Techno-Economic Modelling of Hybrid Renewable Mini-Grids for Rural Electrification Planning in Sub-Saharan Africa

Master's Dissertation

Prepared by:

Gregory Ireland

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Supervisor:

Bruno Merven

ENERGY RESEARCH CENTRE
UNIVERSITY OF CAPE TOWN

Department of Mechanical Engineering, University of Cape Town

***Index Terms*—** Mini-grids, Sustainable Development, Open-Source, Hybrid Renewable Power Systems, Techno-Economic Modelling, Particle Swarm Optimization, Python Jupyter Notebooks.

Abstract— Access to clean, modern energy services is a necessity for sustainable development. The UN Sustainable Development Goals and SE4ALL program commit to the provision of universal access to modern energy services by 2030. However, the latest available figures estimate that 1.1 billion people are living without access to electricity, with over 55% living in Sub-Saharan Africa. Furthermore, 85% live in rural areas, often with challenging terrain, low income and population density; or in countries with severe underinvestment in electricity infrastructure making grid extension unrealistic. Recently, improvements in technology, cost efficiency and new business models have made mini-grids which combine multiple energy technologies in hybrid systems one of the most promising alternatives for electrification off the grid. The International Energy Agency has estimated that up to 350,000 new mini-grids will be required to reach universal access goals by 2030.

Given the intermittent and location-dependent nature of renewable energy sources, the evolving costs and performance characteristics of individual technologies, and the characteristics of interacting technologies, detailed system simulation and demand modelling is required to determine the cost optimal combinations of technologies for each-and-every potential mini-grid site. Adding to this are the practical details on the ground such as community electricity demand profiles and distances to the grid or fuel sources, as well as the social and political contexts, such as unknown energy demand uptake or technology acceptance, national electricity system expansion plans and subsidies or taxes, among others. These can all have significant impacts in deciding the applicability of a mini-grid within that context.

The scope of the research and modelling framework presented focuses primarily on meeting the specific energy needs in the sub-Saharan African context. Thus, in being transparent, utilizing freely available software and data as well as aiming to be reproducible, scalable and customizable; the model aims to be fully flexible, staying relevant to other unique contexts and useful in answering unknown future research questions.

The techno-economic model implementation presented in this paper simulates hourly mini-grid operation using meteorological data, demand profiles, technology capabilities, and costing data to determine the optimal component sizing of hybrid mini-grids appropriate for rural electrification. The results demonstrate the location, renewable resource, technology cost and performance dependencies on system sizing.

The model is applied for the investigation of 15 hypothetical mini-grids sites in different regions of South Africa to validate and demonstrate the model's capabilities. The effect of technology hybridization and future technology cost reductions on the expected cost of energy and the optimal technology configurations are demonstrated. The modelling results also showed that the combination of hydrogen fuel cell and electrolysers was not an economical energy storage with present day technology costs and performance. Thereafter, the model was used to determine an approximate fuel cell and electrolyser cost target curve up to the year 2030.

Ultimately, any research efforts through the application of the model, building on the presented framework, are intended to bridge the science-policy boundary and give credible insight for energy and electrification policies, as well as identifying high impact focus areas for ongoing further research.

PLAGIARISM DECLARATION

Name: Gregory Ireland

Student Number: IRLGRE001

Course: Master of Science in Sustainable Energy Engineering

Declaration

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I have used the **IEEE** convention for citation and referencing. Each contribution to, and quotation in, this dissertation from the works of other people has been attributed to them, and has been cited and referenced.

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TABLE OF CONTENTS

1
INTRODUCTION

"As long as poverty, injustice and gross inequality persist in our world, none of us can truly rest" – Nelson Mandela

1.1 THE ELECTRICITY ACCESS CRISIS IN SUB-SAHARAN AFRICA

Access to clean, modern energy services is an essential requirement for sustainable development. This is underwritten by the United Nations Sustainable Development Goals (SDGs) and Sustainable Energy for All (SE4ALL) program [1]. Although decidedly difficult to measure, the potential direct and indirect positive impacts of clean rural electrification are numerous by allowing: access to health and education services, refrigeration, clean drinking water, street lighting, communications technologies, mobile banking, and local productive and commercial uses of electricity [2]. By doing so using renewable energy technologies, this can be made possible without local or global pollution and environmental damage [3]. Nevertheless, it is estimated that 1.1 billion people or roughly 15% of the global population, do not have any access to electricity [4], with a further 1 billion with access only to highly unreliable, poor quality, illegal, or potentially dangerous supplies [5].

Of those without access, about 80% are in rural areas, with 55% of the total in Sub-Saharan Africa alone [6]. Worryingly, although global percentages of electricity access are rising, in Africa the average population growth rate currently outpaces the overall electrification rate [4]. It is expected that the rate of electrification in low access countries needs to increase roughly seven-fold, from about 2 million connections per year to 15 million per year to achieve universal modern sustainable energy access by 2030 [7]. The extent of the electricity access crisis in Africa can be seen in the map shown in *Figure 1* below.

The challenges relating to national grid-extension as a supply option to reach the remaining unelectrified populations are manifold. The typical remote communities are often in areas far from the national grid and in challenging terrain, making the capital expenditure of extending transmission networks prohibitively expensive. In addition, they generally reside in sparsely populated areas coupled with a limited ability to pay for energy services, limiting the total aggregated demand and thus the economic viability of grid expansion projects [8]. Finally, most Sub-Saharan African countries' existing national electrical systems are already highly constrained with 17 countries having more than 10 outages per month, each lasting on average more than 4.5 hours each [9]. Thereby, leaving many national institutions with critically scarce resources for investment in rural electrification by centralized means. The combination of these factors presents a considerable challenge if there is to be any hope of reversing this trend and achieving the ambitious goals of the United Nation's SDGs and SE4ALL program.

As a promising alternative, the International Energy Agency (IEA) has estimated that 40% [10] of those remaining without access to electricity would most cost-effectively be supplied by mini-grids not connected to the national grid, defined as "off-grid". To achieve universal sustainable energy access by 2030, it is expected to require as many as 350,000 new standalone mini-grid systems to be constructed [11].

The *standalone* mini-grid concept is not new, with many isolated rural areas, islands, military bases, or remote industrial operations deploying various stand-alone generation technologies to generate electricity on-site where a grid connection is not available or where grids are heavily constrained and/or unreliable. These are connected to local distribution networks, forming a mini-grid, able to provide power to users independently [8], [12]. Mini-grids interconnected within the main grids of developed countries are also a rapidly growing global phenomenon used for meeting uninterruptible power reliability requirements, integrating embedded generation, providing grid-resiliency, avoiding upstream generation, transmission and distribution investments, and enabling 'smart-grid' capabilities of two-way communications, control, and intelligent energy management systems [13], [14].

Recently, interests in multi-technology ***hybrid renewable mini-grids***, used specifically for the purpose off-grid rural electrification have risen in popularity [10] [15], illustrated as in *Figure 2* overleaf. These hybrid mini-grids incorporate various combinations of renewables, storage and conventional generators, each with complementary characteristics to provide numerous system benefits. Hybridization can allow larger shares of renewable energy to be included, increasing energy supply diversity, allowing smaller systems to be built with higher overall system availability, and reducing the overall cost of energy compared to single technology systems [16].

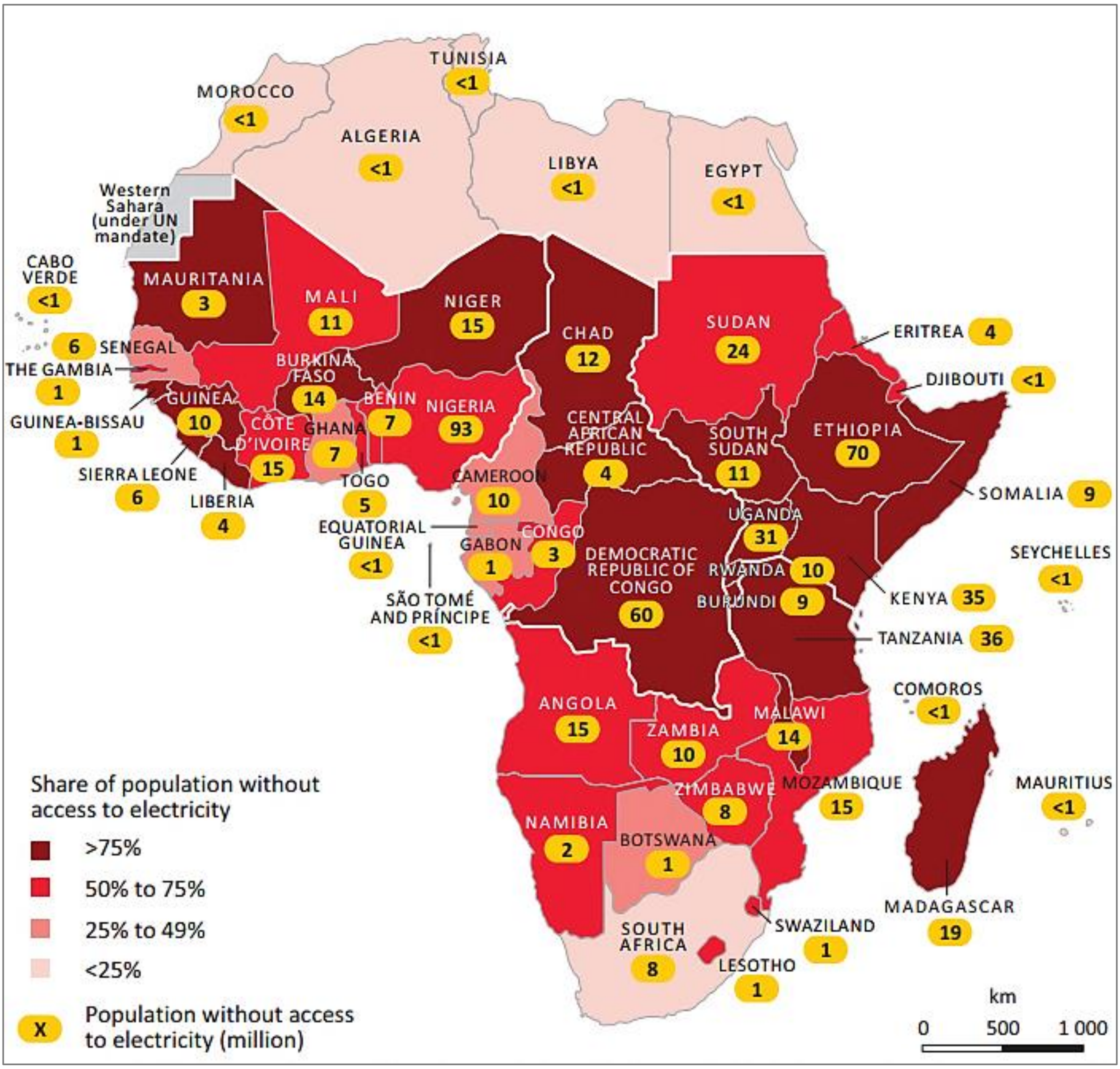

Figure 1: Map of Africa showing the estimated overall electrification rates and total population remaining without access for each country. Source: (IEA, 2014) [10]

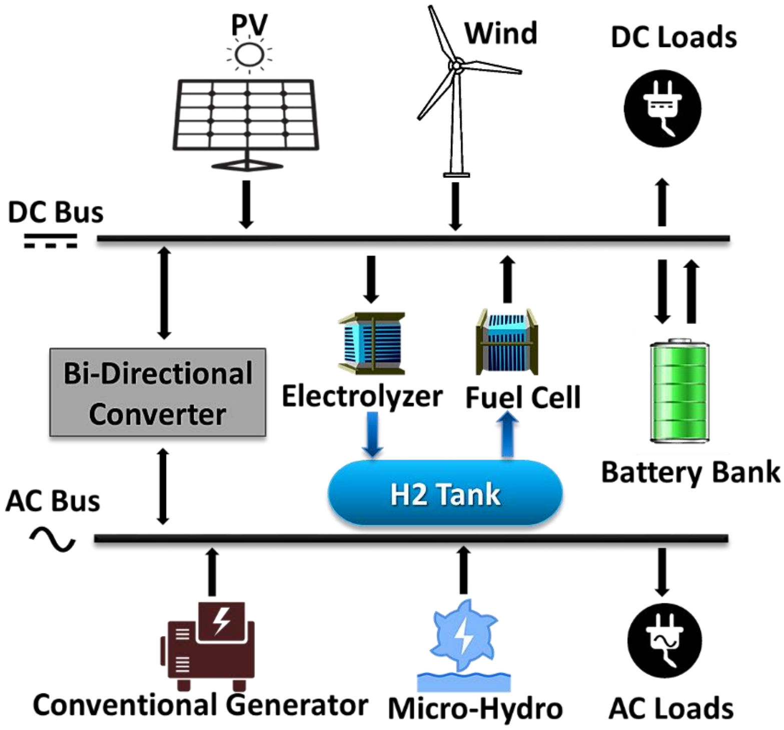

Figure 2: Simplified diagrammatic configuration of a Parallel Functioning Hybrid Mini-grid: AC and DC generators feed into a hybrid bi-directional inverter to integrate, control, and manage the operation of all connected technologies. Hybridized technologies in the figure above include solar PV, wind, hydro, and conventional generators (diesel, gasoline, natural gas, biogasification etc) with energy storage provided by batteries and/or hydrogen electrolysers and fuel cells.

1.2 Renewable Energy Mini-Grids as a Recent Phenomenon

The recent interest in hybrid mini-grids has been spurred, in part, by the increased global focus on climate change, energy access challenges, with continued technological innovation, falling renewable technology costs and widespread abundant solar energy across Africa. A more widespread understanding is spreading regarding the sustainable development benefits and economic opportunities associated with providing universal energy access by way of distributed renewable energy technologies [17].

The global commercial market for mainstream grid connected mini-grids is already considered substantial today, however smaller remote mini- and nano-grids are projected to rapidly grow in the next decade [13]. Navigant Research estimated that the global combined value of remote mini- and nano-grids is expected to grow by almost 20-fold in the next decade from $10.9 billion to $196.5 billion, and annual revenues to grow at a compound annual growth rate of 17.4%. Additionally, the total revenues attributed to the African and Middle East segment are expected to lead the total global market contribution for the next decade's forecast period [18].

Technology cost reductions have been most significant for solar PV and lithium-ion batteries, with costs expected to decrease further. By 2015, the price of solar PV modules had fallen by 80% since 2009, with the overall cost of energy provided by solar PV expected to drop by as much as 60% over the next decade [9]. Similar recent cost reductions have occurred for lithium-ion batteries, with the per kWh capital cost cut by half between 2014 and 2016. Further reductions of between 30% - 50% in the next 5 to 10 years are expected [19] [20].

Africa also has some of the best solar resources in the world, resulting in high solar PV energy yields. However, this resource has yet to be adequately exploited. A PV project at a typical location in Africa generates almost twice as much energy as the same project in Germany. An illustration of significant underutilization of solar power in Africa as a continent as compared to Germany as a single country can be noted in the fact that Germany currently has 40GW of installed solar PV, equivalent to almost one third of the total grid connected nameplate generation capacity of the entire African continent [9].

Finally, innovative new business models along with the introduction of electronic smart grid capabilities have helped to improve the commercial bankability of mini-grids in Sub-Saharan Africa. These have made possible the use of mobile money pay-as-you-go tariff structures with minimal connection fee to the customer, using larger stable users as anchor customers, as well as technology for remote metering and system monitoring, operational control, data analytics, and intelligent energy and demand-side management systems [17], [21] [22].

1.3 OPTIONS WITHIN THE SE4ALL 5 TIERS OF ENERGY ACCESS

The UN SE4ALL program has developed a 5-tier household electrification access matrix, describing several relevant metrics to give a more meaningful and descriptive set of definitions for measuring electricity access. Guidelines are used to evaluate the available power or energy capacity, allowable usage duration, reliability and quality of service, legality and safety, and importantly the affordability of the service [8], [23]. This assessment tool is useful in evaluating access created to electrification by current available technologies.

Tiers of electricity access can also be noted in the variability in size of stand-alone solar home systems (SHS), another typical alternative to mini-grids. Stand-alone solar home systems are small electricity supply devices, with energy generated by solar panels and stored in batteries which can provide a single home or facility with basic energy services at the location of the SHS. They typically supply low voltage DC power and are available in various sizes. They range from very small systems, able only to power basic lighting and cellphone charging, medium sized systems which can run multiple lights with TVs and basic electronic entertainment, and larger systems able to power fridges or other medium power appliances [7]. These can be an effective solution for individual households, businesses, schools or clinics in areas with population densities and ability to pay for energy services which are too low for mini-grids. These stand-alone systems can be a highly effective temporary solution, enabling users to begin to climb the energy ladder as local development and familiarity with using electricity grows [24].

However, SHSs can usually only provide up to a limit of tier-3 or 4 energy access, and only at a single building or dwelling. If these systems successfully provide the local socio-economic development benefits intended, the demand for higher power appliances and more energy services tend to quickly surpass the capacity of the SHS. Additionally, these systems typically cannot provide mechanical productive forms of energy economically [25].

Conversely, if the demand and ability to pay exists for service with higher power, better quality and without usage or duration limitations; mini-grids can then be sized to provide full tier 5 electricity access if required. Mini-grids using renewable energy technologies are inherently modular and scalable, and can be designed to be incrementally expanded to meet demand growth or connect additional customers [17]. By being built-to-purpose, they are also capable of providing productive forms of energy such as agricultural processing, sawmilling or welding at the community or village scale, or even supply off-grid heavy industry such as mining, mineral extraction and processing [25]. Mini-grids are thus considered the only *off-grid* electricity supply option able to provide full tier 4 or 5 to good quality, high power, and reliable electricity affordably.

Multi-tier Matrix for Access to Household Electricity Supply

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Capacity	Power[1]		Very Low Power Min 3 W	Low Power Min 50 W	Medium Power Min 200 W	High Power Min 800 W	Very High Power Min 2 kW
	AND Daily Capacity		Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhrs per day and phone charging	Electrical lighting, air circulation, television, and phone charging are possible			
2. Duration	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hrs	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration < 2 hours
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Affordability					Cost of a standard consumption package of 365 kWh per annum is less than 5% of household income		
6. Legality						Bill is paid to the utility, prepaid card seller, or authorized representative	
7. Health and Safety						Absence of past accidents and perception of high risk in the future	

Figure 3: SE4ALL & ESMAP: 5 Tiers of Household Electricity Supply Access [23]

1.4 Synergy and Learning from Telecommunications Success

In most of Sub-Saharan Africa (SSA), mobile telecommunications have effectively leapfrogged and rendered wired telecommunication infrastructure for rural, and much of urban areas, mostly obsolete. During the mid-1990's Cameroon and Kenya showed annual growth rates of around 300% in mobile connectivity with the percentage of people with access in the rest of SSA growing from 4% to 53% in just ten years [26]. This so-called "information revolution" is said to have been born of a combination of overhauling in national policy, international investment, public private partnerships, decentralization and competition [27].

Remote telecoms towers and mini-grids have many possible synergistic benefits in their implementations. Remote mobile base stations can already act as natural mini-grids in isolated off-grid areas and in areas with unreliable power supply. GSMA estimate that by 2020 almost 1.2 million telecom base stations will be either off-grid or powered by unreliable grids worldwide, with many of them in Africa [28]. These base stations could be ideal central anchor customers and provide mini-grid based electricity to surrounding communities. This would, in turn, enable cost reduction and de-risking of mini-grid project implementation [29].

Furthermore, community members who were previously unable to access mobile services through lack of signal coverage or due to the unaffordability of the cost of charging mobile phones might then become customers of the mobile telecoms company, further reinforcing the mini-grid's viability. The availability and use of mobile communication technologies creates a virtuous circle, by enabling the implementation of smart mini-grid technologies, by allowing mobile money pay-as-you-go energy tariffs, remote system monitoring and control, two-way smart-meter communication, and dynamic real time demand-side management [26], [29].

Successful implementations of hybrid renewable power supply solutions for telecoms base stations have been demonstrated with significant additional economic and environmental benefits [28], [30], [31]. The energy supply for these stations is generally both the highest CAPEX and OPEX item for many mobile network and tower operator companies. Typically, 95% of towers in rural areas are supplied by over-sized diesel generators, with the direct diesel costs, costs of diesel theft and pilferage, and diesel logistics accounting for close to 100% of the energy costs of base stations. By implementing location- and resource-appropriate hybrid generation and storage solutions, the diesel usage at many of these sites has been significantly reduced, and in some favourable renewable energy resource cases, almost eliminated [28].

A tremendous synergistic opportunity exists between the telecoms industry and mini-grids for universalizing energy access in their practical physical implementations, but also through learning from the prior multi-national success of rapid mobile telecoms access growth in Africa. Additional beneficial by-products of the relationship include cost reduction and profit increases for telecom companies and socio-economic development through increased access to both mobile connectivity and electricity for the consumer.

1.5 The Energy Access Revolution Opportunity

The successful combination of the enabling factors discussed above have made renewable energy based mini-grids an increasingly attractive supply option for rural electrification, capable of providing up to tier 5 access where grid extension is impractical or too expensive [17]. Overall, hybrid renewable mini-grids could play a significant role in a potential energy access revolution in Sub-Saharan Africa. By enabling and supporting the successful widespread implementation of mini-grids, Africa has the potential to rapidly leapfrog the more-than-century-old centralized fossil-fuel energy systems and build a sustainable 21st century energy system based on affordable, modern, clean, and decentralized renewable energy resources.

1.6 Remote Renewable Energy Mini-Grids

1.6.1 Balancing Renewable Off-Grid Electricity Supply Systems

Mini-grids powered by intermittent and variable renewables such as PV or wind, like all electricity systems, need to continuously balance their fluctuating power supply with fluctuating demand. Typically, solutions for solar or wind powered systems include battery systems, which are limited by their storage capacity and capital costs or diesel generators, which have high ongoing fuel costs and environmental concerns [32], [33].

For an electricity supply system to operate safely and reliably the supply and demand of electricity needs to be constantly balanced in real time. Failure to do so can cause system brown-outs (extended drop in system voltage) or black-outs (system shut off due to protection, system failure, or energy depletion). Regardless of the size of the system this can only be achieved using ***3 different methods*** [32], [33]

Firstly, one can ***vary the supply*** of the generators in the system to meet the required demand. This is more readily applied to systems where the generator has a controllable power output level such as a diesel engine. This is however, not possible for wind turbines or solar PV systems as their supply is entirely dependent on the weather.

Secondly, one can utilize a ***storage device***, such as a battery. This is essential when the only sources of energy are non-dispatchable renewable generators and the demand is not directly coupled to the supply (e.g. wind powered water pumping or purification). Batteries are an effective solution, but even with significant recent cost reductions, are still relatively expensive and often one of the highest cost items of the system [16]. Batteries can only provide service limited by their stored capacity and most require their state of charge (SoC) and operation to be closely managed to achieve a desirable working life.

Thirdly, one can ***manage the demand*** to meet the available supply. This can be achieved through several Demand Side Management (DSM) techniques that limit the demand including disconnecting loads, wiring limitations, scheduling demand at specified times, and using energy efficient end-use appliances [33]. Education for the consumers on the intended and responsible usage of the system, with its supply limitations, is vital for the fundamental successful implementation of any isolated system, but can also be considered demand side management [15] [34]. Intelligent networked electronic meters or so-called "smart-meters" can also enable *active demand side management,* that allows appliance operation or energy prices to be controlled dynamically based on the real-time status of the system and preferences of the customers. [26], [35].

