac{\sin\delta}{\sin\vartheta_z\cos L}\right)) \tag{32}$$

To calculate the zenith and solar azimuth angles, the declination angle (δ) which specifies the angle of the vertical relative to the equator in degrees is calculated from equation (33) assuming that solar noon is equivalent to 0 degrees and 24 hours equivalent to 360 degrees. The declination angle is dependent on the hourly sun angles (x) calculated for each day number (N) of the year. The declination angle is represented by (Gauché et al., 2017)

$$\begin{aligned}\delta = 0.006918 - 0.399912\cos x + 0.070257\sin x - 0.006758\cos 2x \\ + 0.000907\sin 2x - 0.002679\cos 3x + 0.00148\sin 3x\end{aligned} \tag{33}$$

Where the hourly sun angle in degrees is given by

$$x = \frac{360(N-1)}{365.242} \tag{34}$$

Finally, from the total irradiation the electrical power output of a string of PV panels or a module is given by (Gauché, 2016)

$$P_{mod} = \eta_{inv}\eta_{cell}AI_t\left[(1 - \eta_i(1000 - I_t) + \eta_{temp}(T_{cell} - T_{rated})\right] \tag{35}$$

Where 1000 is the maximum DNI in W/m^2. The inverter efficiency, cell efficiency, irradiation efficiency and temperature efficiency are given by $\eta_{inv,}$, η_{cell},η_i and η_{temp} respectively. The typical rated performance provided by a solar PV panel manufacturer is tested at a rated temperature (T_{rated}) of 25 degrees Celsius (Xu, Nthontho, *et al.*, 2016).

The module aperture area per module is given by the module width by the module height:

$$\mathrm{A} = \mathrm{wh} \tag{36}$$

For a solar PV power plant, the output is the sum of contributions from the total number of modules as shown in equation (37).

$$\mathrm{P_{plant}} = \mathrm{N_{mod}P_{mod}} \tag{37}$$

A2.2 Wind Model

The amount of kinetic energy that can be converted to mechanical energy required to turn a rotor is limited by the Betz Limit (Mohamed, 2006). The Betz limit or law states that a wind turbine is only able to extract a maximum of approximately 59.3% of the energy in the wind (RAE, 2009). This is also known as the maximum theoretical coefficient of performance of 0.59 (RAE, 2009). However, in real world conditions, the Betz limit is typically between 0.35 to 0.45 (RAE, 2009). A simplified model for simulating wind turbine power generation was followed as outlined by the Royal Academy of Engineering (2009) which recommends using an assumed C_p.value from a turbine manufacturer. The C_p value for this study is calculated from Gauché's (2016) modified equation (39) which accounts for minimum, wind speed at hub height and rated turbine speeds. The actual wind speeds are obtained from an hourly time series weather file. The swept area ($\mathrm{A_{swept}}$) of the turbine blades is given by

$$\mathrm{A_{swept}} = \pi \mathrm{r}^2 \tag{38}$$

Where r is the radius of the blade

The coefficient of performance is calculated given the wind speed at hub height (v), minimum (v_1) and rated (v_r) wind velocities.

$$C_p = 0.755 - 0.1cos\left(\left(\pi\frac{v - v_1}{v_r - v_1}\right)^2\right) \tag{39}$$

Finally, the power output of the wind turbine is calculated at each hour from

$$P_{out} = 0.5\rho A_{swept} v^3 C_p \tag{40}$$

Where ρ represents the air density.

A2.3 SS-CSP Model

Giovannelli (2015) explains that SS-CSP plants can be setup under several CSP configurations such as parabolic trough collectors (PTCs), compound parabolic collectors (CPCs), Linear Fresnel Reflectors (LFRs), Heliostat Field Collectors(HFCs) and parabolic dish collectors (PDCs). A typical solar plant is made up of five main sections, namely the (1) primary source, (2) solar collection, (3) thermal conversion and storage, and (4) power conversion (Gauché *et al.*, 2017).

The same solar resource equations used for solar PV apply to the generic SS-CSP solar tower model. For this reason, these will not be repeated in this section. The storage operation strategy is presented in the form of a flow chart in the system simulation run section of this chapter. The hourly solar field optical efficiency is given by equation (41).

$$\eta_{FieldOp} = 0.4254{\vartheta_z}^6 - 1.1148{\vartheta_z}^5 + 0.3507{\vartheta_z}^4 + 0.755{\vartheta_z}^3 - 0.5918{\vartheta_z}^2 + 0.0816\vartheta_z + 0.832 \quad (41)$$

Where the zenith angle (ϑ_z) applies from the solar resource equations in the solar PV model behaviour. The hourly sun angle (x) expresses the day of the year as an angle:

$$x = \frac{360(\mathrm{N}-1)}{365.242} \quad (42)$$

Assuming that solar noon is at 12 pm or zero degrees, the solar time accounting for longitude correction is given by

$$\mathrm{LCT} = \mathrm{t_s} - \frac{\mathrm{EOT}}{60} + \mathrm{LC} + \mathrm{D} \quad (43)$$

Where the equation of Time (EOT) is given by (Tiwari & Swapnil, 2010: 17)

$$\mathrm{EOT} = 229.2\ (0.000075 + 0.001868\cos x - 0.032077\sin x - 0.014615\cos 2x - 0.04089\sin 2x \quad (44)$$

Hourly receiver optical efficiency accounts for the efficiency of the receiver (η_{Rec}), optical efficiency ($\eta_{FieldOp}$) of the solar field and environmental optical factors including heliostat availability (h_a), fouling (h_f) and reflectivity (h_r) as shown in equation (45)

$$\eta_{RecOp} = h_a h_f h_r \eta_{FieldOp} \eta_{Rec} \quad (45)$$

The design parameters of the generic solar tower plant are calculated from the power block in order to size the solar field where energy delivered by the receiver to the turbine is given by

$$Q_{rec} = P_{turbine}/\eta_{teff} \tag{46}$$

The turbine efficiency is approximated by the Novikov cycle (Gauché et al., 2017)

$$\eta_{teff} = 1 - \sqrt{\mathrm{T_L}/\mathrm{T_H}} \tag{47}$$

Power to the receiver is based on the direct normal irradiation (I_b) from the Sun

$$P_{re} = I_b\, A_{ap}\ \eta_{FieldOp} \tag{48}$$

The aperture area (A) is calculated from the optimum number of heliostats for a given heliostat width (h_w) and height (h_h):

$$\mathrm{A} = h_h h_w \tag{49}$$

The thermal energy from the receiver

$$Q_{re} = P_{re}\ \eta_{Rec} \tag{50}$$

For a CSP plant with storage, the solar multiple (SM) directly influences the thermal energy that can be stored:

$$Q_{re,TESS} = \eta_{Rec} SM Q_{re} \tag{51}$$

The storage capacity in terms of the number of hours ($Hours_{TESS}$) is given by the hourly power block efficiency (η_{pb}), the thermal energy based on the solar multiple and the full load capacity of the power block (Gauché *et al.*, 2017).

$$Hours_{TESS} = \frac{Q_{re,TESS}\eta_{pb}}{P_{turbine}} \tag{52}$$