1.6.2 Power vs Energy Limitations

It is also important to note the difference between power limited (kW) and energy limited (kW*h*) mini-grids as the general kinds of challenges for each type differ depending on the specific usage context, energy sources used, or technical configuration.

A ***power limited system***, for example most micro-hydro or conventional generator mini-grids, where the system is typically limited by the maximum instantaneous power output it can supply [8], [33]. Common interventions used in power limited mini-grid systems include load limiters or circuit breakers/fuses, home wiring restrictions (limits on light fixtures or plug sockets), banning the use of non-efficient lights, and limited usage contracts with load-exceedance penalties [34].

Energy limited systems, such as solar or wind powered systems with storage, are however usually limited by the overall amount of collected renewable energy and capacity limits of the battery systems supplying them. It is common practice to oversize the wiring, conversion equipment, and storage of these kinds of systems by up to 30% to accommodate future load growth, and thus shifting primary concerns from power to energy [15]. Energy limitation challenges occur when a lack of sunshine or calm winds cause energy collection and battery charging to be low, or if the overall energy service demands increase. Conversely, there may also be periods of excess energy being wasted if the batteries are fully charged and excess solar or wind capacity is available without sufficient demand, requiring the available electricity generation to be *"curtailed",* to ensure system stability [33].

1.7 Problem Description

To evaluate hybrid renewable mini-grids among alternatives such as grid extension or stand-alone systems, a **comprehensive and flexible energy system modelling framework is needed** to provide useful and credible insight for the creation of politically actionable and economically optimal rural electrification pathways.

This dissertation focuses on exploring a set of interrelated problems central to addressing this issue, identified here as: ***(1)*** the basic **component sizing and selection** problem, ***(2)*** the fundamentally **unique contexts of every mini-grid** and their complex interaction with technology cost and performance characteristics, and ***(3)*** the lack of **transparency and flexibility** of energy system models which intend to **bridge the "science-policy boundary"** and deliver credible and actionable results and recommendations to stakeholders.

1.7.1 The Component Sizing and Selection Problem

To establish whether hybrid renewable mini-grids are the least-cost solution, **detailed techno-economic modelling** needs to be applied to determine the cost-optimal sizing and combination of technologies which are expected to provide the lowest energy cost over the system's lifetime. Determining an accurate estimate for the optimal size of each mini-grid component requires a simulation of the system's lifetime dynamic operation, using accurate models of each of the included components and balancing the multi-directional power flows at all times.

Under-sizing of components often causes challenges with insufficient energy collection resulting in battery depletion or the system's inability to meet peak demand. This will result in unserved energy, and can cause so-called *"vicious cycles"* [34] whereby overuse of the system leads to low service availability and user dissatisfaction, leading to reduced tariff collection. This can then cause neglect of system maintenance, with further unreliability and customer dissatisfaction, repeating the cycle. If unresolved, this can often result in the project's financial unsustainability or physical breakdown [34], [36]. Additionally, if a diesel genset is included as an energy source in a hybrid system, the undersizing of other technologies will increase the reliance on diesel, increasing the cost of energy through additional spending on fuel and increased maintenance requirements.

Over-sizing the generation components may conversely lead to the curtailment of energy that cannot be sold if the storage systems are full. Oversizing the inverters or any diesel generators can cause underutilization of power capacity, as well as inefficient operation at low power levels [32]. The underutilization of installed capacity, lost curtailed energy, and decreased efficiency all increase the overall cost of energy provided by the system [33].

1.7.2 Unique Contexts and Hybrid Technologies

Challenges exist stemming from the numerous variables that need to be incorporated into the modelling framework, many of which could have a major impact on deciding the most appropriate electricity provision option for the ***unique contexts*** surrounding *every* potential individual mini-grid [17], [37].

The limitations of individual renewable energy technologies can be partly addressed by combining multiple technologies with complementary characteristics into ***hybrid mini-grids*** [15], [16]. However, this introduces added complexity as system configurations, and techno-economic interactions between technologies increase.

Overall, major variables generally include, but are not limited to the following: Firstly, the total amounts and availability of local renewable resources, and their complimentary or mismatched alignment due to local resource seasonality and overall intermittency on various timescales. Secondly, the performance and cost characteristics of any included energy technologies, including their possible future cost reductions and performance improvements need to be considered. Thirdly, the number of potential customers to be connected as well as any local economic or community activities, household density, along with the overall level of income all have a direct effect on the electricity demand profile. Finally, the larger practical or policy contexts, such the community's distance to the grid, existing national electrification plans, taxes or subsidies, energy regulatory policies, and public subjective perceptions of technologies, etc. Every one of these factors could have a significant impact on determining the best individual configurations or overall applicability of a mini-grid in every unique context, and need to be suitably accounted for in determining the most appropriate electrification options.

To demonstrate the effects that multiple interacting technologies have on optimal hybrid component sizing, a systems effect diagram is presented in *Figure 4*. Starting with the simplest diesel only mini-grid, having a low capital expenditure (CAPEX) but high fuel operating expenditure (OPEX), adding solar and wind can reduce diesel fuel use at the cost of increased CAPEX to install them. This however also increases the possibility of excess energy being available if wind and/or solar generation exceed the demand, needing the energy to be curtailed which cannot be sold, indirectly increasing overall system energy costs. Adding storage options such as batteries and/or hydrogen storage add CAPEX but store excess solar and wind energy for later use, preventing the curtailment of energy and reducing the fuel used need for diesel backup.

Whether the solar and wind resources match favorably or not in the short, medium or long term can also affect the best storage choices. When solar and wind generators are combined and their resource profiles do not match favorably to the demand, more excess energy is often curtailed. Batteries have high cycle efficiencies, but have self-discharge and high energy capacity costs – more appropriate for daily cycling. Whereas, electrolysers with fuel cells have low round-trip efficiencies with high capital costs, but compressed H_2 capacity is cheaper and does not have long duration self-discharge concerns – more appropriate for seasonal storage [31], [38].

Adding further to the sizing problem are the overall levels of local renewable resources, the cost of fuel, the different respective costs and performance characteristics of each component, as well as their different individual expected future learning rates.

Without a system lifetime simulation with an effective optimization algorithm, appropriately incorporating these variables, it will not be possible to accurately estimate the optimal least-cost combination of technologies for a hybrid mini-grid for each unique location and context.

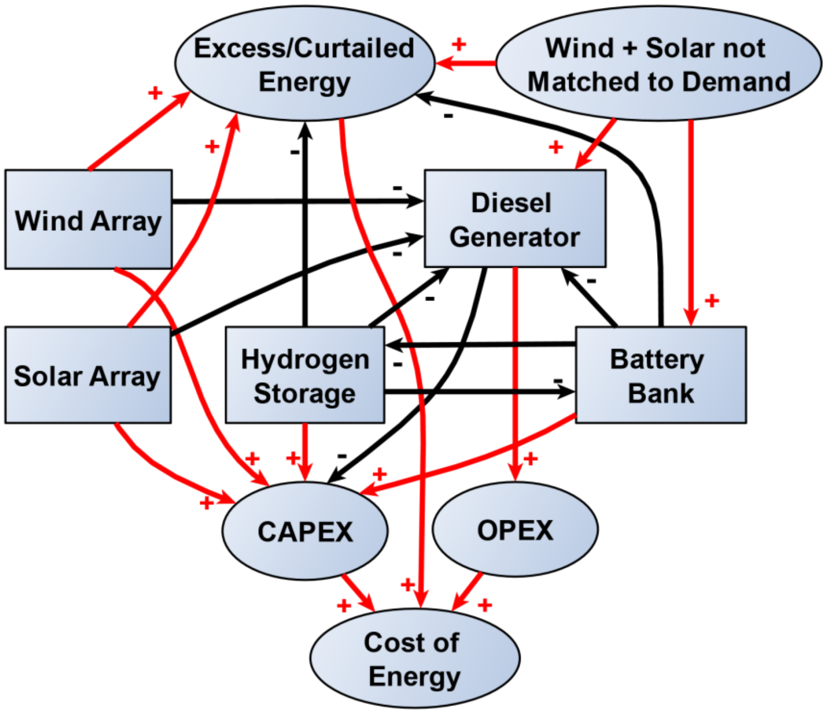

Figure 4: Mini-Grid Component Sizing Cost Dynamics: Simplified systems diagram illustrating the fundamental systems dynamics the various hybrid technologies have on the overall system sizing when minimizing the cost of energy.

1.7.3 Model Transparency and Flexibility

Many research models, especially complex energy system models, face challenges concerning a lack of transparency, reproducibility, high computational complexity from increased spatial and temporal resolution, and the use of proprietary software and data. All combined, this can result in the ineffective bridging of the *science-policy boundary* and ultimately nullify the potential impact of modelling and research outputs [39], [40], [41].

Research that is focused on using models to make recommendations for questions relating to possible energy futures, often decades into the future, are inherently uncertain and enter the realms of "post-science" or "post-truth". The models used to gain insight into these questions are also often "black-box", where the inner workings, details of mathematical and computational implementations, and physical and economic assumptions made are not open to review or scrutiny [42]. Proprietary software packages are also often used, requiring expensive ongoing license subscriptions, and the data used may have been purchased commercially or is confidential. Furthermore, when internal details can be viewed they are often unintelligible to non-subject matter experts, requiring trust in those claiming to be experts in the field. This results in reducing confidence in results and may hinder non-technical or non-expert stakeholders from being able to make decisions for policy or deployment plans, or to garner support from the public.

The assumptions made and possible scenarios modelled will invariably entail some level of subjectivity imparted by those involved in the research. This subjectivity could be influenced by political or ideological leaning, personal stakes in competing technologies, or by securing funding based on publishing results of positive outcome or novel findings. Without open model transparency and reproducibility of results, modelling results and policy suggestions may be disregarded or refuted by stakeholders with claims of bias or manipulation of results.

Applying a modelling framework to these types of complex mini-grid planning questions must always be understood in the context of constantly changing global and local contexts. Therefore, if a model is to remain relevant to ongoing related research questions, it must be fully flexible in accommodating modifications to include the potential impact of any important existing factors, as well as relevant factors yet to be discovered.

1.8 RESEARCH QUESTION

Following the introduction and problem description, the research presented in this dissertation aims to explore the following primary research question:

What are the key techno-economic modelling features needed for determining the applicability of hybrid mini-grids for electrification planning in Sub-Saharan Africa?

This is to be explored in parts, through the following secondary research questions:

- What ***attributes*** must the model exhibit to maximize the ***applicability*** and ***impact*** of ***results***?
  - How must the model be designed to be appropriate for ***any particular local context***?
  - What attributes are necessary to support the ***credibility of the outputs***?
  - How can the model's ***flexibility*** and ***relevance*** be maximized for the investigation of evolving ***future research questions***?
- What ***input data*** is required for the techno-economic evaluation of mini-grids against alternatives?
  - Which ***technologies*** should be included and how should their ***performance characteristics*** be modelled and parameterized?
  - Which ***minimum energy services*** and their resulting ***electricity demand profiles*** should be provided as model inputs?
  - What context specific ***energy resource data*** is needed?
- What ***outputs*** must the model produce for determining the ***least-cost combination of technologies*** for a particular context?
  - How can a meaningful ***measure of least-cost*** be determined for the fair comparison of mini-grids to other electricity supply alternatives?
  - Which model ***visualisations*** and ***key performance metrics*** would the model need to produce?
  - What ***technology characteristics*** and ***resource dynamics*** affect the modelling results of multiple technology hybrid mini-grids?

1.9 AIMS AND OBJECTIVES

The primary objective of this research is **to present a flexible modelling framework that helps to provide useful and credible results for the evaluation of mini-grids as an electrification option in Sub-Saharan Africa**. It is intended that the results and ongoing improvements of such modelling exercises are ultimately able to provide valuable insight for creating more effective national energy policies, regulations, and electrification deployment plans that are **politically actionable and economically optimal in each unique context**.

Supporting this objective, and to be presented within the project, are the individual aims summarised below:

1. Develop a flexible model that is transparent, customizable, computationally scalable, and as widely understandable as possible with the aim of more effectively bridging the science-policy divide.
2. Demonstrate the functionality of the developed model's implementation through its application in the South African context; through describing the typical input data required and the basic outputs of several least-cost optimization scenarios.
3. Demonstrate the potential for energy cost reduction and increased accommodation of renewable energy in mini-grids through technology hybridization and future technology learning effects.
4. Estimate future hydrogen technology cost targets at which fuel cells combined with on-site electrolysers would become an economic storage option for several renewable resource contexts.
5. Release the model code as an open source collaborative project.
6. Attract other actors to peer review the model and spark potential for further collaboration on possibly unknown future research questions.

1.10 SCOPE AND RESEARCH LIMITATIONS:

Due to the complex nature of modelling mini-grids, and of academic research in general, it is important to refine the focus of research by briefly listing several key areas which this research will *not* discuss in detail. It is recognized that these areas all play vital roles for the successful implementation of renewable Mini-Grids, but they will not be explored in detail in the project.

The project's scope exclusions and research limitations are briefly listed below:

Technical Modelling Details:

- Power electronics: Voltage, frequency control or power conversion.
- Communication architecture design, protocols, etc.
- Arrangement design, land use constraints of technology alternatives.
- Site Layout, distribution reticulation, prospecting etc.
- Operational research of logistics chain: Construction in rural areas, transportation of equipment.
- DC Micro-Grids as a potential alternative to AC.
- Research is focused on energy limited systems rather than power limited systems. Energy management and overall system component sizing rather than short term electrical and control system dynamics.

System Configurations/Alternatives modelling:

- Solar Home Systems: Can be modelled using the same basic model but with unique contextual demand modelling and SHS specific costs and components.
- Micro-hydro or biomass gasification, biodiesel etc. for local renewable generation options etc.
- Full community energization and potential energy system integrations: Water, biogas, hydrogen CHP.
- Grid Extension not explicitly modelled: Separate grid extension modelling would need to be done to determine if it is a more appropriate alternative.
- Hydrogen Fuel Cells and Electrolysers are only implemented as an energy storage device. Hydrogen production for other uses such as thermal, chemical or vehicle are not included.
- Using centrally produced hydrogen delivered to the site to use in the fuel cell acting as a backup or prime power generator is not modelled.

Possible Future Scenario Modelling: Sensitivity analysis and inclusion of stochastic variables

- Various future technology cost reduction scenarios (only one implemented here).
- Technology performance learning rates and expected future disruptive technologies or alternatives such as flow batteries, lithium air etc.
- Fuel price evolution scenarios and grid price evolution scenarios.
- Local demand growth scenarios.
- Extreme weather scenarios and climate change impact on renewable resource availability.

Smart-grid technologies and demand side management:

- Demand side management exclusions: Active DSM, load prioritization, dispatchable loads, variable reliability for different users.
- Energy efficient appliances.
- Predictive energy management and operational strategies including weather or demand forecasting.

Social and Policy:

- Local employment, social acceptance, understanding of electricity and its benefits, using the system responsibly, user inclusive design.
- Environmental impacts: Carbon, NOx & PM emissions, battery and hydrogen safety, fuel spills, NIMBY.
- Health benefits: Energy provision enabling better healthcare services.
- Education: Access to lights, ICT, and rural teacher retention.
- Subsidies: Both direct energy and indirect; fuel, tax breaks, import duties, renewable energy targets etc.
- Electricity and equipment theft
- Business models, financing, funding, tariff design etc.

Modelling implementation practical limitations not to be done in time-frame:

- Graphical user-friendly interface or commercial readiness/capability of model beyond code.
- Highly optimized computational efficiency and parallel programming.
- No testing on clusters, GPUs, or multiple processors cores etc.
- Release, management, documentation, and version control of open source code.

2

OVERVIEW OF METHODOLOGY

"A lack of transparency results in distrust and a deep sense of insecurity" – Dalai Lama

2.1 INTRODUCTION: METHODOLOGY AND DESIGN OVERVIEW

In the following chapter a methodological overview of the developed modelling framework is presented along with the approaches and design choices taken in its development. A top-level description of the model's functioning is presented here, laying out the individual component modules, the integration of the modelled information and energy flows that form the basis of the model architecture.

The system *energy cost metric* used for the least-cost comparison between different system sizing configurations, as well as the *component sizing optimization algorithm,* are described both in their basic mathematical representations as well as the applicability of each in the overall framework.

The *meteorological data sources* used to model and simulate the dynamic operation of solar and wind generation technologies are briefly discussed in terms of what characteristics the data itself exhibits, as well as where the data was sourced from.

The basic details of the model's *coding implementation framework* using *Python and Jupyter Notebooks* is explained, as well as where the current version of implementation is linked online.

The details of the overall model design philosophies will be further discussed below in *Chapter 2*, while specific details pertaining to the actual implementation thereof will be detailed in *Chapter 4*.

2.2 MINI-GRID SIMULATION AND OPTIMIZATION MODEL SYNOPSIS

The mini-grid simulation and optimization model, implemented in the presented modelling framework, is a quasi-steady-state energy system simulation covering a full year of hourly mini-grid operations. The model can be applied to any particular location or context where meteorological time series data for renewable resources are available and where an appropriate electrical demand profile can be formulated.

The tasks undertaken in a typical single application of the model are listed overleaf:

1. Renewable resource electricity generation is simulated using time-synchronized solar and wind data for the specific geographic location.

2. Hourly demand profiles are formulated using a bottom-up modelling approach representing the served area's expected daily electricity demand profile.

3. The annual operation of all system components is modelled according to each respective technology's capabilities and performance characteristics while ensuring the system's energy balance requirements are met in each hourly time step.

4. To find the cost optimal component sizing and combination of technologies a particle swarm optimization algorithm (PSO) is implemented with a lifecycle energy cost minimization objective, based on best available cost data for all components.

***Figure 5* provides a diagrammatic illustration of the full model**, with each functional sub-model block and their integration shown. **This diagram should be used as a top-level reference map** of the modelling framework throughout the following chapters. It shows the high-level structure and connections of all the applicable energy and data flows included within the current version of the model, but is not intended to be a static design.

2.3 MODEL DESIGN ATTRIBUTES

The model developed for this study has been designed and implemented according to several guiding principles which aim to ensure its widest applicability and relevance.

By increasing the overall credibility of the methodology, assumptions, implementation, and results, the model seeks to support actionable electrification policy updates and economically optimal deployment plans. Ultimately, the aim of incorporating these design principles is to maximize the impact and ongoing relevance of the research.

This is aimed to be achieved by allowing for an in-depth peer-review process, access to the model code and data, the possibility continuous updates and integration with other related models, scalable resolution and computational power, as well as future active input from the scientific community, government and industry.

The guiding principles applied in the design of the model are:

- **Flexibility, Customizability and Interoperability Between Models:** Continuous updates and modifications to the model and methodology and integration with other models must be accommodated for the investigation of other relevant research questions.
- **Reproducibility and Transparency:** Model results must be reproducible by other users and the inner workings of the model open to scrutiny. Practical implementations of model components should be as simple as possible to remain comprehensible to non-technical and non-subject-matter expert stakeholders.
- **Accuracy, Efficiency and Simplicity:** Results of sufficient accuracy should be obtained in reasonable time without convoluting the modelling process or using highly specialised programming or computational techniques.
- **Computational Scalability:** Increased size, resolution, or complexity of the model should be able to be accommodated, allowing scalability by adding computational resources, without needing to fundamentally re-design the base model or optimizer.
- **Free and Open:** No proprietary software licences or access to confidential or commercial data should be required for any potential collaborator to view the details of implementation, assumptions, input data or to run the model themselves. The code used in the model should eventually be released into the public domain as an open source project.

It is for the above reasons that existing mini-grid sizing software models such as HOMER [43], RETscreen [44] and DER-CAM [45] etc., were not deemed suitable for this present study. Although these tools have many strengths, there is, to the author, no known comprehensive free software package available that can provide all the desired characteristics mentioned, with the flexibility required for yet unknown research questions necessitated by an evolving technological, political, and economic environment.

Top Level Modelling Framework Diagram

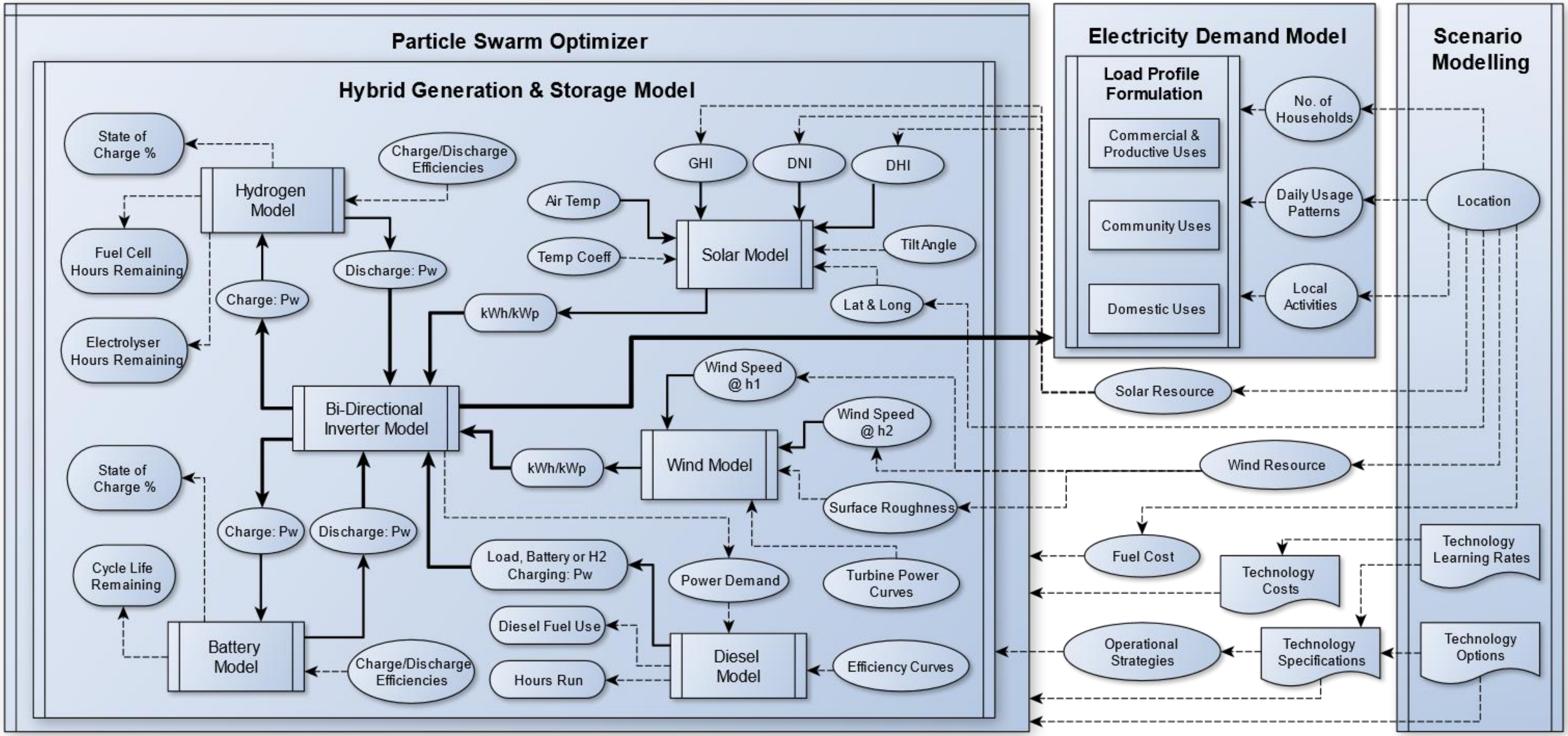

Figure 5: Full Mini-Grid Simulation, Sizing and Costing Model (Solid black lines indicate energy flows, dotted lines indicate data flows). Each functional block of the model and their respective integration is illustrated above. The modular and open source nature of the blocks in the model allows for full flexibility in customizing functionalities, assumptions, input data or simulated internal effects. Validation of individual functional blocks can be done in isolation, allowing for input and review by third parties, without detailed knowledge of the full model, and with components being able to be managed separately if needed. This architecture allows for a high degree of flexibility in the model's use, and allows it to be adapted and customized to suit any context or intended research question. Diagram designed and rendered in the free yEd software [46].

2.4 Comparison of Least-Cost Alternatives and Tariffs

In this modeling framework the ***Levelized Cost of Electricity*** (LCOE) is used as the optimization objective function and primary metric to compare the ***cost*** of different electricity supply alternatives within the model [47]. The LCOE represents an estimate of the minimum price which each unit of energy would need to be sold at to recover the lifetime costs of the system. The formulation used in the model implementation is described below.

Here we consider the LCOE as the most accurate value for the comparing costs of different mini-grid configurations, as it is a closely representative value of the eventual ***price*** or ***tariff*** charged to customers. Several other factors would be included in a more detailed comparison and comprehensive inclusion of modelling total expected installation and system costs. A few of these considerations are briefly mentioned below.

2.4.1 Levelized Cost of Energy Calculation (LCOE)

Using assumed technology cost and performance data, the ***Levelized Cost of Energy*** **(LCOE)** over the projects lifetime can be calculated. This is found by dividing the sum of the total discounted lifetime costs by the sum of the total discounted energy sold. The basic LCOE calculation is shown below [47]:

$$\boldsymbol{LCOE} = \frac{\sum_t^n \frac{(\boldsymbol{CAPEX_t} + \boldsymbol{O\&M_t} + \boldsymbol{Fuel_t})}{(\boldsymbol{1}+\boldsymbol{r})^{\boldsymbol{t}}}}{\sum_t^n \frac{(\boldsymbol{Sold\ Energy_t})}{(\boldsymbol{1}+\boldsymbol{r})^{\boldsymbol{t}}}} ,$$

where ***LCOE*** represents the *Levelized Cost of Electricity*, ***n*** is the lifetime of the project in years, and ***r*** is the discount rate. $\boldsymbol{CAPEX_t}$ is the annualized initial investment expenditure (including all capital, construction, commissioning and owner's costs), $\boldsymbol{O\&M_t}$ is the combined fixed and variable operations & maintenance cost, $\boldsymbol{Fuel_t}$ is the cost of fuel, and $\boldsymbol{Esold_t}$ is the total amount of energy that was sold, all of which are for the year ***t.***

If energy and cash flows are the same for each year, the LCOE can be simplified and calculated using a single year's expenditure and sold energy, denoted by the subscript ***a*** and split into the cost components of each individual technology ***i,*** resulting in:

$$\boldsymbol{LCOE_i} = \frac{\boldsymbol{CAPEX_{a,i}} * \boldsymbol{CRF}}{\boldsymbol{Esold_{a,i}}} + \frac{\boldsymbol{O\&M_{a,i}}}{\boldsymbol{Esold_{a,i}}} + \frac{\boldsymbol{Fuel_{a,i}}}{\boldsymbol{Esold_{a,i}}} \quad \text{and}$$

$$\boldsymbol{CRF} = \frac{\boldsymbol{r}(\boldsymbol{1}+\boldsymbol{r})^{\boldsymbol{n}}}{(\boldsymbol{1}+\boldsymbol{r})^{\boldsymbol{n}} - \boldsymbol{1}} ,$$

where ***CRF*** is the Capital Recovery Factor, which is used to annualize the CAPEX over the project's lifetime.

2.4.2 Exclusions in Comparisons and Cost Considerations

The tariff which the energy would eventually be sold at would still need to incorporate any appropriate taxes, levees, profit margins, subsidies or clean energy credits etc. which may be applicable. These are highly context specific and are currently not included in the scope of the model at this point.

In the current implementation of the model, the distribution system costs are not included in the total system costing scope. This is highly site specific and would need a costing and optimization procedure on it's own. However, in a direct comparison to grid based electricity for higher tier energy services these costs should be equivalent as the same local distribution system would likely be built in either case.

Levelized costs are calculated for the initial day-1 installed system, and not for future system upgrades or expansions, and represent only the costs of the energy provided by the initial system. Future system additions will likely provide energy at a lower cost, using future lower cost components. This must be considered in the structuring of power purchase agreements and tariff setting to allow continually dropping costs for the consumer.

Total capital versus operational costs are not explicitly compared here. This could be a key factor in system selection trade-offs for upfront capital and construction costs and ongoing operational and fuel costs.

Externalities, negative or positive, such as greenhouse gas or local emissions, or electrification benefits are also not included here but would be an important consideration in top level comparisons between alternatives.

2.5 Optimal Component Sizing: Particle Swarm Optimization Algorithm (PSO)

The ***Particle Swarm Optimization*** (PSO) algorithm was the chosen optimization algorithm implemented for individual component sizing using the system LCOE as the objective minimization function. The PSO algorithm was selected due to it having several desirable characteristics fitting the design principles stated above. The basic algorithm is explained below and a description is provided for how it matches the model's design principles.

The PSO algorithm is an evolutionary computational optimization algorithm resulting originally from the simulation of the swarm behaviour of animals such as bird flocks or schools of fish. It was found to be a simple, yet powerful and versatile meta-heuristic optimization algorithm applicable to many types of problems [48], [49].

Many other optimization algorithms are capable of efficiently finding solutions to this multi-dimensional and non-linear optimization problem [50]. The PSO algorithm was chosen mainly due to its attributes of simplicity, versatility, customizability, competitive performance, and computational scalability – these are described below.

Excluded from the scope of this research were detailed algorithm performance evaluations, benchmarking, competing algorithm comparison, or heavy coding efficiency optimizations. The algorithm is neatly coded from scratch in just a few lines of Python and is visible as its own function in the attached code. Due to the PSO's flexibility it could be revised, customized, and scaled – or another optimization algorithm used entirely.

The basic process of the Particle Swarm Optimization algorithm is described below [51]:

1. **Initialization:**

A population of particles is initialized at random co-ordinates, with a random starting velocity, within an N dimensional solution search space. Each particle's coordinates represent the N different optimization variables representing the component sizes of each technology in the mini-grid's configuration.

The algorithm is then iterated through several timesteps, ***t***, carrying out the following in each step:

2. **Fitness determination:**

The position variables of each particle, $\boldsymbol{x_p^t}$, represent a mini-grid's configuration and component sizing which are used to simulate the system's annual hourly operation and LCOE. The LCOE is used to determine the fitness of each particle's position and the ultimate minimization objective function.

3. **Swarm knowledge update**:

Each particle then compares and updates the new position to its own known best solution's position, storing the information in ***Pbest.*** The population's global best solution and position as stored as ***Gbest***. Each particle has memory of its own best position, with the population's best position, but not the best positions of other particles.

4. **Swarm velocity update:**

The velocity vectors of each particle, $\boldsymbol{v_p^t}$, are then updated using a velocity update formula which accelerates the particles towards a randomized weighted combination of the particle's ***Pbest*** position and the population's ***Gbest*** position. The velocities of each particle are updated using the vector update formula for each of the ***p*** particles over ***t*** iterations, given by:

1. $$\boldsymbol{v_p^{t+1} = w * v_p^t + c_1 * rand_1 * \left(Pbest\,_p^t - x_p^t\right) + c_2 * rand_2 * \left(Gbest^t - x_p^t\right)} \ ,$$

where $\boldsymbol{rand_1}$ and $\boldsymbol{rand_2}$ are random numbers between 0 – 1, with $\boldsymbol{c_1}$and $\boldsymbol{c_2}$ weighting factors for ***Pbest*** and ***Gbest,*** and ***w*** an inertial weighting component of the previous velocity. The weight of $\mathbf{c_1}$ is sometimes referred to as the 'cognitive', 'independence', or 'memory' component weighting, and $\boldsymbol{c_2}$ referred to as the 'social' or 'cooperation' component weighting. Each particle's position for the next timestep is then updated using the position update formula as follows:

$$\boldsymbol{x_p^{t+1} = x_p^t + v_p^{t+1}}$$

5. **Convergence:**

This is process is repeated until a convergence criterion is met or a set maximum number of iterations is reached. The algorithm is then completed and the final ***Gbest*** solution is returned as the optimization solution. It is important to note that this result is not the *exact* optimum solution and can only ever closely approximate it.

The randomized weighted vector update can be seen illustrated below in *Figure 6* for a 3-dimensional optimization search space showing a single particle's velocity and position updates with the respective influences of the inertial, memory, and cooperation components.

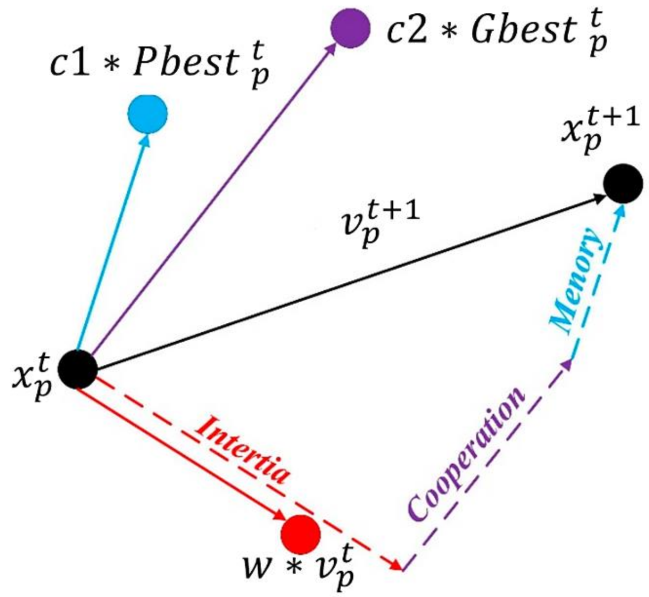

Figure 6: Particle swarm vector update diagram for a single particle in a 3-dimensional solution search space (diagram adapted from [52]*)*

The PSO algorithm was chosen as the model's optimizer to support the modelling framework's required capabilities and attributes due to PSO exhibiting the following characteristics [51], [49]:

- **Simple with Good Performance:** Relatively simple to understand, program and implement in few lines of readable code while performing competitively with other evolutionary algorithms. In a 3-dimensional problem, the algorithm can be graphically demonstrated and visualised, aiding wider understandability, and thus transparency, especially to non-technical or optimization specialised stakeholders.

- **Versatile & Flexible:** Optimizes non-linear and discontinuous functions – does not need gradient information. It is a meta-heuristic algorithm that can optimize different problems with the same base algorithm and can optimize for binary, continuous and integer variables simultaneously [51]. Population based algorithm allowing for Multi Objective Optimization (MOO) using Pareto Dominance or other methods [53], [54], [55].

- **Customizable and Extendable:** Other optimization algorithms or heuristics can be combined within a PSO allowing implementation of independent sub-problem optimization algorithms. Numerous modifications of the PSO algorithm also exist to improve or customize its performance; including dynamic adjustment of weighting factors [51], swarm size and number, [56], particle mutation [57], fuzzy-logic [58], and chaotic randomization [59] among many others [51], [49].

- **Computationally Scalable:** The basic structure of the algorithm is *embarrassingly parallel* – meaning the possibility exists for parallel calculation of each individual particle's fitness simultaneously, enabling full computational scalability with additional processing units (multiple CPUs, GPUs - graphics cards, or scalable computing clusters).

2.6 Meteorological Data

Various meteorological data sources need to be used as timeseries data inputs for the simulation of expected renewable energy generation potential at every potential mini-grid site. Typically, the most accurate data would be ground-measured meteorological data covering multiple years, measured on site, using high accuracy instruments. If this kind of data is available for a mini-grid site under investigation, it should be used, however in a study mapping the initial expected cost over wider areas this kind of data would not be available. Therefore, in these cases, data sets derived using earth observation satellites and weather models simulating the conditions in the atmosphere are typically used.

Time synchronized data for both solar and wind are needed for each site, to capture the daily and seasonal correlations between local solar and wind resources. Data of a sufficiently high resolution in both space and time are needed to accurately simulate the typical climatic conditions at the exact insular mini-grid location and to capture the higher levels of intermittency that would typically be averaged out when measured or modelled over a wider geographic area.

The *actual* future renewable resource generation performance can never be exactly predicted and is inherently subject to uncertainty. Every actual mini-grid project implementation requires a more detailed site-specific layout analysis and local insular resource prospecting. This is typically done with on-site measured data including extreme weather cases, to determine the overall expected renewable generator performance and dynamics more accurately.

In this research, the application of both ground-measured and satellite/weather-model derived data are demonstrated. Data can be given to the model either as raw windspeed/irradiation data or as preprocessed hourly capacity factor data. Solar and wind atlases (GIS resource data maps) are also used to verify the chosen years of simulation with the long-term annual averages of global horizontal irradiation (GHI) for the solar generation, and wind speed at hub height for wind generation.

All the data used in this research is in the public domain and can either be downloaded or requested from the author. Confidential/proprietary data can, however, also be used in the model and results not made public. The various particular details pertaining to all of the used data sources, how these data sets were developed, and how they were utilized in the implementation of the model are explained in more detail in Chapter 4.

2.7 Model Framework Coding Implementation

2.7.1 Open-Source Project Code and Notebook Hosting:

The code, input data, and a Jupyter Notebook of the primary code blocks of all the core model components that were developed in this project are hosted on Github, linked below. **This has been released as *open-source* and is available under the liberal MIT license**.

http://bit.ly/ERCMini-GridModelJupyterNotebook

(Use the above link for the correctly rendered notebook with included visualisations)

The Github repository that will host the most up-to-date code and ongoing applications of the model will be hosted and maintained at:

https://github.com/GregoryIreland/mini-grid-model

***The Notebook and Github repository should be used as the primary reference for any of the model's computational or algorithmic implementation details within this dissertation*,** which are described in the coming chapters. The notebook describes its own layout, with basic code explanations in the comments, and incremental outputs demonstrating each of the model's major code blocks.

2.7.2 Python & Jupyter Notebooks:

The details of the programmatic implementation of the computational components that together make up the mini-grid simulation and optimization model have been developed using the *Python* v3.6.0 programming language [60] coded into an interactive computing environment called a *Jupyter Notebook* [61]. This has been defined by the Jupyter developers as follows:

"The Jupyter Notebook is an open-source web application that allows you to create and share documents that contain live code, equations, visualizations and explanatory text. Uses include: data cleaning and transformation, numerical simulation, statistical modeling, machine learning and much more." – Project Jupyter: https://www.jupyter.org

This is demonstrated with a simple example allowing anyone to try the notebook themselves, which is available online at https://try.jupyter.org/ . Navigating here, and starting the "Welcome to Python.ipynb" notebook, will bring you to the example shown in *Figure 7* overleaf.

This starts an empty Python kernel where code can be entered through the browser into a cell and run, displaying the outputs of that code block directly below it. Any libraries, functions, variables or data created are persistent and kept open in the Python kernel throughout the session. These can be manipulated or explored interactively by entering and running or rerunning code from within other cells. Running the code in the cell in *Figure 8* below, imports some core scientific packages, then plots 4 random timeseries directly in the browser.

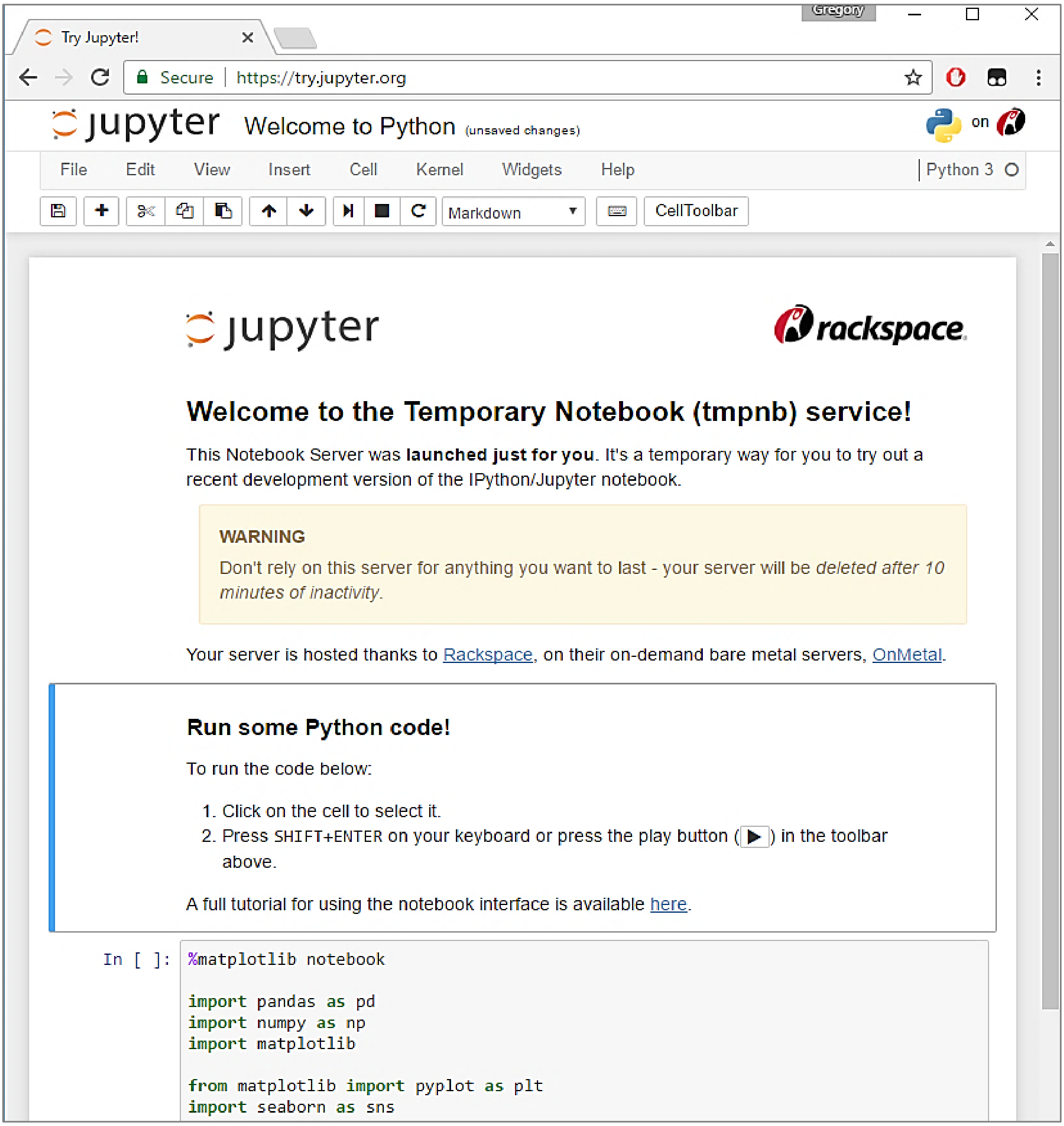

Figure 7: Example demonstrating the Jupyter Notebook concept online with the "Welcome to Python.ipynb" Notebook. The notebook's editing tools with its code and text cells are shown. Available at: https://try.jupyter.org

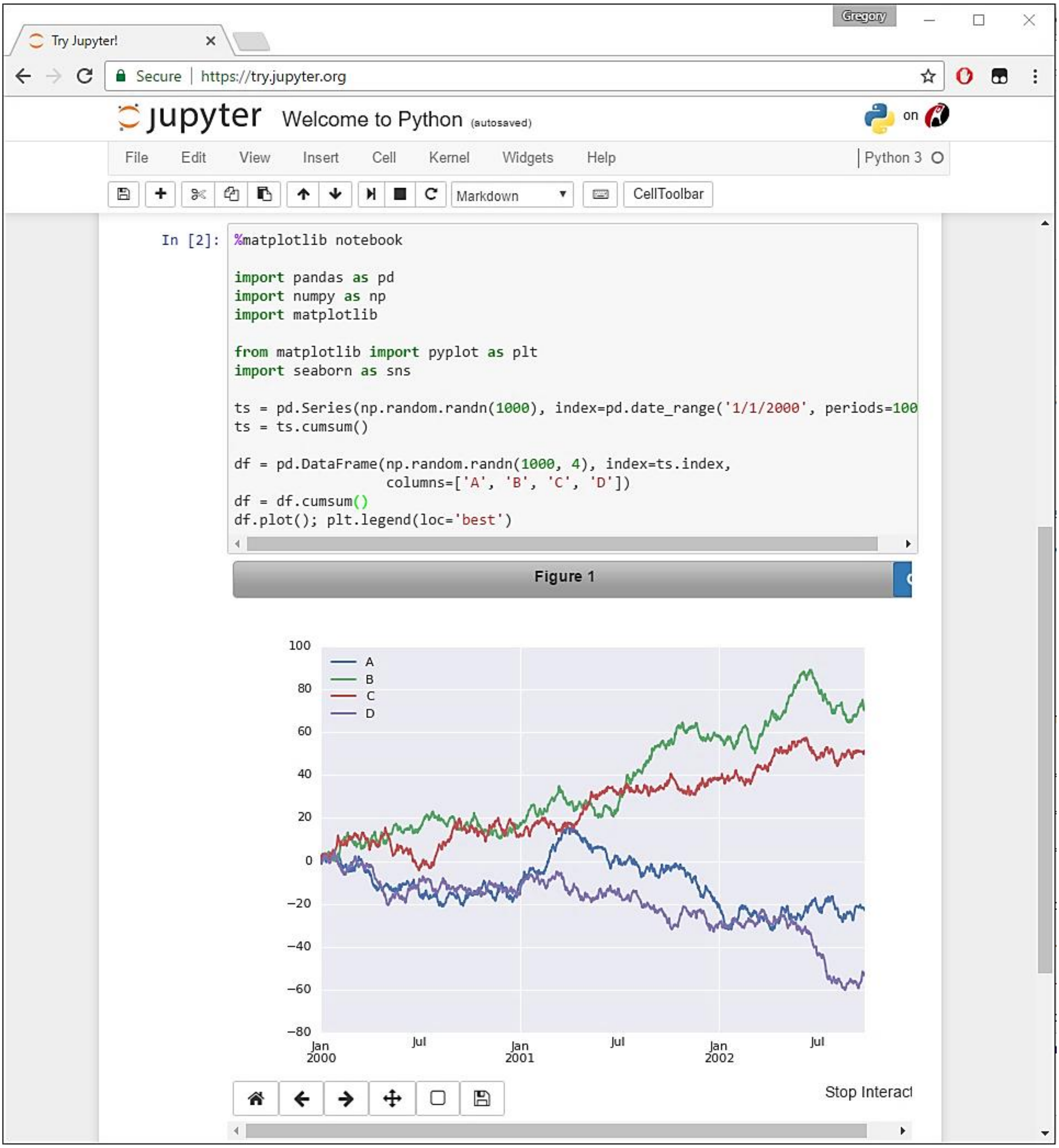

Figure 8: Example demonstrating the Jupyter Notebook concept online with the "Welcome to Python". Showing the resulting timeseries graphical output from the code snippet above.

2.8 Model Framework Design Choice Summary

Shown in *Table 1* below is a summary outlining the specific design choices of the model implementation and their expected benefits supporting the aims of the overarching design philosophies described above.

Table 1: Summary of modelling framework design choices and their benefits.

Design Choice	Benefits
Coded in Python with 'Jupyter Notebooks'	• High level, flexible, and widely understandable coding language • Completely free interactive development environment • Python has many packages with continuous global input allowing functionality expansion and easier integration with other models • Reproducible computation and independent handling of individual code blocks possible in Jupyter • Jupyter notebooks support multiple programming languages and are easily shared and collaborated on between researchers
Open-source with input data from publicly accessible sources	• Model workings are transparent and open to scrutiny and continuous updates and collaboration • Allows independent ongoing input, peer-review, and model benchmarking from global scientific community • Data is accessible for external results reproduction • Data sources are open for verification and validation through peer review and continuous updates of input assumptions
Optimization Algorithm: Particle Swarm Optimization (PSO)	• Meta-heuristic algorithm allows non-linear objective function optimization and modifications without algorithm redesign • "Embarrassingly Parallel" computation possible for individual particles, allowing scalability of problem resolution or applications • Population based algorithm allows for the implementation of multi-objective optimization using Pareto dominance principle
Simple & Modular components	• Model is coherent and understandable to a wider audience supporting overall transparency and stakeholder buy-in for results • Simpler to expand or modify model functionality and manage in parts • Individual contributions can be made to specific sections without highly specialist knowledge of other modules or code integration

3

DESCRIPTION OF MINI-GRID SIMULATION AND OPTIMIZATION MODEL

"Everything should be made as simple as possible, but not simpler." – Albert Einstein

3.1 INTRODUCTION: MODEL COMPONENT DESCRIPTIONS

This chapter describes the mini-grid model implementation in more detail, with each of the sub-models for the various power generation and storage technologies, as well as the balance of plant components that make up the mini-grid. Each component model is displayed and individually and described below within the larger framework, showing its direct interfaces to other blocks via energy or information flows. The individual component parameterizations chosen to describe the components mathematical representations and quantify their costs are summarised at the end of the chapter.

3.2 SOLAR PV MODEL IRRADIATION TRANSPOSITION AND POWER CALCULATIONS

The solar PV model module calculates hourly energy yields using a tilted irradiance transposition model, temperature based power reduction losses, and estimated balance of system losses.

The combined solar energy calculation for each hour, $\boldsymbol{E_{pv}}$, is as follows:

$$\boldsymbol{E_{pv} = Arr_{Wp} * \frac{G_{tilt}}{1000}\left(1 - \rho_{pwr}(T_{cell} - T_{NOCT})\right) * \eta_{bos}} .$$

The methods used, and assumptions made, to calculate each of these inputs for each simulation timestep are referenced and described below:

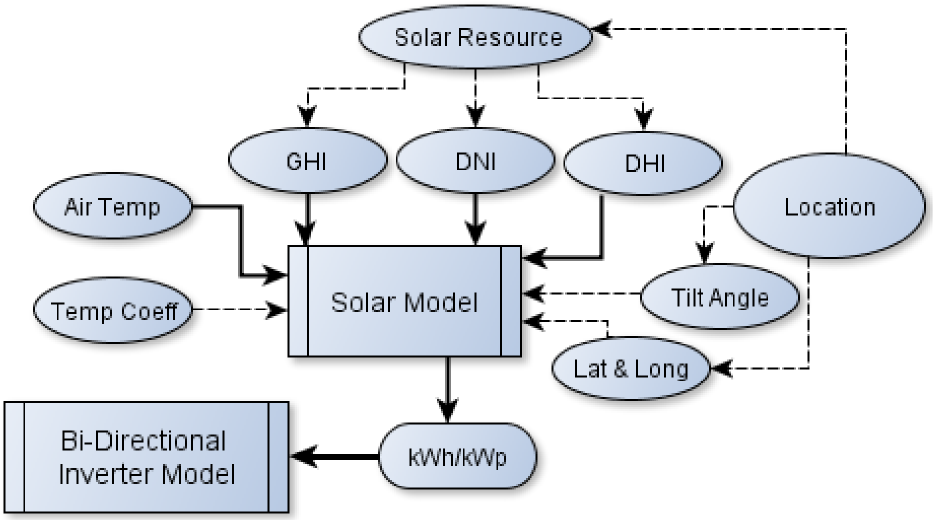

Figure 9: Solar PV System Model Diagram

The well-known simplified ***solar irradiation transposition model***, as mathematically described in [62], is used to estimate the total hourly irradiation on an inclined surface, G_{tilt}, at an inclination angle of ***tilt***. Arr_{Wp} is the total peak power rating of the installed solar array. This is done using hour-averaged time series of Global Horizontal Irradiation (GHI), Direct Normal Irradiation (DNI), and Direct Horizontal Irradiation (DHI), as well as solar geometry with and ground reflected and diffuse transposition factors. The solar transposition equation is given as follows:

$$G_{tilt} = (DNI)\cos\theta + (DHI)R_d + \rho(GHI)R_r \ ,$$

where **θ** is the angle of incidence between the tilted surface and the sun's rays. R_r is the transposition factor for ground reflected irradiation which is modelled using an isotropic approximation, given by:

$$R_r = \frac{1-\cos(tilt)}{2} \ ,$$

where ρ, the foreground albedo, is roughly approximated here to 0.3 for flat and dry conditions. R_d is the diffuse irradiance transposition factor. In this model implementation, it is also approximated isotropically, using:

$$R_d = \frac{1+\cos(tilt)}{2} \ .$$

The angle of incidence, **θ**, is calculated once per hour at the 30-minute midpoint of each simulated hour using the Python ***Pysolar*** package [63]. This is done using the solar array's position on earth, array azimuth facing orientation (typically north or south, towards the equator), and the tilt angle as inputs to determine the specific earth-solar geometry at that historical point in time.

The operating temperature of the cell is estimated each hour from the ambient air temperature and incident solar irradiation levels and is used with the module's rated temperature coefficient of power to determine losses due to temperature effects as per [64], and [65]. The temperature, T_{cell}, of the cell is calculated as follows:

$$T_{cell} = T_{amb} + \frac{NOCT - 20}{800} G_{tilt} \ ,$$

where T_{amb} is the ambient air temperature, and ***NOCT*** is the Nominal Cell Operating Temperature, and is given by the module manufacturer, and used here as **44 °C**. The temperature coefficient of power, ρ_{pwr}, is also given by the manufacturer and is used as **-0.41%/°C**, both from [66].

Solar cell cooling effects due to wind are not currently included in the model but can be can be implemented using the local wind speed and direction as in [65]. Inverter losses are calculated depending on power flow directions using typical manufacturer rated efficiencies. All other energy losses including soiling, module mismatch, inter-row shading and ohmic wiring losses etc. are collectively assumed to total a constant 5% as in [67], although this can be adjusted to site conditions if necessary.

3.3 WIND TURBINES

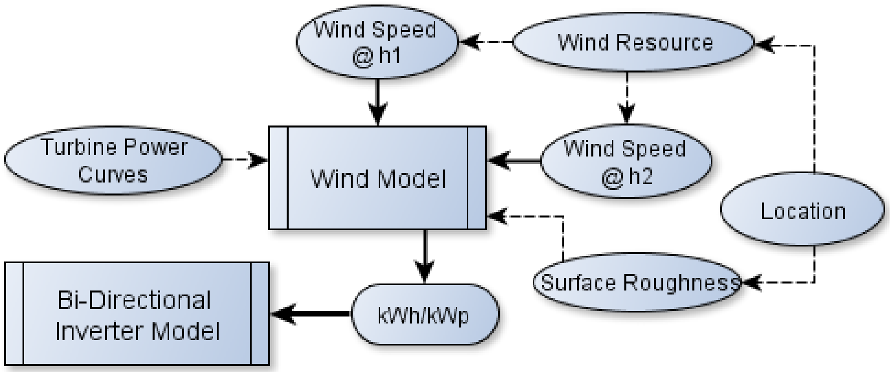

Figure 10: Wind Turbine System Model Diagram

The wind turbine model receives wind speeds at 15-minute resolution calculating the energy output using an appropriate wind turbine power curve. Separate 15-minute energy totals are calculated, then summed over an hour to improve non-linear cubic wind power law accuracy. 1 hour wind data can also be used. The kWh/kW capacity factor at each 15-minute interval is calculated by matching the wind speed at hub height to the corresponding normalized output of the turbine curve with values lying between wind speed bins.

The power curves of six certified small-scale wind turbines ranging from 1.5kW – 10.4kW are shown below in Figure 11. These were sourced from the Small Wind Certification Council (SWCC), and tested using the AWEA Standard 9.1 – 2009 [68]. Turbine curves from Xzeres, Pika, Kingspan, Kestrel, and Bergey are shown. The *3kW Kestrel e400nb* wind turbine curve is used in the model because local cost data being more readily available, and it being designed and manufactured in South Africa [69], [70]. The wind speed bins corresponding to turbine output are 0.5 m/s each and the turbine has no cut-out speed implementing blade furling in high windspeeds.

If wind speeds are not available at hub height, data at another height with an appropriate terrain surface roughness can be used to estimate hub height wind speed using *logarithmic extrapolation*, using [71]:

$$\frac{v}{v_0} = \frac{\ln(H \,/\, Z_0)}{\ln(H_0 \,/\, Z_0)},$$

where v is the wind speed at height H, v_0 is the wind speed at height H_0 and Z_0 is the surface roughness length. The surface roughness can be found from GIS data-sets, by using the above formula with wind speeds at two alternative heights, or estimated using values such as those described by [71] and [72] included in Table 2 below.

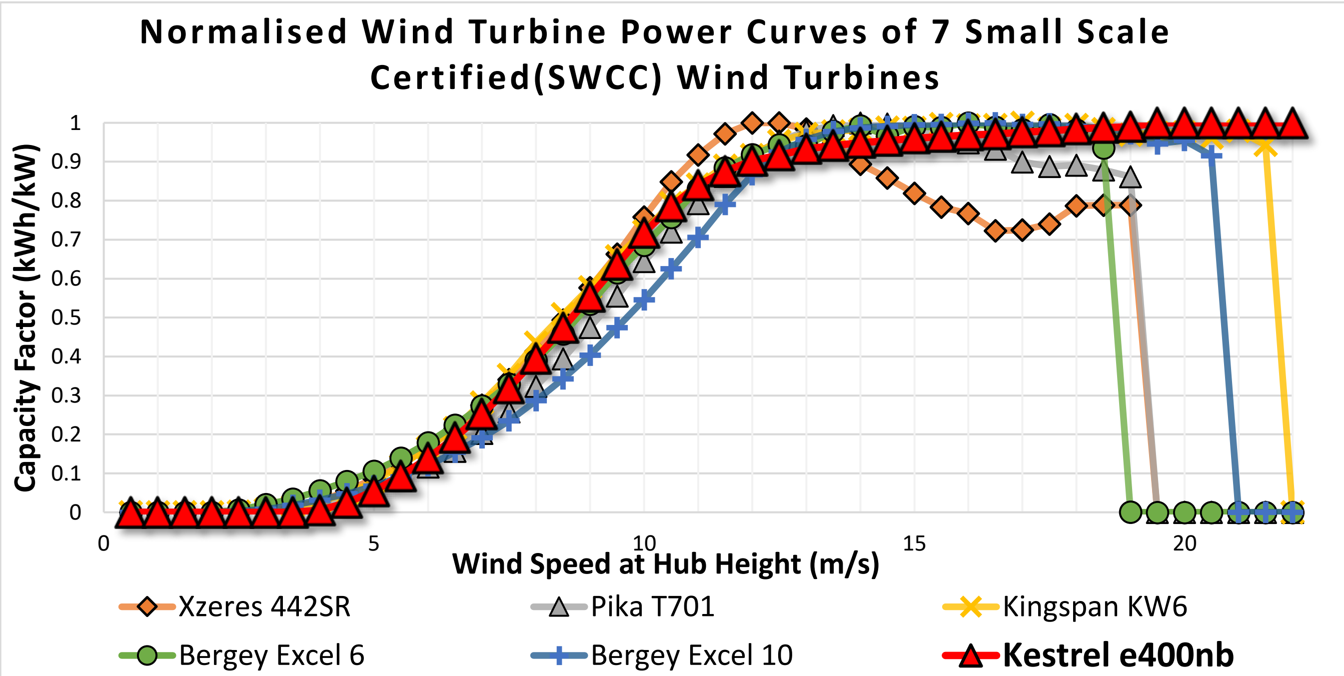

Figure 11: Normalised Wind Turbine Power Curves

Table 2: Approximate roughness classes and lengths [71], [72].

Roughness Class	Description	Roughness Length Z_0 (m)
0	Water surface	0.0002
1	Open areas dotted with a handful of windbreaks	0.03
2	Farmland dotted with some windbreaks more than 1km apart	0.1
3	Urban districts and farmland with many windbreaks	0.4
4	Densely populated urban or forest areas	1.6

3.4 DIESEL GENERATOR

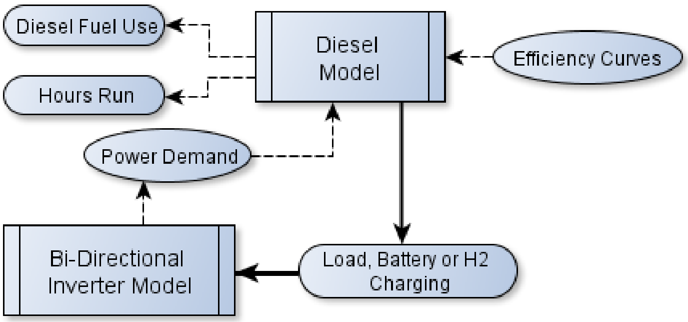

Figure 12: Diesel Generator System Model Diagram

The diesel generator model takes the power demand as input and calculates fuel use according to a set of typical generator efficiency curves for different generator sizes running at part load. The details are as follows:

- In each hour where the diesel generator is needed to provide power, both the size of the generator and the load factor at which it would run are used to find the operational efficiency point on the appropriate fuel efficiency curve to determine hourly diesel fuel use.
- The hour's average load factor is determined as the ratio of the average hourly power demand divided by the installed capacity.
- Efficiency for load factors and generator sizes between fuel curve data points are linearly interpolated.
- A minimum generator loading level of 25% is implemented. If the residual load is lower than this, the generator will run at the minimum load and use the excess power to charge the batteries or run the hydrogen electrolyser or otherwise lose the remainder.
- Total running hours are recorded for maintenance and overhaul calculation purposes.

Shown below in *Figure 13* are the typical diesel engine efficiency curves, operating at various loads, obtained from [73] for 20kW to 200kW generators.

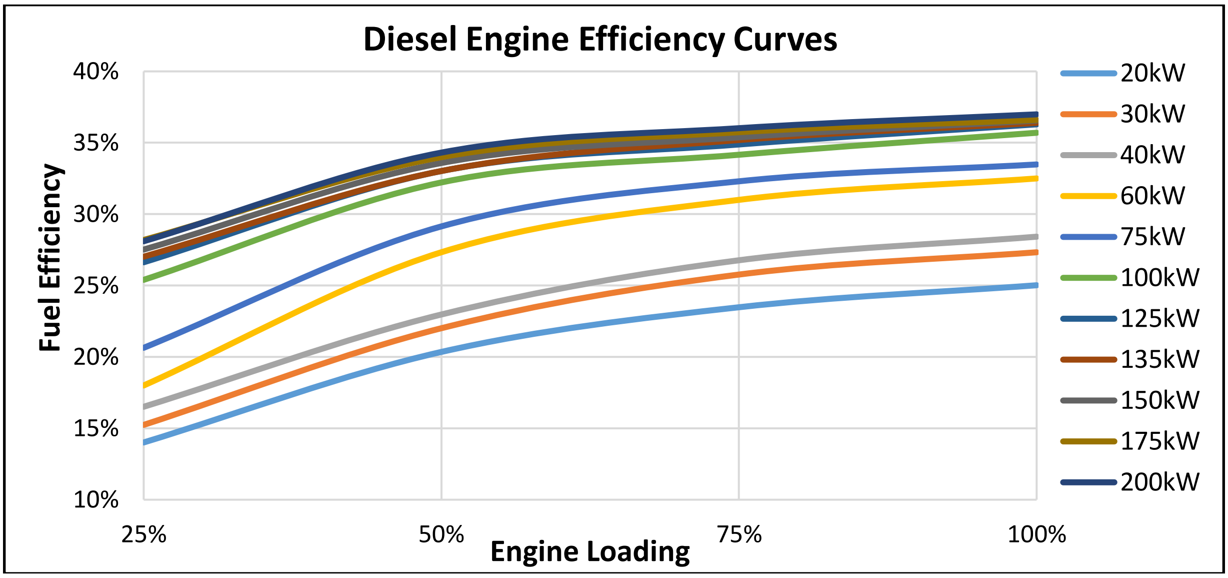

Figure 13: Typical Diesel Engine Efficiency Curves

3.5 LITHIUM-ION BATTERIES

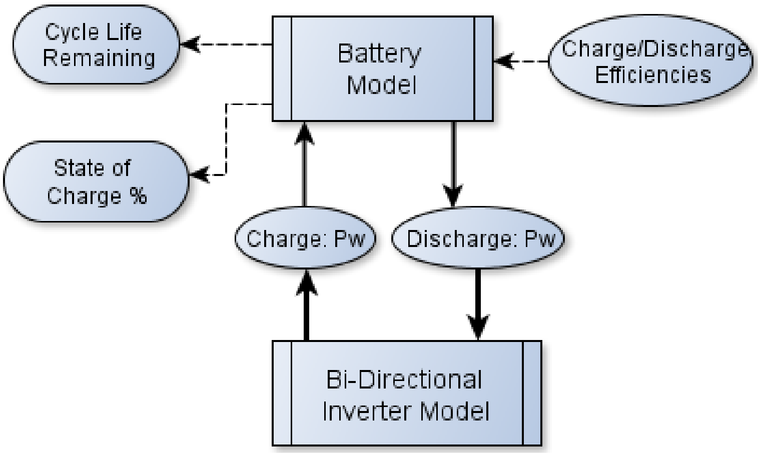

Figure 14: Battery System Model Diagram

Lithium-ion batteries are used in the model as opposed to lead-acid due to their lower levelized cost and significant further expected cost reductions [20], [74]. Any other chemistry can be used, given the basic parameters of cost and performance are given. The fast-acting response times of batteries as a power source allow the battery and inverter combination to take the role of 'forming the grid' to be described in Section 3.7 below. This also gives the batteries the ability to balance any rapid changes in renewable generation output, for example due to wind gusts or clouds passing over the PV array.

The details of the battery system model's programmatic implementation are described as follows:

- Charging and discharging modes of operation based on the excess or shortage of energy are controlled by the implemented dispatch strategy described below in Section 3.9.
- The battery's State of Charge (SoC) is calculated and updated in each time step based on the energy used or absorbed in relation to that of the previous time step. Here, the included rated charging and discharging efficiencies are used to calculate cycling losses.
- Self-discharge effects are not explicitly modelled and are included in the cycling efficiency losses.
- Replacement frequency is determined by dividing total available cycle life into an assumed daily cycling regimen. Alternatively, cycle life and replacement needs can be recorded using a simple battery rainflow model that will record all partial battery cycles separately [75].
- Battery total energy capacity degradation is not explicitly calculated in the simulation. Batteries are replaced at the end of the quoted total warrantied cycle life.
- The maximum charging or discharging power of the batteries is set to 1C. (That is, hourly charging or discharging rates cannot exceed the capacity of the battery per hour)

3.6 PEM Hydrogen Fuel Cells and Electrolysis

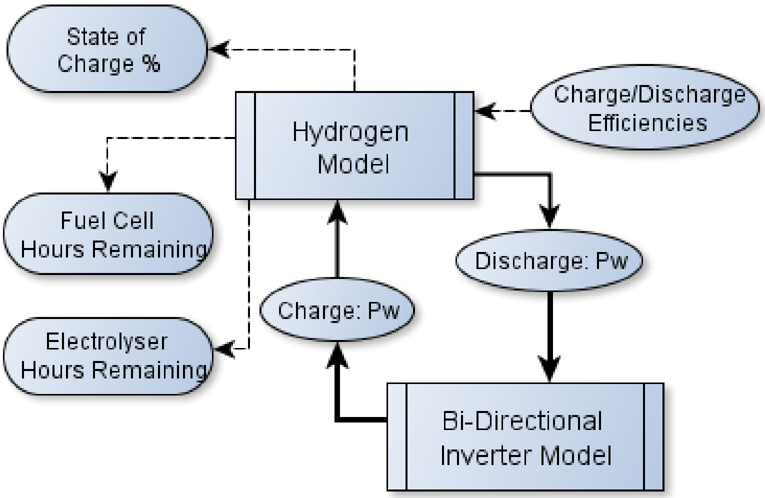

Figure 15: Hydrogen Fuel Cell, Electrolysis and Storage System Model Diagram

The rationale for the use of Polymer Electrolyte Membrane (PEM) fuel cell and electrolyser technologies are manifold, only a subset of which are discussed here. As opposed to other fuel cell or electrolyser technologies, they are capable of highly variable operation range with fast acting response at low temperatures, ideal for integrating intermittent renewables. PEM electrolysers can also produce hydrogen at high pressure directly, without the need of a compressor, and at very high purity [38], [76]. They are also modular and scalable, which can allow for wide variations in sizing and gradual system expansion to meet demand growth.

The hydrogen fuel cell and electrolyser combination functions very similarly to the battery model implementation described above. Like the battery model, H_2, electricity, and energy flows are calculated using the respective individual efficiencies of the electrolyser and hydrogen fuel cell. The hydrogen is stored as a gas in pressurized tanks and the amount stored in each hour is recorded as the H_2 ‘state of charge’.

The details of the specific implementation in the current model are briefly listed overleaf:

- The respective component sizes for the fuel cell and electrolyser power capacities as well as the hydrogen storage capacity are given in the model as 3 independent optimization variables.
- Hours of operation for the electrolyser and fuel cell are recorded for remaining lifetime.
- Energy flows are calculated using the rated electrolyser and fuel cell efficiencies and the lower heating value (LHV) of 33.33kWh/kg for hydrogen [77].
- System pressures and hydrogen volumetric flows are not explicitly modelled.
- A hydrogen fuel cleaning or compression system is not included in the model due to the ability of the PEM electrolyser to produce very high purity hydrogen at high pressure directly.
- Only pure hydrogen is modelled as an energy vector, usage of other hydrogen rich fuels or reformate systems are not included.
- Characteristic curves for output level and temperature based efficiencies are not included, flat efficiency curves are assumed.

3.7 Multi-Functional Bi-directional Grid Forming Inverter

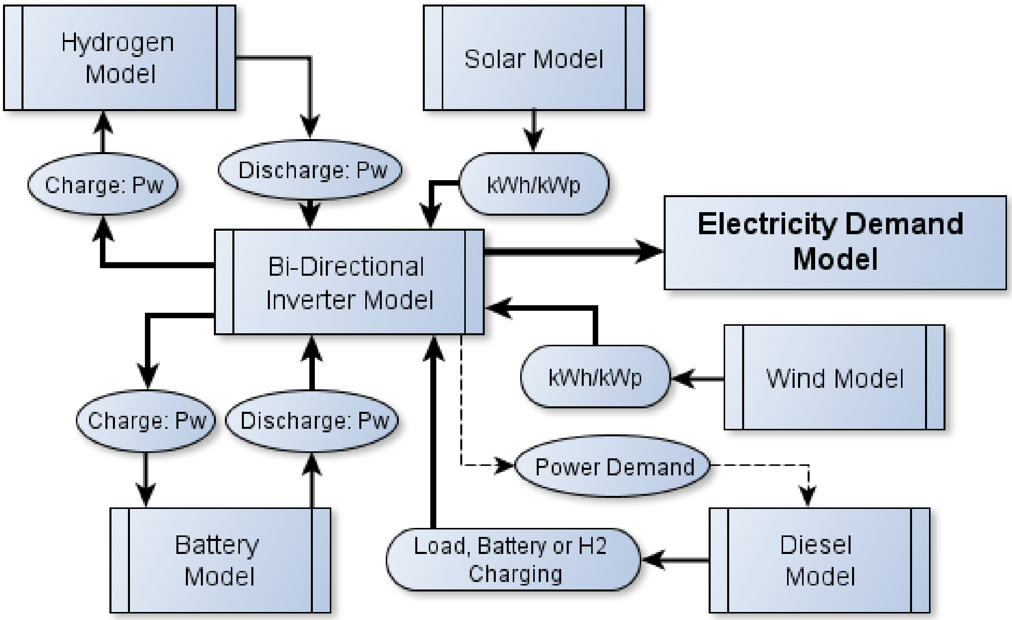

Figure 16: Multi-functional Central Inverter System Model

Isolated mini-grids require an inverter to interface to both convert bi-directionally between DC and AC electricity, and in the case of suppling AC power they are needed to regulate and form the central frequency and voltage of the mini-grid. Accordingly, these inverters are called bi-directional grid-forming inverters (GFI). Frequency regulation is typically achieved by controlling real power (kW) while voltage regulation results from reactive power (kVAR) control. These inverters typically also act bi-directionally and are able to receive power from multiple connected power sources. This allows DC to AC conversion (inverter mode – to supply AC loads with direct renewable feed in or from the batteries/fuel cell) as well as AC to DC conversion (rectifier mode – to allow possible DC loads and battery charging with the diesel generator if required) [16], [78].

The programmatic implementation of the grid forming inverter's simulation within the model is as follows:

- Allocation of the grid forming role to batteries or diesel or fuel cell are allocated as per the respective operational mode and which resources are available at that time. This is described in detail further below in Section 3.9.
- Losses due to bi-directional DC and AC conversion are calculated using the inverter/rectifier efficiency based on the route of energy flow.
- DC sources supplying DC loads, electrolysis or charging batteries are not subjected to inverter losses, nor AC sources (such as a diesel generator) to AC loads.
- No stand-by or auxiliary loads are modelled in times when the inverter is not used, nor for the communications or controllers necessary for power quality and energy management systems. These are instead included in overall bi-directional conversion efficiencies.

3.8 Balance of Plant

Any losses or auxiliary power requirements due to remaining balance of plant, such as required Maximum Power Point Trackers (MPPT), DC/DC conversion, charge controllers, wiring and distribution are accounted for in the efficiency losses attributed to the respective generation, storage or inverter modules.

Any other balance of plant components such as wiring, protection, control signalling and monitoring, as well as other larger system auxiliaries such as cooling systems, oil filtration or fuel processing etc. are not explicitly modelled. The effects of these are included in the individual component efficiencies and capital costs throughout.

3.9 Energy Management and Dispatch Strategy

The mini-grid *dispatch strategy* implemented here forms a simple rule based dispatch priority to simulate the *energy management system* that the central mini-grid control system would implement at all times to monitor and control the operation of all connected technologies. If any of the technologies included in the dispatch strategy below are not implemented in the system, that step would simply be skipped. The dispatch strategy is described below:

The *residual load* is first calculated by subtracting the total renewable energy generation from the total demand. Renewable generation has the highest priority, and when available is used to serve loads directly.

If the residual load is negative, therefore renewable generation exceeds the demand, the following rules apply:

1. Renewable generation has the highest priority and is used to serve loads directly.
2. Remaining renewable energy is used to charge the batteries first.
3. When the batteries' state of charge reaches 100%, the electrolyser is run until the H_2 storage is full.
4. Following this any remaining renewable generation is curtailed to ensure system stability.

When the residual load is positive, therefore available renewable generation cannot meet the demand, the following rules apply:

5. First the batteries are discharged meeting the residual load until their minimum State of Charge (SoC).
6. Following this the hydrogen fuel cell is run until the H_2 storage is empty.
7. Once all storage devices are depleted or are unable to meet peak demand the diesel generator is started and serves any remaining residual loads. At this point the diesel generator is also given the grid forming role.

Finally, any remaining demand that cannot be met by the system will be counted as "Energy Not Served" (ENS).

Note: The mini-grid's energy management system can be programmed using any defined operational strategy, which would simply need to be coded into the model where the dispatch strategy logic is defined. This allows the model to be used to test the performance of any existing or newly developed energy management system, including dynamic or predictive real-time energy management systems.

3.10 Primary Component Parameterizations

The parameters used to characterise and represent each component mathematically are summarised below:

Table 3: Matrix of cost and performance parameters used to model each included technology. X's indicate the technology is characterized (in part) using the corresponding parameter on the left.

	Solar PV	Wind	Diesel	Inverter	Battery	Fuel Cell	Electrolyser
Capital: USD/kW	X	X	X	X	---	X	X
Capital: USD/kWh	---	---	---	---	X	X	X
Fixed O&M: USD/kW/year	X	X	X	X	X	X	X
Variable O&M: USD/kWh	---	---	X	---	---	---	---
Efficiency	X	X	X	X	X	X	X
Lifetime	X	X	X	X	X	X	X
Replacements	---	---	X	---	X	---	---

4

APPLICATION OF THE MODEL: SOUTH AFRICA

"To study, and when the occasion arises to put what one has learned into practice – is that not deeply satisfying? "– Confucius, Analects 1.1.1

4.1 MODEL APPLICATION

To demonstrate the functionality of the developed model's implementation a *case study* is undertaken using the model to investigate mini-grids within the *South African context*. The status of electrification in South Africa with the specifics relating to off-grid supply options for rural areas is first introduced. The set of *modelling assumptions* relating to the overall system design, component cost determinations, system size scaling and demand growth considerations which have been applied in this model application are then defined.

The full set of the used *technology cost and performance parameters* are listed with all publicly available data sources referenced below. The future component cost projections to 2030 which were used for solar PV, small-scale wind turbines, and lithium-ion batteries are also presented here.

Maps of a sample set of *15 representative mini-grid sites* covering the spatial extents of the rural unelectrified populations across South Africa are displayed with the rationale for their selection. Maps are shown depicting the distribution of potential unelectrified areas across South Africa, as well as the areas where closer focus is made.

The particulars of the publicly available solar and wind meteorological data used in the implementation are referenced and presented. High resolution long-term average renewable energy resource maps showing the geographical renewable resource distribution across South Africa are also shown. Finally, the details of the bottom-up formulation of a 100-household total electricity load profile are shown. The electricity demands of a suite of household, commercial, and community electricity technologies for a representative village are shown.

4.2 South African Current Electrification Context

South Africa has committed to providing universal electricity access by 2030 through the New Household Electrification Strategy (NHES), aligned with the goals and objectives of the UN's SE4ALL program [79]. Approximately 8 million people remain without access, and 300,000 households or 1.5 million people, have been identified for electrification using quality non-grid systems, including mini-grids and hybrid systems, [80].

A map, developed by the Energy Research Centre of the University of Cape Town (ERC-UCT) and the South African Energy Development Institute (SANEDI), geospatially mapping the electrification rates across South Africa using census data [78] is shown below in *Figure 17*.

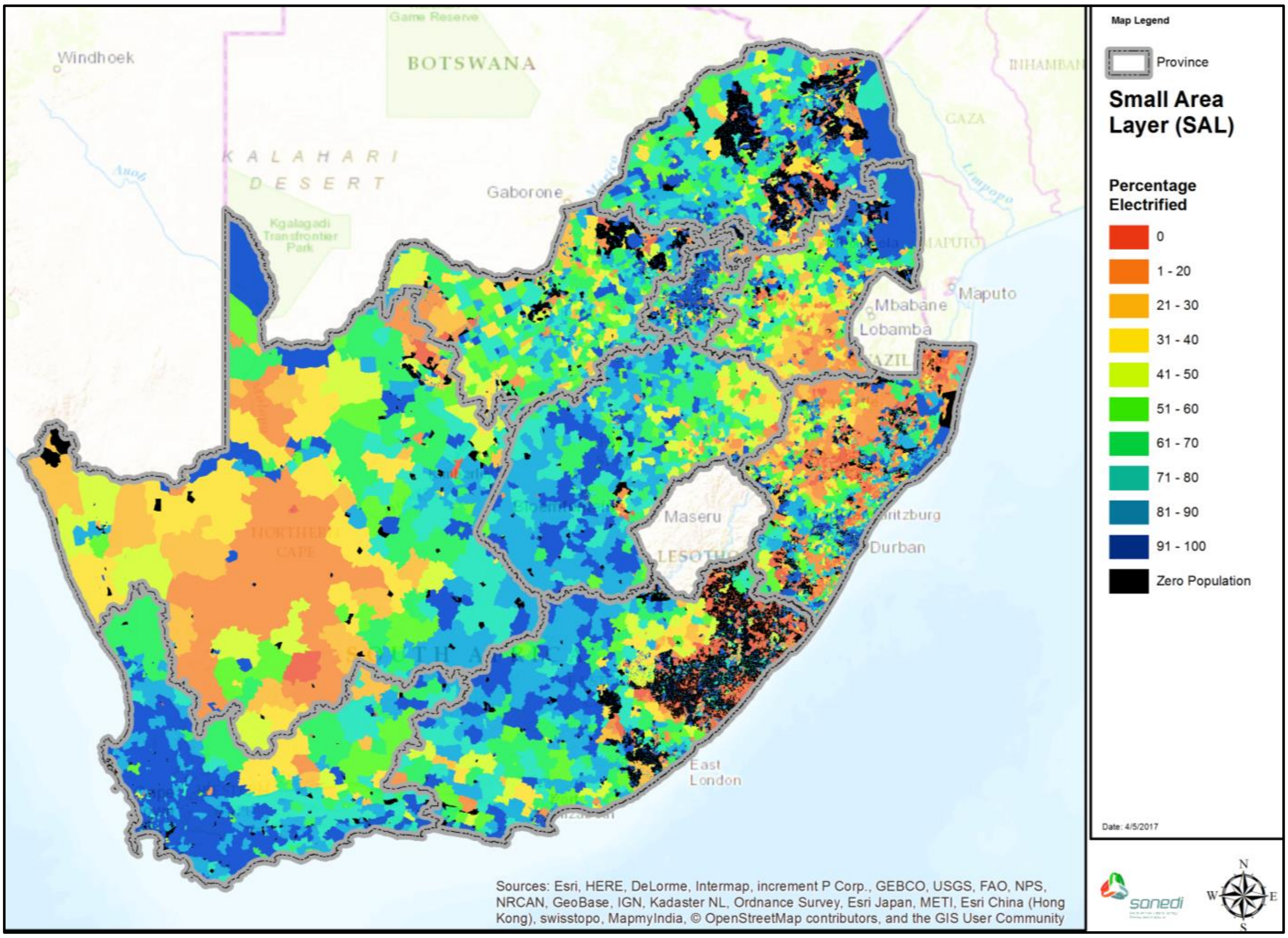

Figure 17: Electricity Access rates mapped across South Africa with 2011-2013 Data from 2011 Census StatsSA. Approximately 8 million people, of which 1.5 million are identified for mini-grid electrification [78], [80].

4.3 System Component Sizing Variables and Configurations

The specific individual technologies and the component sizes that are included as system configuration variables to be chosen by the optimization algorithm for least-cost determination are as follows:

- **Solar PV:** Total DC Solar array peak *power* installed capacity – **kWp**
- **Wind:** Total DC *power* installed capacity of wind turbines – **kWp**
- **Batteries:** Total 100% depth of discharge usable battery *energy* installed capacity – **kWh**
- **Hydrogen Fuel Cell:** Total PEM hydrogen fuel cell DC installed *power* capacity – **kW**
- **Hydrogen Electrolyser:** Total PEM electrolyser DC *power* installed capacity – **kW**
- **Hydrogen Compressed Cylinder Storage:** Total discharge hydrogen *energy* capacity – **kWh**

The specific combinations of technologies modelled for each case presented below in this study, and the included scenarios and any added system constraints, will be described in each of their respective sections below.

4.4 ASSUMPTIONS, TECHNOLOGY SPECIFICATIONS AND COST DATA

The technology performance specifications and cost assumption data used in this study are listed in *Table 4.* This data has been obtained from a wide range of recent sources (2015-2016) in the public domain and focuses, where possible, on the South African context. References are included directly below the table and are excluded from the final reference list.

- All costs in this study are quoted in 2015 USD, and where necessary, an exchange rate of 13:1 (ZAR: USD) has been used to convert, when South African technology prices were sourced.
- Most costs have been rounded to the nearest 10 or 5 for the sake of clarity and simplicity. Any differences in the results due to the rounding are assumed to be negligible and well within the typical uncertainty relating to these types of cost estimates.
- The discount rate has been set at 8.4%, which is the value that was calculated by National Treasury for use in the Integrated Energy Planning process and the Integrated Resource Plan 2016 [81].
- The base diesel price is set at ZAR 13 per litre i.e. USD 1 per litre. However, because of logistical challenges, diesel theft, pilferage, and other losses, the price is increased by 50% to USD 1.5 per litre. This was based on the experience of cell phone service providers using remote diesel generators [28].

4.4.1 System Design Sizing and Component Cost Separation

Several assumptions have been made relating to the sizing and costs of certain components that are not variables chosen by the model for optimization. These are listed below:

- The diesel generator and Hybrid Inverter are sized at 1.2 times the maximum demand. These are subjective design variables; 1.2 is used based on the “best practice” of a 15-30% oversizing factor, to accommodate demand growth or exceptional peak power demand cases [15].
- Systems including diesel backup are assumed to be able to meet all demand that may remain if there is insufficient renewable generation or storage capacity.
- The system configuration is assumed to have 100% availability and reliability; i.e. random system breakdowns are excluded and planned maintenance can be carried out without system down time.
- Electrolyser and Fuel cells are each assumed to cost the same per kW for cost target determination.
- Maximum Power Point Tracking (MPPT) charge controllers are included separately for the PV and Wind capital costs and are sized according to the respective generation capacities and not the inverter.
- Maintenance costs for each technology are all included additively and do not include potential reductions through joint maintenance e.g. single team, transport, shared system components, etc.
- Location and rural specific additions to any costs e.g. distance to site, ruggedness and accessibility of terrain, non-availability of on-site facilities, etc., are excluded. These would mostly apply to each modelled alternative and could largely balance out in direct comparisons.

2015 Costs (USD)	Solar PV	Wind Turbines	Diesel Generator	Hybrid Inverter	Battery (Li-Ion)	Fuel Cell (PEM)	Electrolyser (PEM)
Capital USD/kW	2,930 (AC)[1,2] *-15% to DC*[1,2] 2,465 (DC)	Turbine[3]+ Tower[4, 5] (40m) (30% of total CAPEX) 1,910 + 820 = 2,730 (DC)	600[6]	400[7]	---	10,000[8]	12,500[9]
Capital USD/kWh	*+ 200 USD/kW Hybrid MPPT Charge Controllers for each of PV and Wind*[10]		---	---	400[11]	15 (Compressed Cylinders)[12]	
Fixed O&M USD/kW/year	20[13]	50[14]	15[6]	17.5[13]	1.5% of CAPEX[11]	5% of CAPEX[15]	
Variable O&M USD/kWh	---	---	0.015[6]	---	---	---	---
Efficiency	95% (BoS loss)[16]	98%[20] (Wind & PV MPPT loss included in battery eff.)	As per efficiency curves[17]	94%[7]	92% (round-trip)[11]	47%[18]	65% (LHV)[19]
Lifetime	20 years[12]	20 years[20]	20 years[6]	15-20 yrs[13]	4,000 cycles[11]	~15 years[18]	~15 years[19]
Replacements	---	---	65% CAPEX (25,000 hrs)[6]	inc. in O&M [11]	225 $/kWh (10 years)[11]	Stack 40% of CAPEX (inc. in O&M)[18]	

Table 4: Complete Mini-grid Component Cost and Performance Data Matrix

1. IRENA, 2016. Solar PV in Africa: Costs and Markets. International Renewable Energy Agency, Abu Dhabi, UAE.
2. NREL, 2016. 2016 Annual Technology Baseline. National Renewable Energy Laboratory, Golden, Colorado, USA.
3. Sustainable.co.za, 2017. "Kestrel e400n 3500W Wind Turbine," Sustainable Online Ltd. Available: http://www.sustainable.co.za/kestrel-e400n-3500w-wind-turbine.html. (Accessed 9 January 2017).
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15. IEA, 2015. Technology Roadmap - Hydrogen and Fuel Cells. International Energy Agency, Paris, France.
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18. NREL, 2014. Backup Power Cost of Ownership Analysis and Incumbent Technology Comparison. National Renewable Energy Laboratory, Boulder, Colorado, USA.
19. Hinkley, J., Hayward, J., McNaughton, R., Gillespie, R., Matsumoto, A., Watt, M., & Lovegrove, K., 2016. Cost assessment of hydrogen production from PV and electrolysis. CSIRO, Australia.
20. Kestrel, 2017. e400nb Technical Specifications. Available: http://www.kestrelwind.co.za/assets/documents/e400nb.pdf. (Accessed 32st January 2017).

4.4.2 System Scaling and Expansion with Demand Growth

A conservative scale has been used when selecting costs for components, by using prices quoted for the smallest scale, single systems, without economies of scale, e.g. for solar PV USD 2,930/kW (5kW system) has been used as opposed to the USD 1,400/kW for utility scale solar PV projects [9], [82]. Wind turbines share similar significant cost reductions through economies of scale with larger utility scale wind turbines having roughly 50% of the per kW capacity cost [83]. Thus, significant cost benefits may be realized through scaling up to larger individual systems, developers building multiple systems, or joint power generation installations for nearby communities/villages if appropriate.

It is highly likely that the energy and power demand from the community will grow as local economic development occurs, less income is spent on expensive energy alternatives, and users become more familiar with using electricity. Renewable energy technologies are however inherently modular and additional generation, storage, inverters, and fuel cells can be added to the system in parallel. Furthermore, diesel generators can be added as per demand growth and sized to allow more efficient part load operation by only running the generator combinations best matching the load. This overall system expansion can be done as and when required and with the cost-optimal combination of technologies available at the time. The investigation of various demand growth scenarios are therefore not included at this stage and the optimum configurations determined here represent the initial systems to be installed.

4.4.3 Technology Cost Projections to 2030

Expected future capital cost curves are included for solar PV, wind turbines, and lithium-ion batteries, while all other technology performance parameters are kept constant. Future potential maintenance, operational or installation cost improvements are not included. Solar PV capital costs are from NREL [82] and IRENA [9], wind capital costs from DWEA [83], and li-ion batteries based on ICCT [20], CSIRO [84], and Lazard [74]. Technology cost projections are all based on the respective mid-range estimates and obtained from 2016 sources. This additional comparison to other industry estimates is done for Li-ion due to recent rapid changes in cost and higher uncertainty for future reductions.

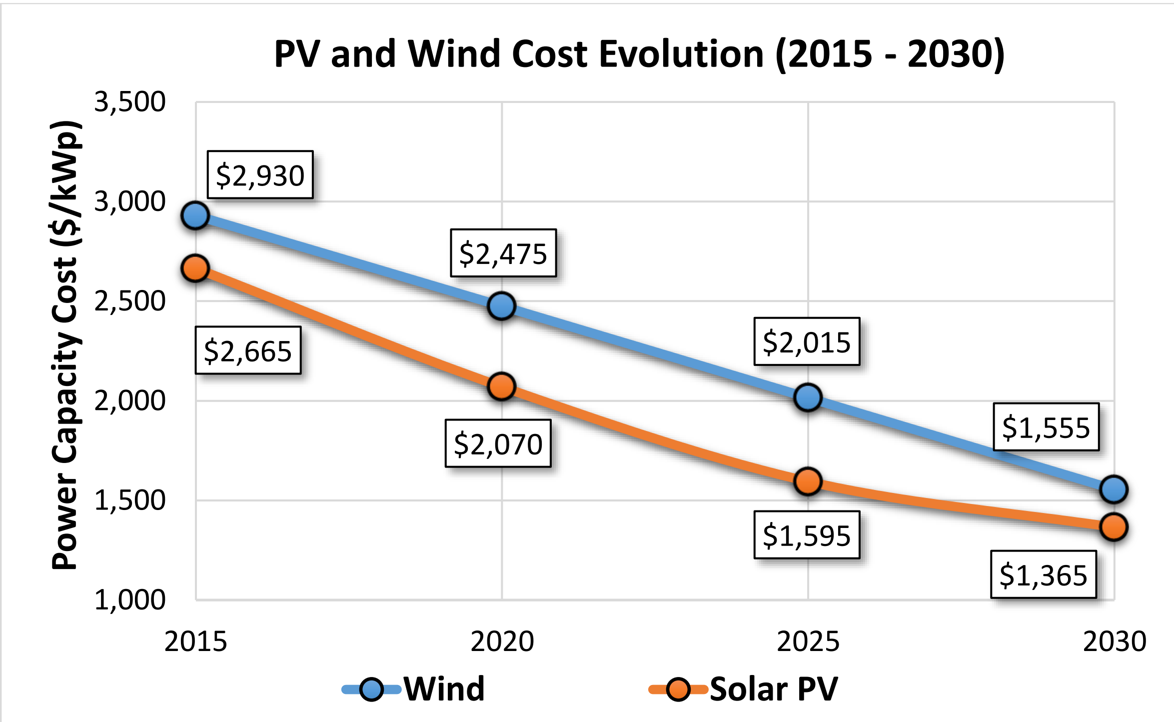

Figure 18: Solar PV and Wind Capital Cost Evolution Estimates to 2030[21]

[21] Including individual Hybrid MPPT Charge Controllers for PV and Wind CAPEX

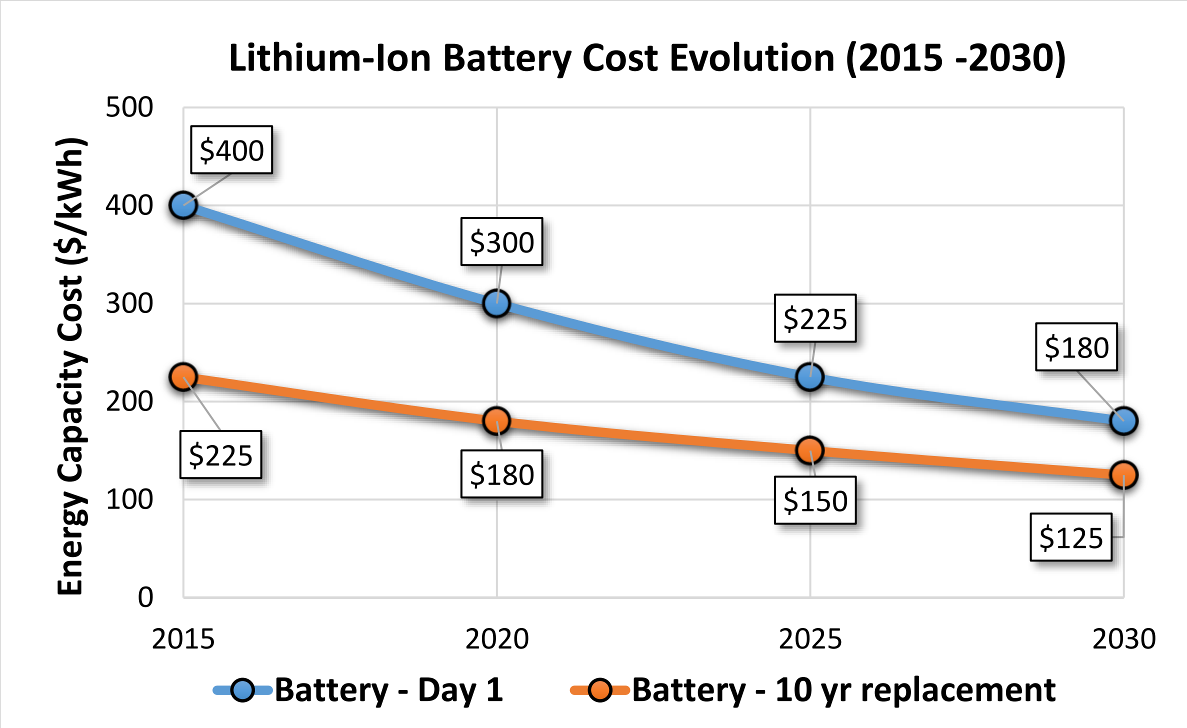

Figure 19: Lithium-Ion battery and replacement cost evolution estimates to 2030

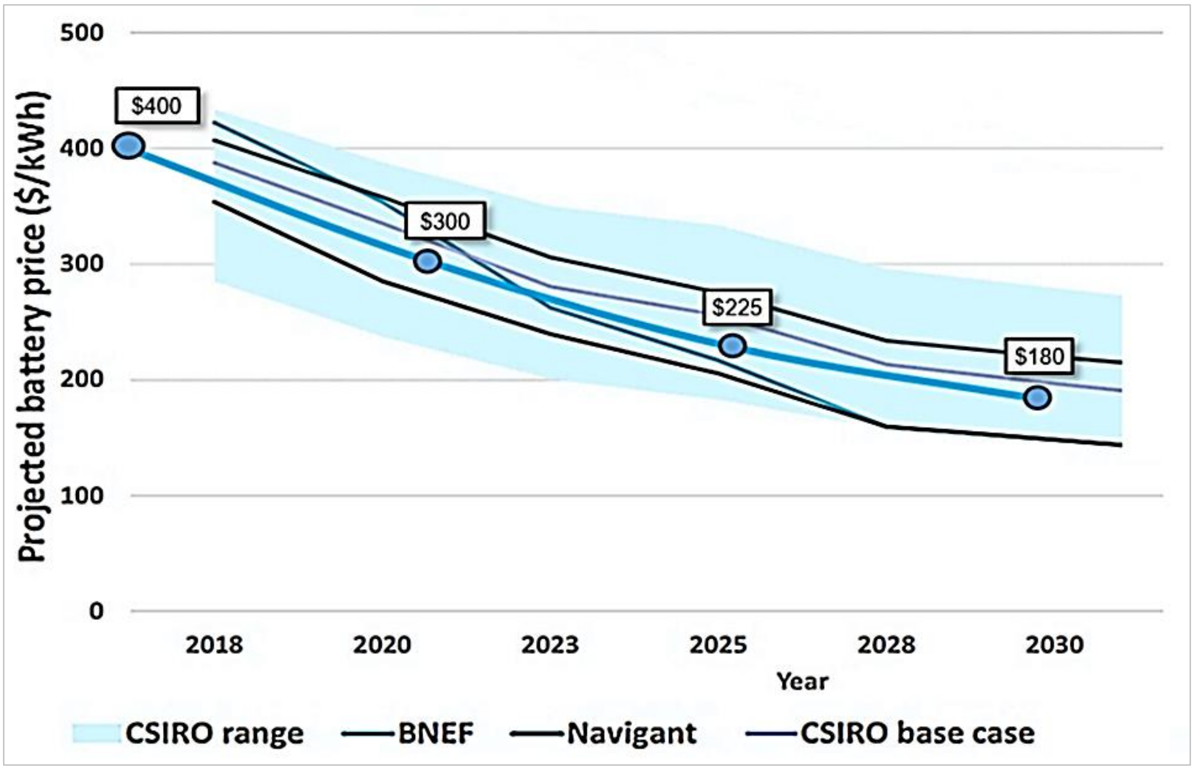

Figure 20: Lithium-Ion battery cost evolution estimates benchmarked versus CSIRO, BNEF and Navigant[22]

[22] Overlaid on CSIRO, Bloomberg New Energy Finance and Navigant projections. Adapted from [74]

4.5 Site Selection for Least-Cost Modelling Application

Fifteen sites were selected across South Africa to act as hypothetical mini-grid implementation locations, constituting a representative sample of un-electrified areas in South Africa. The main deciding factor for the placements of the selected sites is primarily to provide the widest spatial coverage of the un-electrified areas throughout South Africa. This creates a sample with covering a wide distribution of solar and wind resources [78].

The number of sites selected for modelling in each province are as follows: Eastern Cape (4), KwaZulu Natal (4), Limpopo (2), Mpumalanga (2), Northern Cape (2) and North West (1). The relative number of the total sites within each province are prioritized according to the relative number of households identified in each province for off-grid electrification [78].

Map of South Africa's Unelectrified Areas with Modelled Mini-Grid Sites

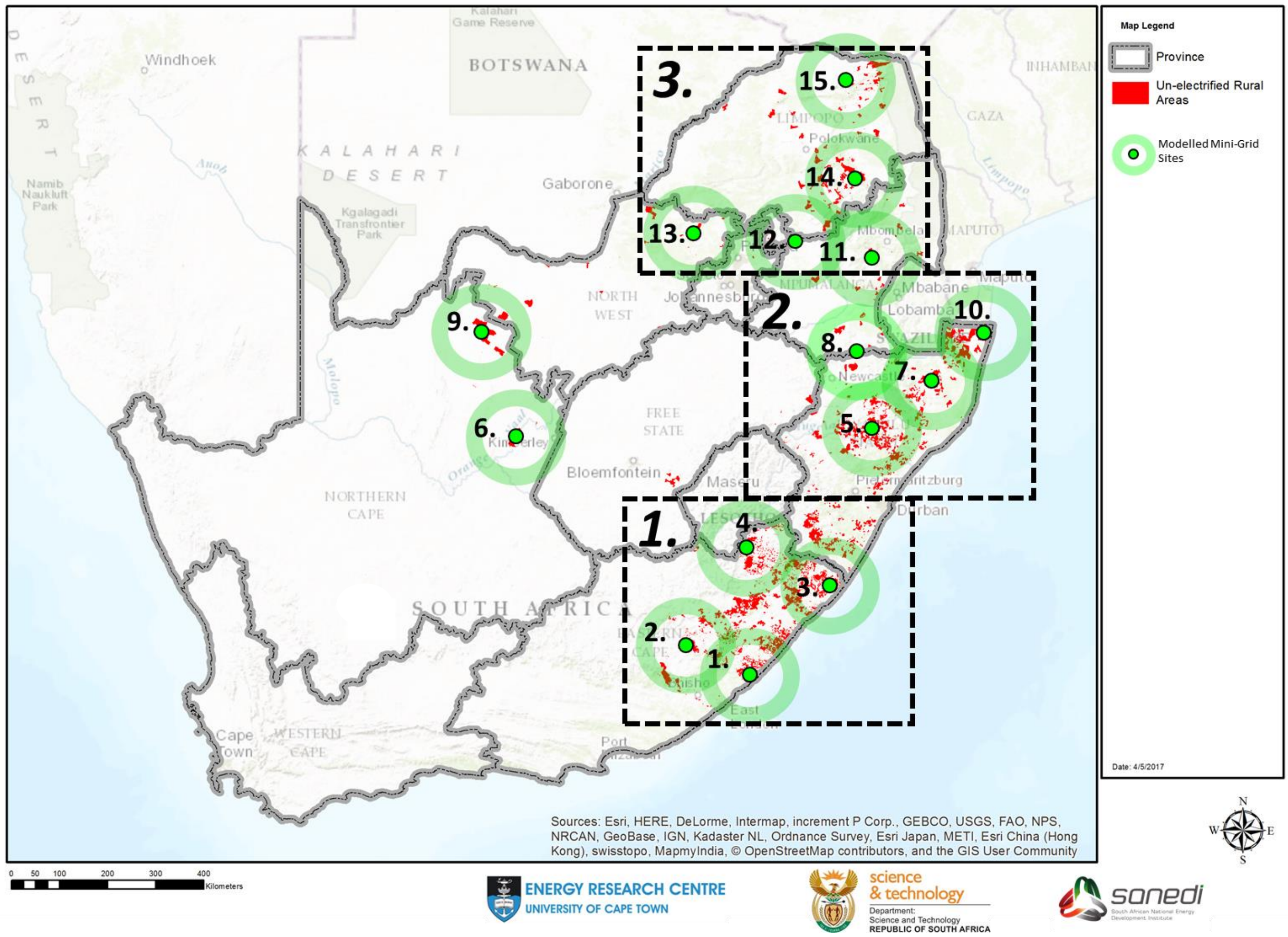

Figure 21: Map showing the distribution of the 15-modelled representative hypothetical mini-grid sites covering the spatial extents of remaining unelectrified areas in South Africa (2011 SA Census Geospatial Data analysis done by SANEDI and the ERC of UCT [78]).

The numbered dotted black boxes show 3 pop-out zoomed maps of the primary unelectrified areas in South Africa, which include all but two of the selected sample sites. These zoomed maps are shown in *Figure 22*, *Figure* 23, and *Figure* 24 *below.*

Sites 6 and 9 were modelled for the sake of wider geographical coverage and for the inclusion of the Northern Cape province. Their results were very similar to that of site 15 due to the similarly high and consistent solar resource. They are therefore not discussed in any detail in the modelling results in Chapter 5.

<u>These maps should be referred to when reading the modelling results section and their discussion.</u>

Table 5: Basic details of the 15 Sites selected across South Africa for techno-economic modelling for component configuration and sizing optimization

Site No.	Longitude	Latitude	Elevation (m)	GHI (kWh/m²)	DNI (kWh/m²)	Municipality	Province
1	28.4478	-32.5463	135	1,616	1,571	Mnquma	Eastern Cape
2	27.2404	-32.0334	911	1,853	2,108	Lukanji	Eastern Cape
3	30.0489	-31.2195	93	1,617	1,571	Mbizana	Eastern Cape
4	28.7537	-30.1607	1,623	1,946	2,239	Matatiele	Eastern Cape
5	30.6242	-28.5823	972	1,848	1,848	Nqutu	KwaZulu-Natal
6	24.4027	-28.4893	1,042	2,139	2,602	Dikgatlong	Northern Cape
7	31.8491	-27.6788	515	1,720	1,590	Nongoma	KwaZulu-Natal
8	30.3709	-27.3417	1,403	1,853	1,879	Emadlangeni	KwaZulu-Natal
9	23.3837	-26.9544	1,186	2,228	2,736	Joe Morolong	Northern Cape
10	32.8668	-26.8789	18	1,782	1,638	Umhlabuyalingana	KwaZulu-Natal
11	30.6971	-25.663	1,457	1,820	1,761	Mbombela	Mpumalanga
12	29.2591	-25.4307	1,191	2,037	2,083	Thembisile	Mpumalanga
13	27.3145	-25.3841	1,065	2,084	2,203	Rustenburg	North West
14	30.4482	-24.3873	1,139	1,936	1,900	Greater Tubatse	Limpopo
15	30.0786	-22.6991	593	2,007	2,006	Musina	Limpopo

Map Zoom no. 1

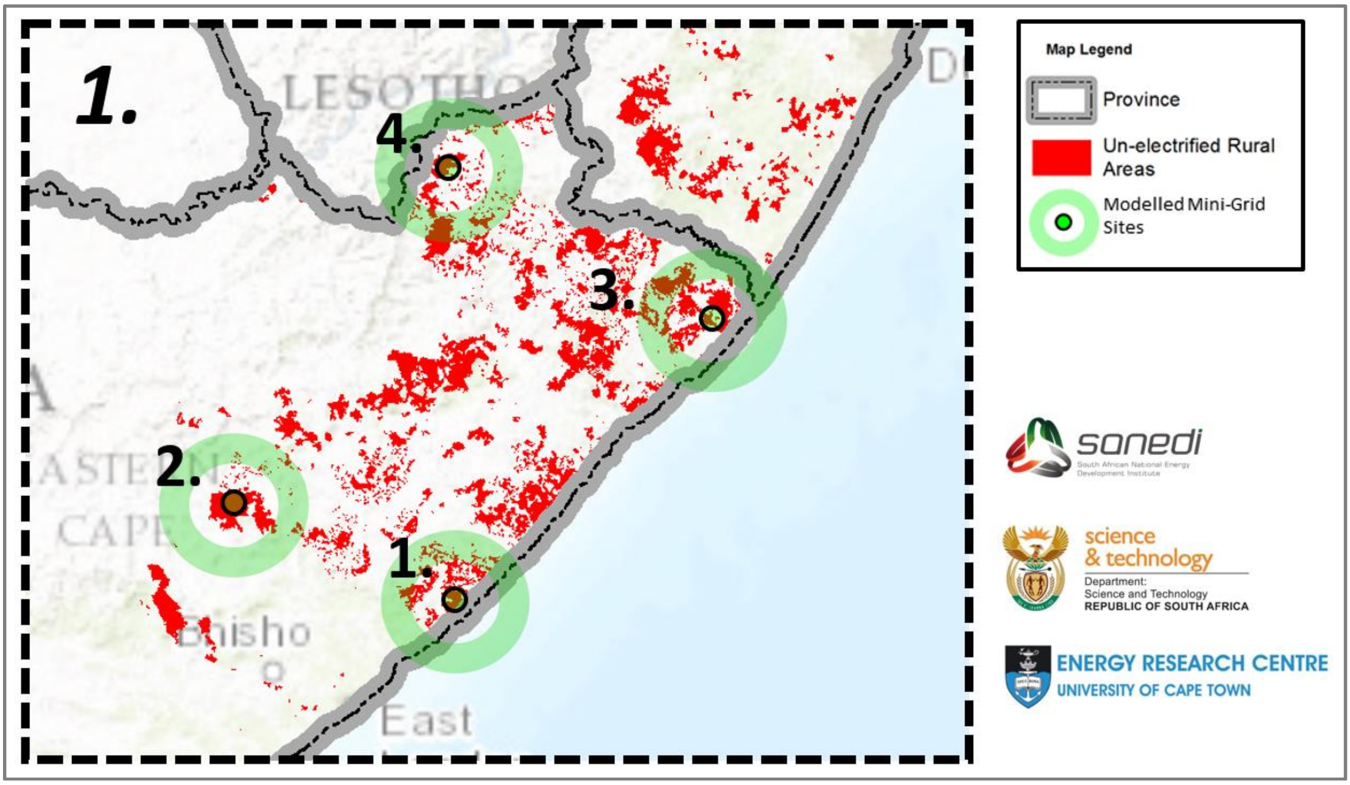

Figure 22: Zoomed map of sites 1 through 4 covering the unelectrified areas in the Eastern Cape province and Southern Kwazulu-Natal Provinces in South Africa.

Map Zoom no. 2

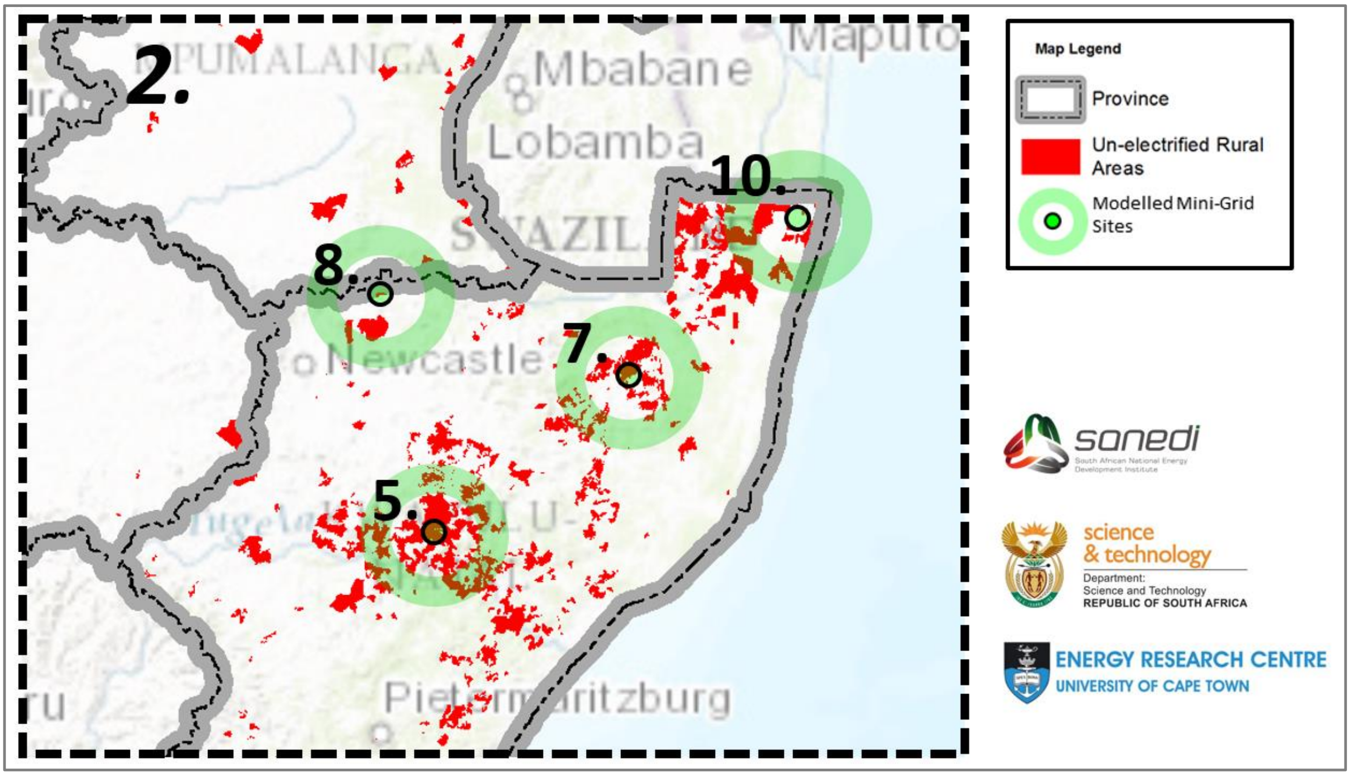

Figure 23: Zoomed map showing sites 5, 7, 8, and 10 across the unelectrified areas of the Central and Northern Kwazulu-Natal province in South Africa below the borders of Swaziland and Mozambique.

Map Zoom no. 3

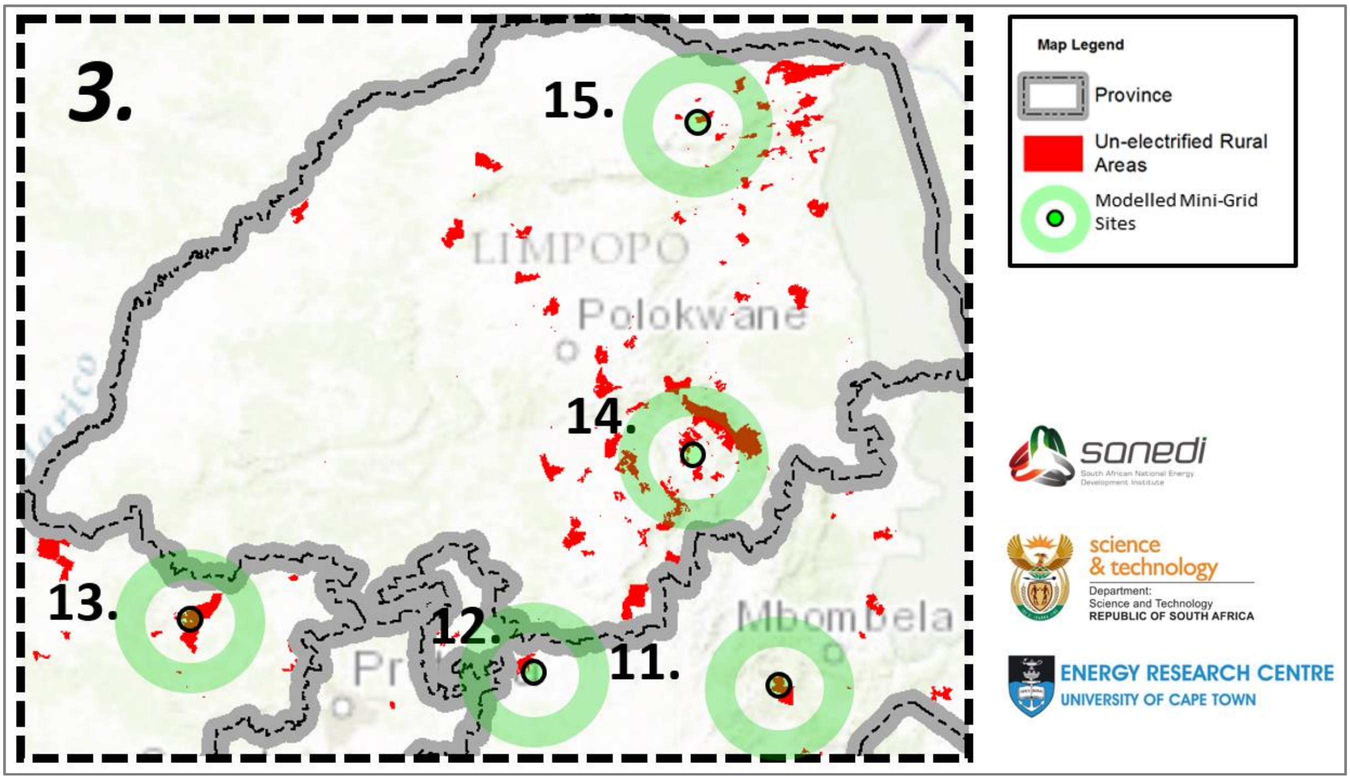

Figure 24: Zoomed map showing sites 11 through 15 covering the Northern most areas of the North West and Mpumalanga provinces and the North and South extents of the unelectrified areas in the Limpopo province in South Africa

4.6 METEOROLOGICAL DATA OF APPLICATION: SOUTH AFRICA

Various meteorological data sources have been used as timeseries inputs for the simulation of expected renewable energy generation potential at each of the 15 mini-grid sites. Solar and wind data time series for each site are obtained from weather model datasets used to represent onsite historical meteorological conditions. The details surrounding the data-sets used are described below with an overall summary shown in *Table 6* below.

Time synchronized data for both solar and wind from 2013 are used for each site, retaining local solar and wind daily and seasonal meteorological correlations. The 2013 data inputs are scaled to match the long-term annual averages of global horizontal irradiation (GHI) for the solar generation and wind speed at hub height for wind generation. Currently only 1 year of data is used in this application of the model.

The satellite modelled solar data used in this particular application of the model has been obtained from the NASA MERRA-2 satellite measurements [85] made available by Stefan Pfenninger [86]. This data has a spatial resolution of 0.50° latitude and 0.66° longitude and a time resolution of one hour.

The weather model created timeseries data used for the 15 sites is sourced from a project between the Fraunhofer Institute, the Council for Scientific and Industrial Research (South Africa) [87], and the Wind Atlas of South Africa (WASA) project [88]. The data covers South Africa at a higher resolution than the solar data at 5x5km with 15-minute wind speed averages at heights of 50m, 80m, 100m, and 150m.

Solar and wind atlases are used to verify the chosen years of simulation to the long term modelled annual averages where coverage is available. The solar maps used are those produced by SolarGIS [89], [90], while the wind maps are from WASA [88]. High resolution renderings of these maps are shown in *Figure* 25*, Figure* 26, and *Figure* 27 below.

Table 6: Summary of Meteorological Time Series Data Used for System Modelling

Year: 2013	**Data Sources** (Public Data)	**Timeseries Temporal Resolution**	**Timeseries Spatial Resolution**	**Long-term Average Maps Resolution**
Wind Data	CSIR & WASA	15-min timestep (over 2013)	5km x 5km (CSIR)	250m x 250m (limited to WASA 1)
Solar Data	MERRA-2, SAURAN & SolarGIS	1 hour timestep (over 2013)	0.50° lat x 0.66° long (MERRA-2: NASA)	1 km x 1 km (SolarGIS)

Note: The *actual* future renewable resource generation performance can never be exactly predicted and is inherently subject to uncertainty. Every actual mini-grid project implementation requires a more detailed site specific layout analysis and local insular resource prospecting. This is typically done with on-site measured data including extreme weather cases, to determine the overall expected renewable generator performance and dynamics more accurately.

4.6.1 Solar Data Implementation Details

The solar data used in this particular application of the model has been obtained from the NASA MERRA-2 satellite measurements [85] which is processed into power output using the open source GSEE model (Global Solar Energy Estimator) written and made available by Stefan Pfenninger [86].

The irradiance striking the solar PV modules of a particular orientation, at the particular system location on earth, is estimated with the BRL transposition model, as it has been shown to perform best amongst a variety of similar models. The BRL model requires a clearness index, which is estimated by the fraction of ground irradiance to top of atmosphere irradiance from the MERRA-2 data [85].

The SolarGIS maps used for time series validation and adjustment are generated using Meteosat satellite data of 15- and 30-minute time steps spanning from 1994 to 2013 [89], [90]. 14 high quality ground measurement stations along with high resolution terrain data were used to enhance the resolution and accuracy of the map. The data from these ground stations is publicly available, provided through the Southern African Universities Radiometric Network (SAURAN) [91], which was used to test the solar generation model in the framework.

The following solar atlas shown in *Figure 25* is obtained from the World Bank and SolarGIS [90]. It represents long term annual GHI averages across South Africa. A 1km x 1km GIS data set of these underlying irradiation averages has been made publicly available by the South African Department of Environmental Affairs [92].

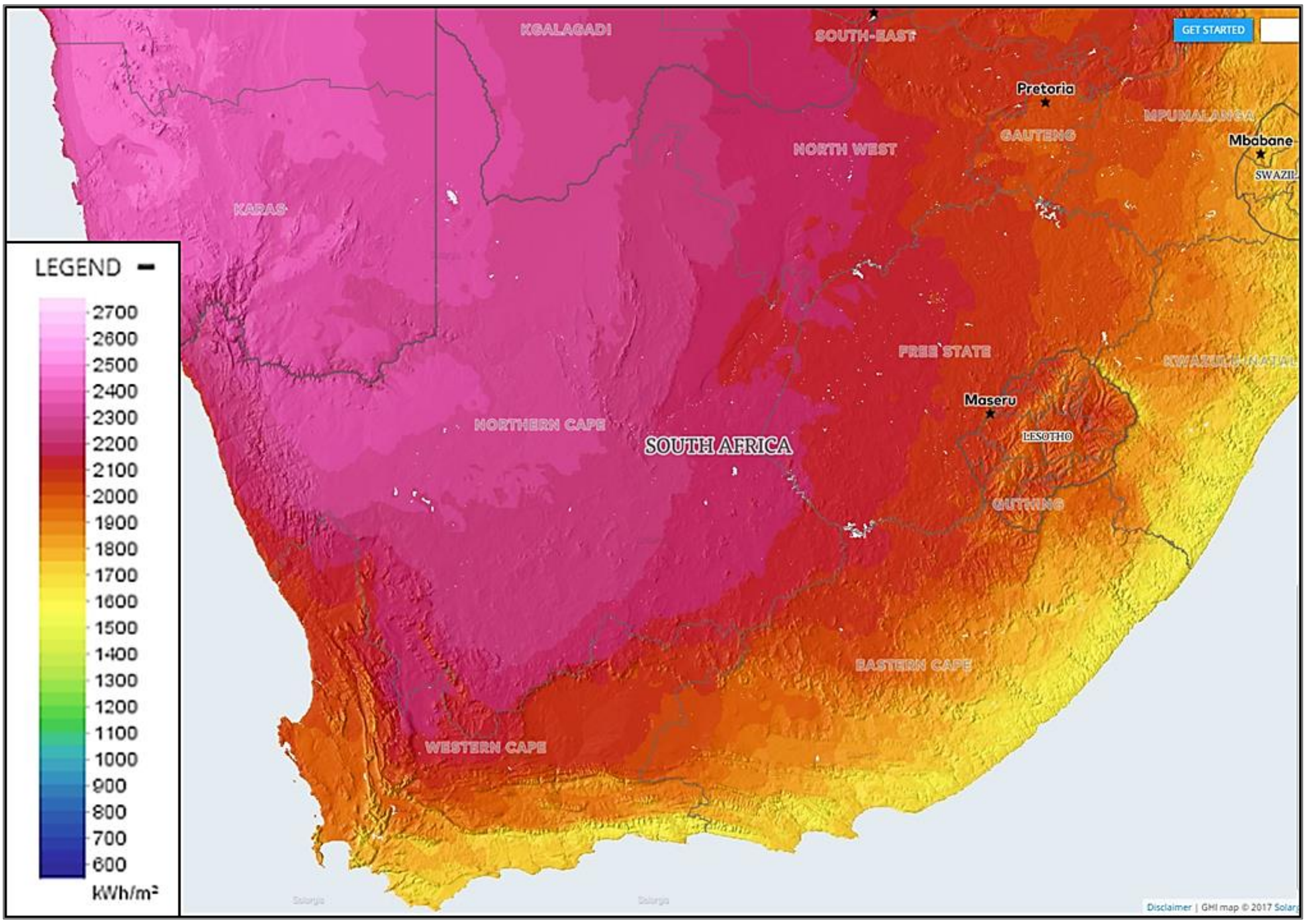

Figure 25: Solar Atlas of South Africa [89], [90].

4.6.2 Wind Data Implementation Details

For the modeled wind data, the Weather Research and Forecasting model (WRF), which is an industry standard meteorological modelling framework, was used for the creation of the WASA data; this same model was then used and extrapolated by Fraunhofer and the CSIR over the rest of the country. Wind speed maps and underlying wind timeseries of South Africa were generated by the application of macro, meso and micro-scale modelling using the statistical-dynamical downscaling methodology [87], [88], [93].

Measured wind data timeseries are also made available through the WASA project from 15 high accuracy wind masts scattered across South Africa at 62m, 60m, 40m, 20m, and 10m above ground. All meteorological mast sensors sample twice per second and record the 10-minute mean, max, min and standard deviations [94].

The windspeed timeseries data is run through the implemented wind generation model using the turbine power curve to determine average hourly capacity factors. 15-minute power outputs are calculated with the turbine curve separately to increases the accuracy of the results due to the non-linear cubic power law of wind energy and the turbine's non-linear cut in and maximum power speeds. The implemented e400b Kestrel turbine has no cut-out speed, by implementing blade furling in high windspeeds [69].

The CSIR modelled wind timeseries for the 15 selected sites are used in this case study application, while the WASA ground measured wind mast data was used for the mini-grid wind model validation and functional testing. This is shown in the Jupyter notebook implementation but will not be detailed here.

Shown below in *Figure 26* and *Figure 27,* are the wind atlases showing the annual average wind speeds for ZA.

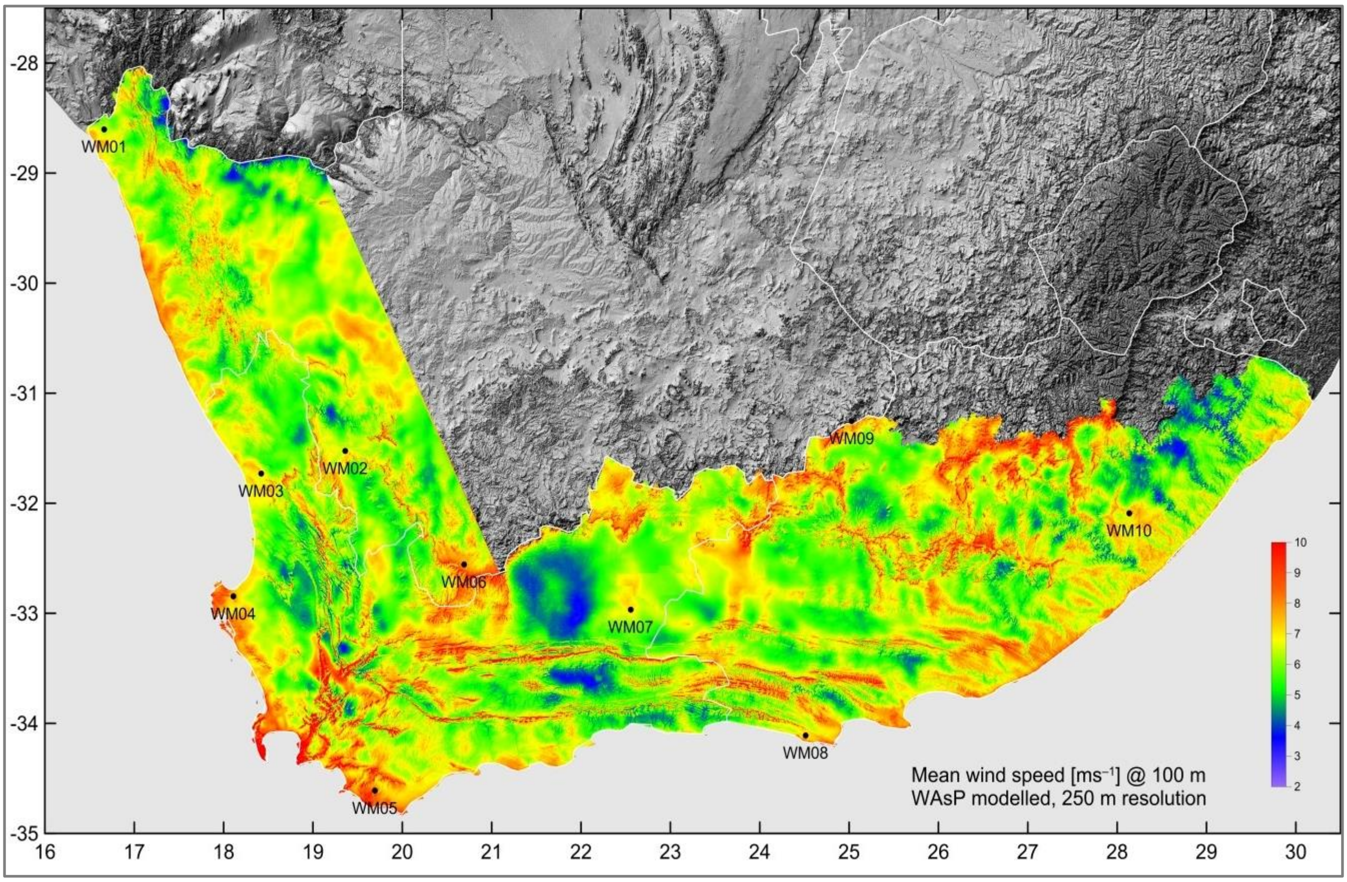

Figure 26: Wind Atlas of South Africa including 250m x250m microscale modelling using the WASP software (1st Phase completed of the Project. 2nd and 3rd Phases are under development) [88].

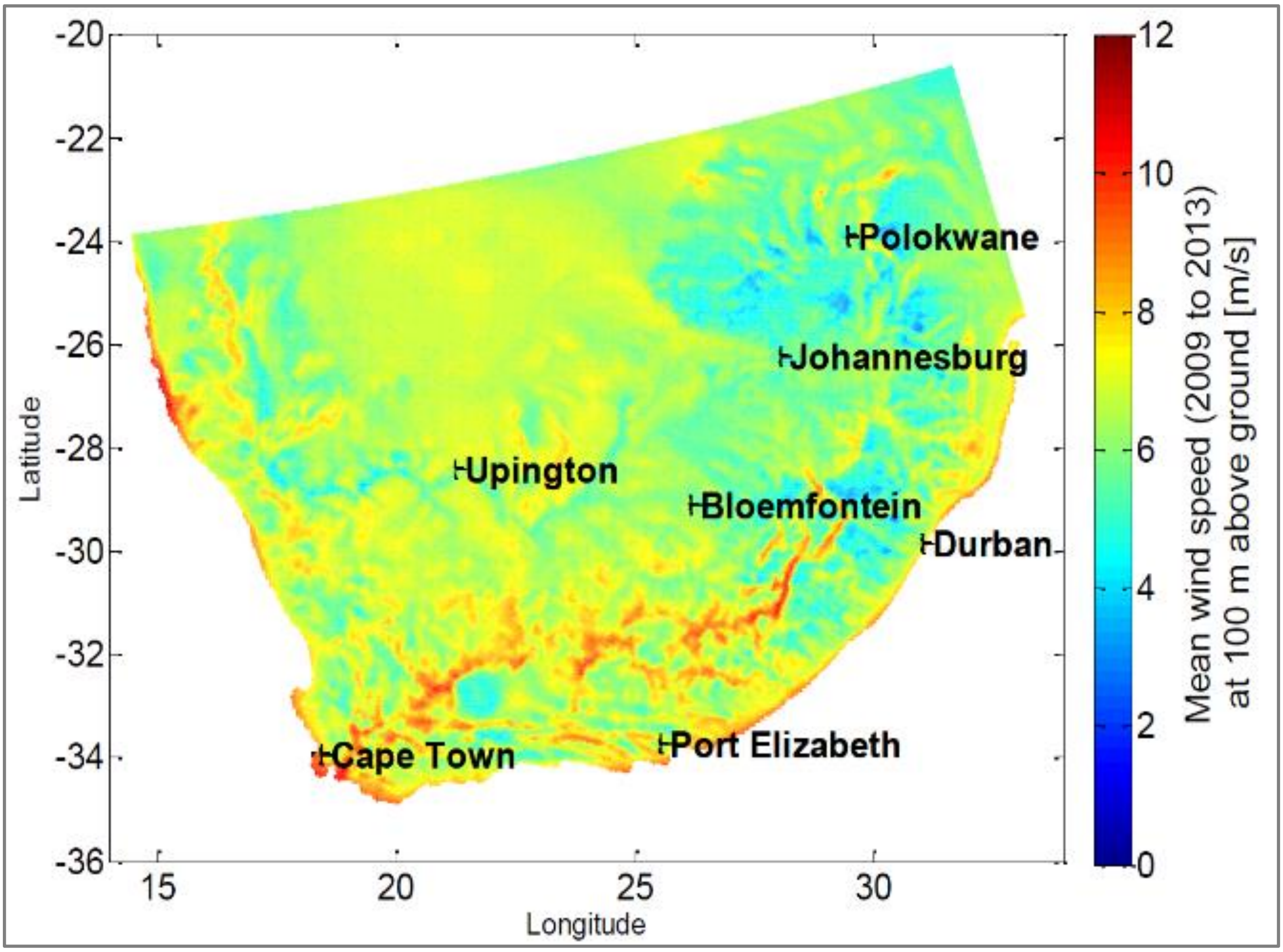

Figure 27: Wind Speed Averages from the Fraunhofer/CSIR Dataset covering South Africa at 5km x 5km Resolution [87].

4.7 LOAD PROFILE MODELLING

To formulate a load profile for use in this study, bottom-up demand load profile modelling was conducted using a selected suite of energy services with assumed wattage and daily usage in a 100-household community with a laundry, shop, and water pumping and purifying system, as shown in *Table 7* below.

Domestic (H) (100 Households) 15.9 kWh/day	Lights 3 W	no. 6	Fans 15 W	no. 2	Phone Charger 5 W	no. 2
	Fridge 75 W	1	TV 15 W	1		
Commercial (C) (Laundry - CL)	Lights 15 W	no. 3	Washing 300 W	no. 1		
(Shop/Kiosk - CS) 6 kWh/day	Lights 15 W	no. 3	Fridge 200 W	no. 1		
Productive (P) & Community 5.6 kWh/day	Water Pumping 200 W	no. 2	Water Purifying 150 W	no. 2		

Table 7: Suite of Electrical Appliances Modelled and Power Ratings Used.

The following figure shows the interplay between the various parameters used to build up the load profile incorporating: location-specific community size, local energy services and assumed temporal usage patterns for household, community, commercial and productive uses.

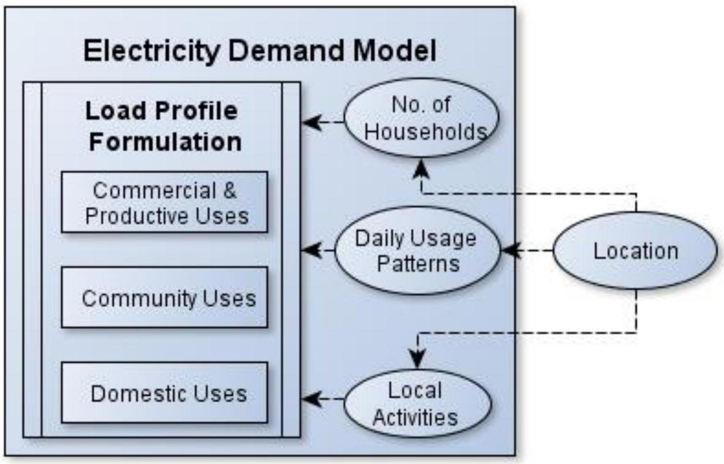

Figure 28: Load Profile Formulation Schematic

It is important to emphasise that, in keeping with the suite of electricity supply policy guidelines that are applicable to all licensed entities implementing the INEP on behalf of the DoE, energy services such as space heating, cooking and water heating are to be supplied by alternative energy carriers. These include Liquefied Petroleum Gas (LPG) and solar water heaters (SWH) [78], [80].

Certain assumptions have been made in the load profile modelling, as follows:

- The operating durations and duty cycles of each appliance are estimated for a typical day to formulate the hourly demand profiles and total daily energy demands
- Demand profile includes a significant midday peak in addition to the usual morning and evening peaks due to the inclusion of mostly daytime commercial and community uses. Water pumping and purifying is statically modelled to roughly follow the typical daily solar profile.
- The overall community electricity profile is dominated by domestic energy demands
- The profile is simply repeated 365 times over the year i.e. without any seasonal or daily variation.

Figure 29 shows the formulated community electricity demand profile, which will be served by the mini-grid being modelled, while the subsequent three figures illustrate the demands that contribute to this composite:

- *Figure 30:* Domestic Daily Demand Profile;
- *Figure 31:* Commercial Daily Demand Profile
- *Figure 32:* Community and Productive Use Demand Profile,

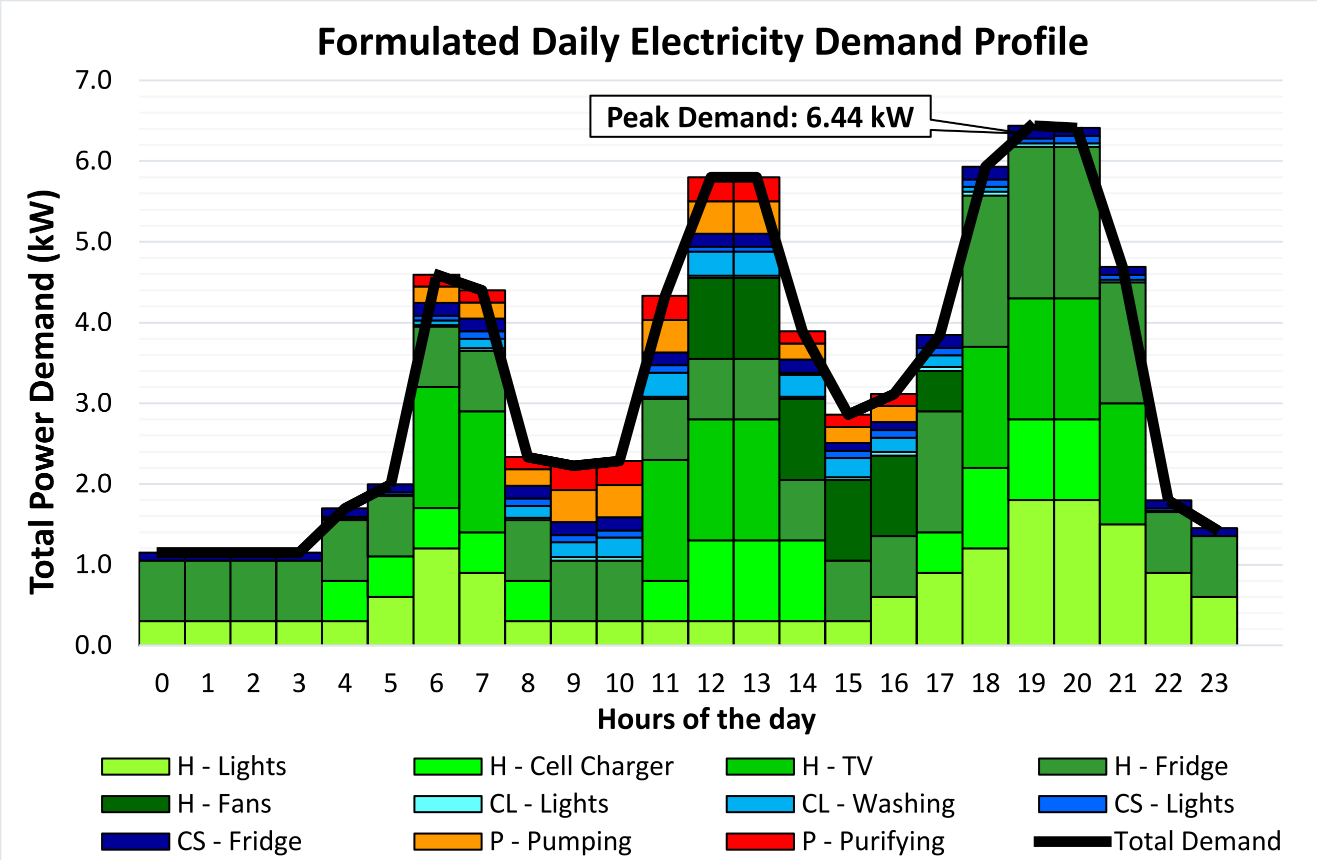

Figure 29: Formulated Composite Daily Demand Profile: of a hypothetical 100-household mini-grid

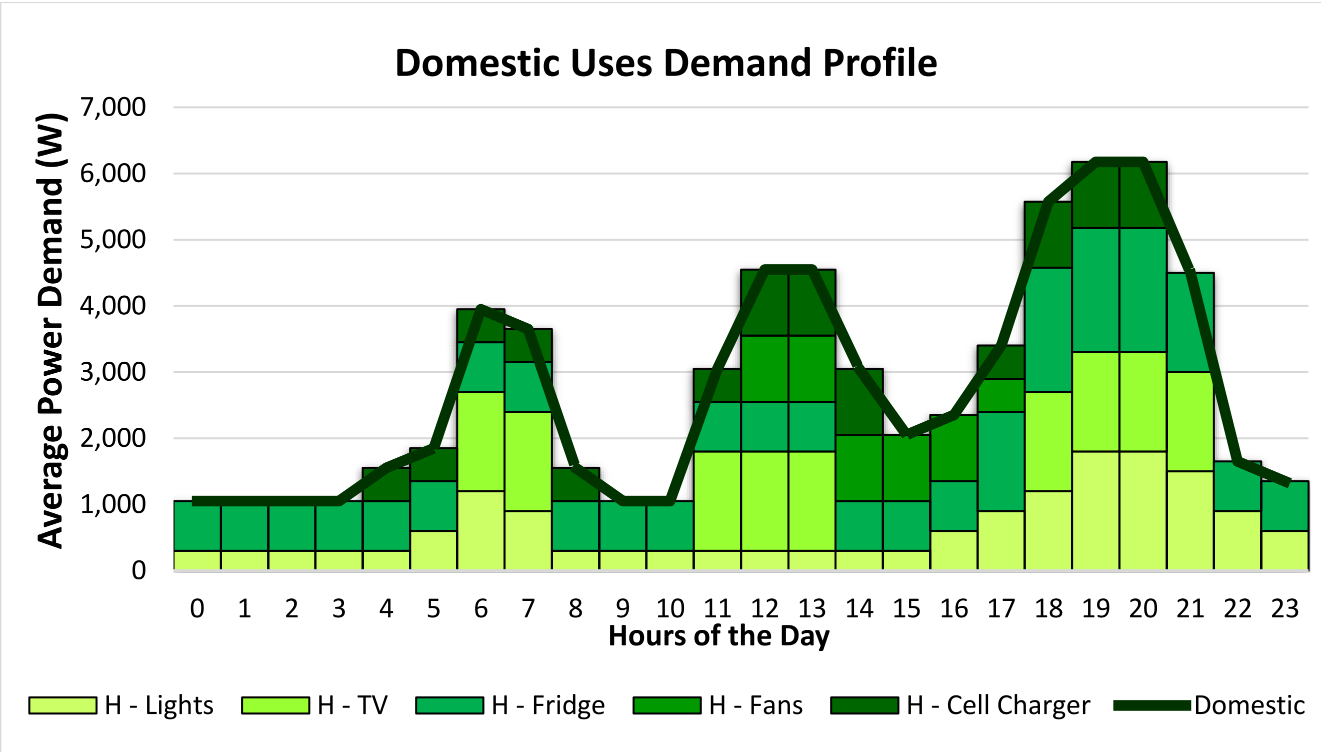

Figure 30: Domestic Daily Demand Profile: from the 100-households themselves.

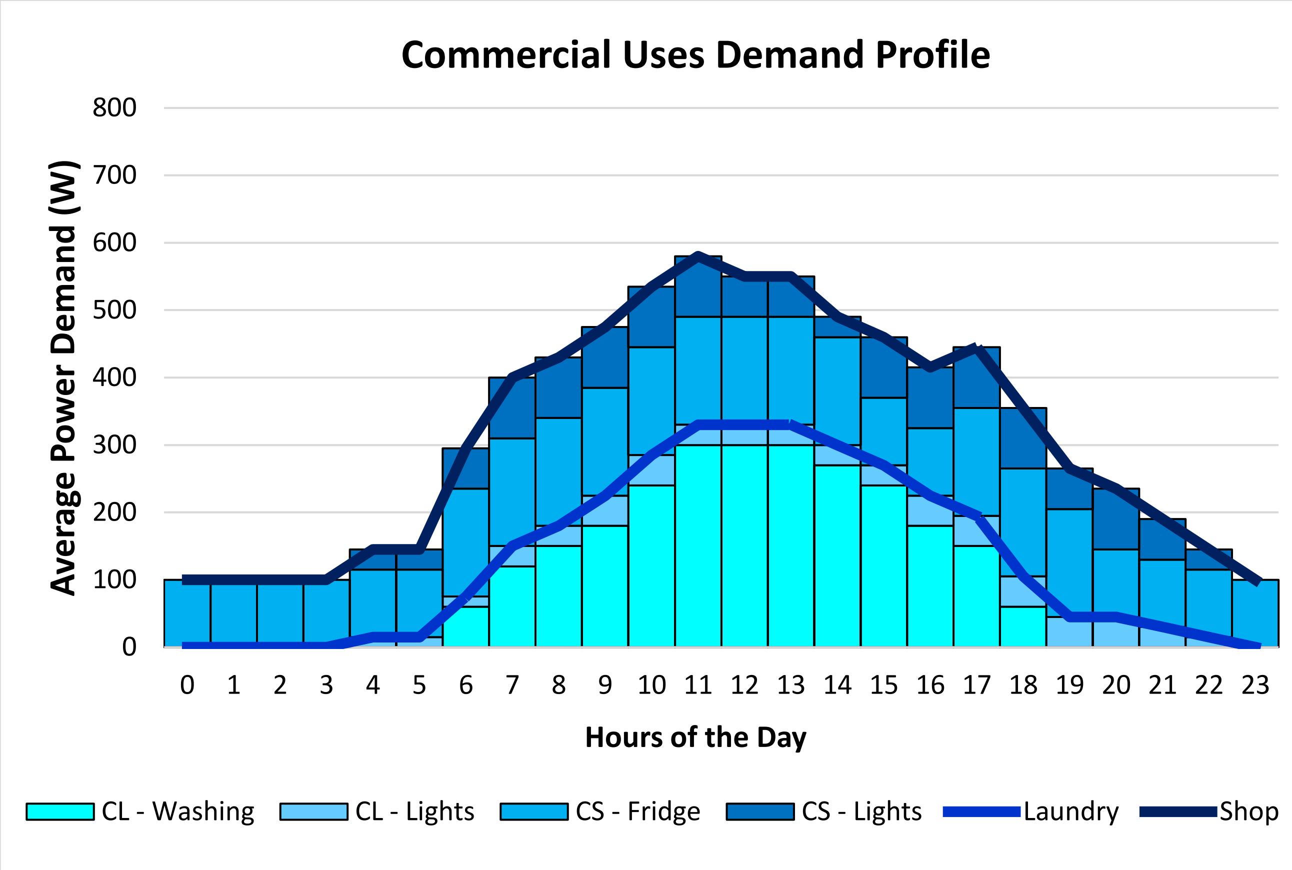

Figure 31: Commercial Daily Demand Profile: from a local shop and laundry. (Not to scale of the total profile)

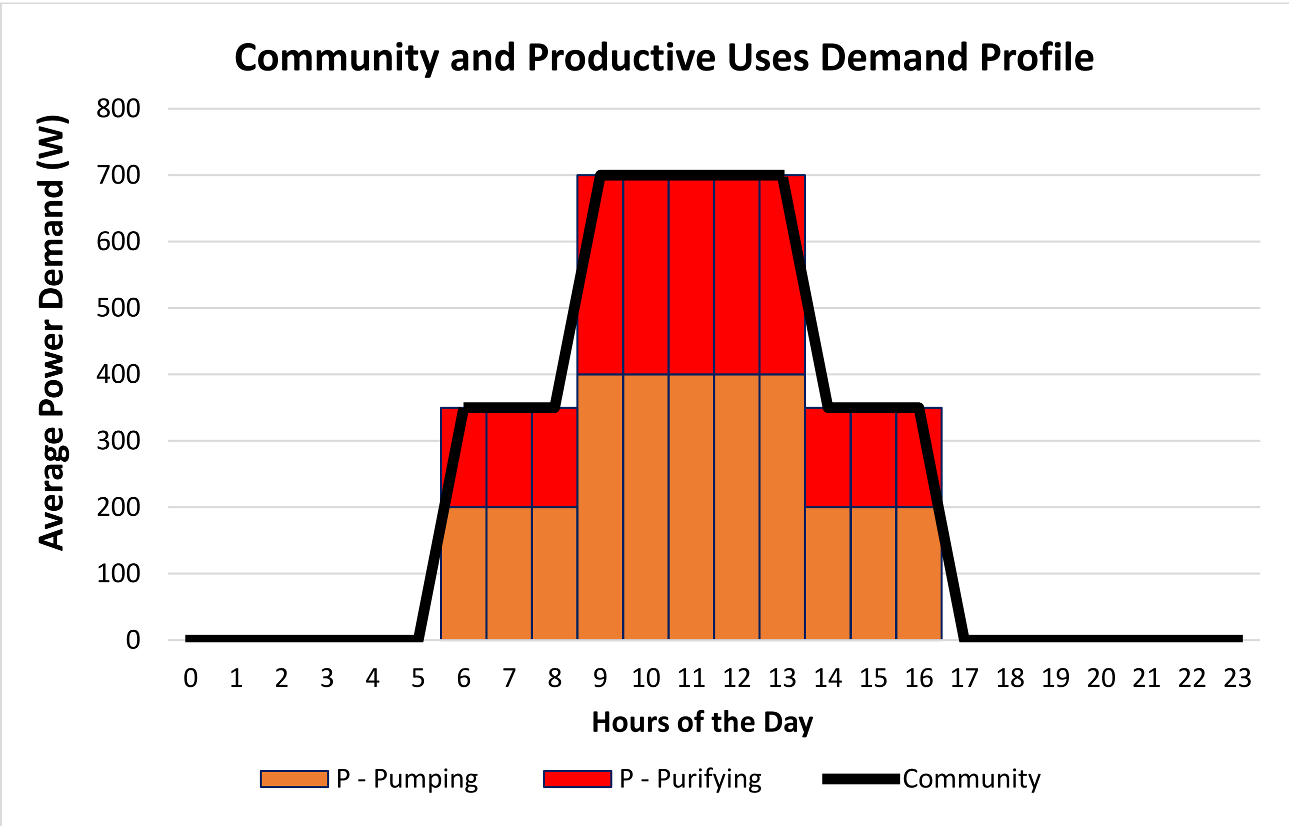

Figure 32: Community and Productive Use Demand Profile[23] (Same scale as the above commercial profile)

[23] Water pumping and purification are specifically run during the day to follow the typical daily solar generation profile.

5

RESULTS

"Essentially, all models are wrong, but some are useful"– George Box

5.1 RESULTS OF MODEL CASE STUDY APPLICATION IN SOUTH AFRICA

In this chapter, the results of the application of the techno-economic mini-grid modelling of the *15 representative mini-grid sites* are presented.

Shown in the results first, are the impacts of both *mini-grid hybridization* from the inclusion of multiple renewable technologies, as well as the progressively falling costs of these technologies going into the future. For each added energy technology, successive cost and diesel fuel use reductions are illustrated, with the resulting increase in renewable energy shares of the power supply sources. Furthermore, this trend is largely followed by the expected *future technology cost reductions* projected for solar, wind, battery and hydrogen.

At currently available hydrogen technology market costs, it is shown that combinations of PEM fuel cell and electrolyser technologies are currently not an economical energy source or storage medium at any of the 15 modelled sites across the un-electrified areas in South Africa.

PEM hydrogen technology is yet to be scaled up to high production quantities where economies of scale and technology learning can be achieved, making them significantly cheaper to manufacture [84], [95], [96]. Thus, the cost modelling objective was changed to estimate an approximate *hydrogen technology cost target curve* at which they would become an economically competitive energy storage choice in the hybrid systems. Future technology cost targets must be evaluated against the expected future costs of any of the other components available. Therefore, technology cost projections are evaluated at five-year price points to 2030.

The above modelling exercises will be demonstrated first in basic detail for an individual site. Thereafter, for simplicity, the specific results to be presented and discussed here will be limited to four sites representing a diverse overall coverage of South Africa's geographic renewable energy resource distributions. Summary results will be included incorporating the modelling results of all 15 hypothetical sites.

The sites will be referred to by their numbers, corresponding to the site selection numbers in Figure 5. The sites that are presented in more detail below are as follows, listed overleaf:

1. **Site 1: EC** Southern Coastal Extent of Un-electrified areas in the Eastern Cape
2. **Site 2: EC** Central Eastern Cape, North-Western extent of the un-electrified Eastern Cape
3. **Site 10: KZN** North Eastern Coastal tip of South Africa in Empangeni, Kwazulu-Natal
4. **Site 15: LMP** Northern Extent of un-electrified populations in Limpopo Province

5.2 BASIC MODEL RUN SIMULATION OUTPUTS

The figures below show example graphics of the mini-grid simulation timeseries and LCOE cost component decompositions. These are relating to a *hypothetical example system* including all modelled technologies. These plots are interactive, allowing zooming into desired sections, with panning and rescaling. They are available directly from within the Python code Jupyter notebook implementation, can be saved as images, or uploaded to the Plotly cloud and edited or shared from there.

5.2.1 Mini-Grid Timeseries and Hourly Energy Balance Visualisation

In Figure 33 below is a representative *example system* timeseries plot depicting the overall temporal operation of the mini-grid simulation. Included, are the wind and solar generation, complemented by battery storage, with the inclusion of hydrogen fuel cells and electrolysers. Shown are 3 days of hourly averaged mini-grid power levels from renewable generation feed in, storage charging and discharging and the hourly demand to be met.

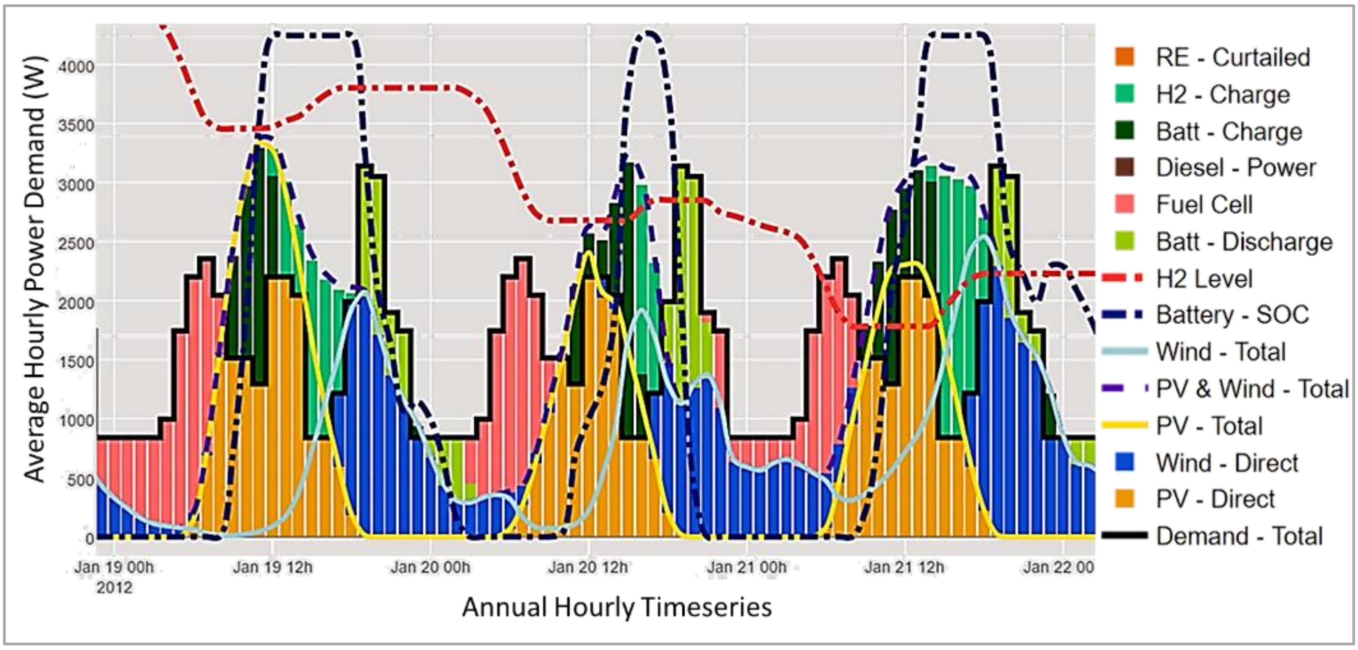

Figure 33: Mini-Grid simulation timeseries covering 3 days from 19th Jan to 22nd Jan. What can be seen are the respective profiles of the generation and storage meeting the demand and energy balance requirements (Example).

From midnight of 19th Jan, the demand (black line), including most of the early morning peak before sunrise, is met using the hydrogen fuel cell (pink bars) with some direct wind generation feed in (blue bars) while the batteries were empty – the state of charge is shown for hydrogen (dotted red) and batteries (dotted blue) respectively.

During the next day, the solar generation (yellow bars) meets all the daytime demand and can fully charge the batteries with the excess. The batteries reach 100% state of charge at noon with the wind turbines starting to generate as well - here the electrolyser is run to convert and store the combination of excess solar and wind energy as high purity H2 in the compressed storage cylinders.

Most of the evening peak and night time load are met with direct wind generation, supplemented with the available battery storage (light green bars). At 3am the battery is depleted again with the similar next two days of operation starting again with the hydrogen fuel cell meeting the morning peak.

This example exhibits a relatively stable daily energy balancing cycle between the hybrid technologies. The renewable energy daily generation profiles are shown, with daily solar feed in and wind generation peaking from midday to evening, the daily complete battery charging and discharging cycle, and the hydrogen providing a short term stepped daily contribution as well as a roughly week long multi-day storage capability.

5.2.2 Example Data Visualisation Plots

Figure 34 below shows several data visualisation outputs available from the developed mini-grid model. These figures are accessible from within the Jupyter notebook and assist in understanding the data itself (exploratory visualisation) and can also be used to share results to other stakeholders (explanatory visualisation). Shown for Site 1 in the Eastern Cape are annual timeseries for the optimal energy mix, the hourly operation of the mini-grid, and the levelized cost components. At the bottom are the daily resource distributions of the solar and wind resources.

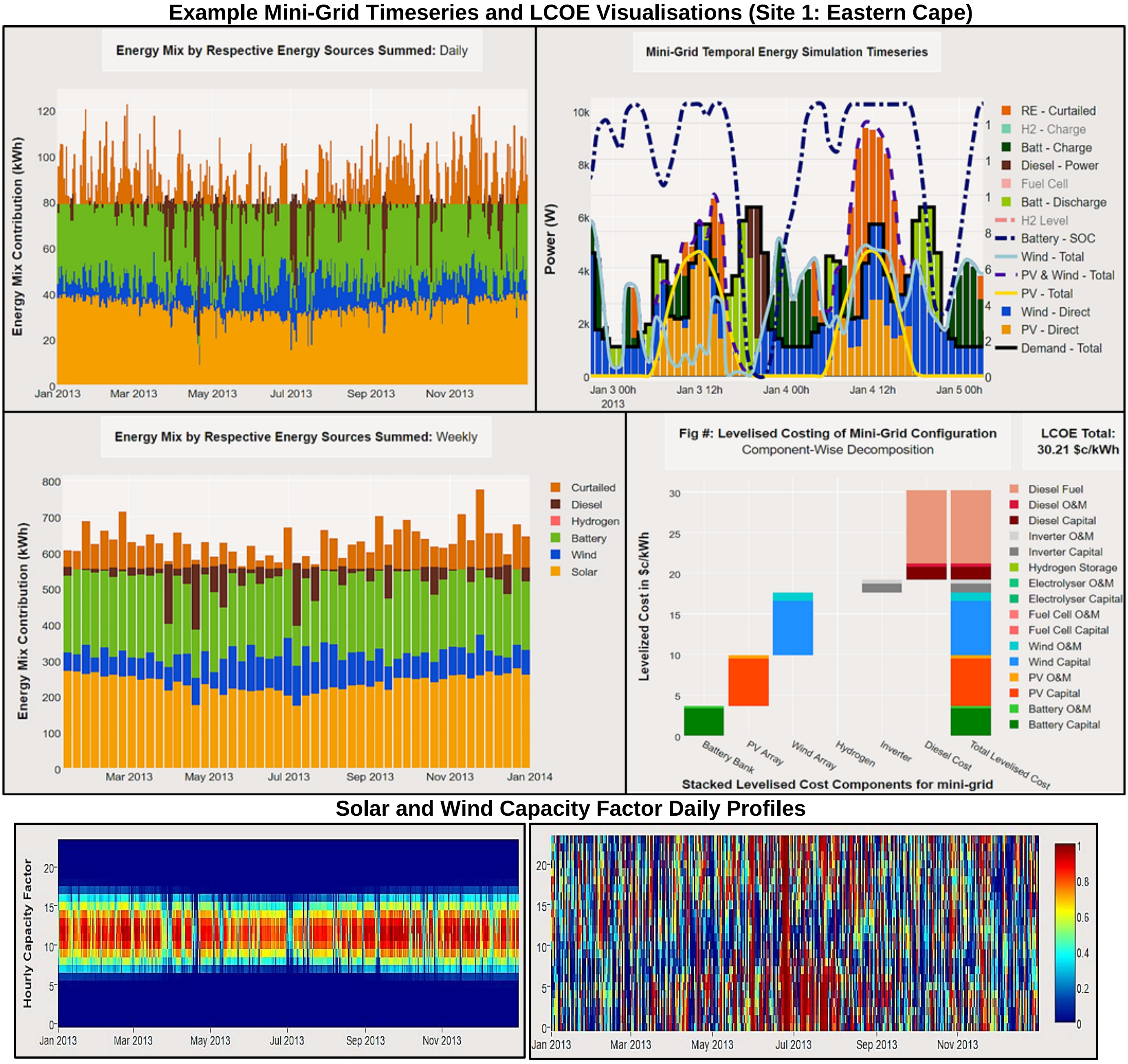

Figure 34: Example Data Visualisation Outputs available from within the implemented Jupyter Notebook. The top left two plots show the variations in the energy mix provisions at a daily and weekly resolution over the year. The top right show the mini-grid's dynamic operations timeseries as above, and the bottom two plots show the daily profiles (vertical direction) of the solar and wind power capacity factors over the year (horizontal axis)

5.3 Effects of Technology Hybridization and Cost Reductions to 2030

The justifications for using multiple complimentary hybrid technologies in mini-grids as well as the expected reduction in system prices with technology learning are demonstrated below. By allowing the use of multiple complementary technologies, significant cost reductions are realized through the inclusion of higher renewable energy shares. The technology combinations scenarios modelled are defined below:

- **D:** Diesel Only
- **S+D:** Solar and Diesel
- **B+S+D:** Battery, Solar, and Diesel
- **W+B+S+D:** Wind, Battery, Solar, and Diesel
- **W+B+S+D+H2:** Wind, Battery, Solar, and Diesel as well as Hydrogen Storage Technology Options

Shown below in Figure 35 are the successive effects of adding additional technology options to the system in the left half of the figure, and the estimated effects of technology learning up to 2030 on the right half of the figure. Shown for each combination; are the system LCOE, energy mix contribution percentages, total curtailed energy and the percentage of renewable energy in the energy mix.

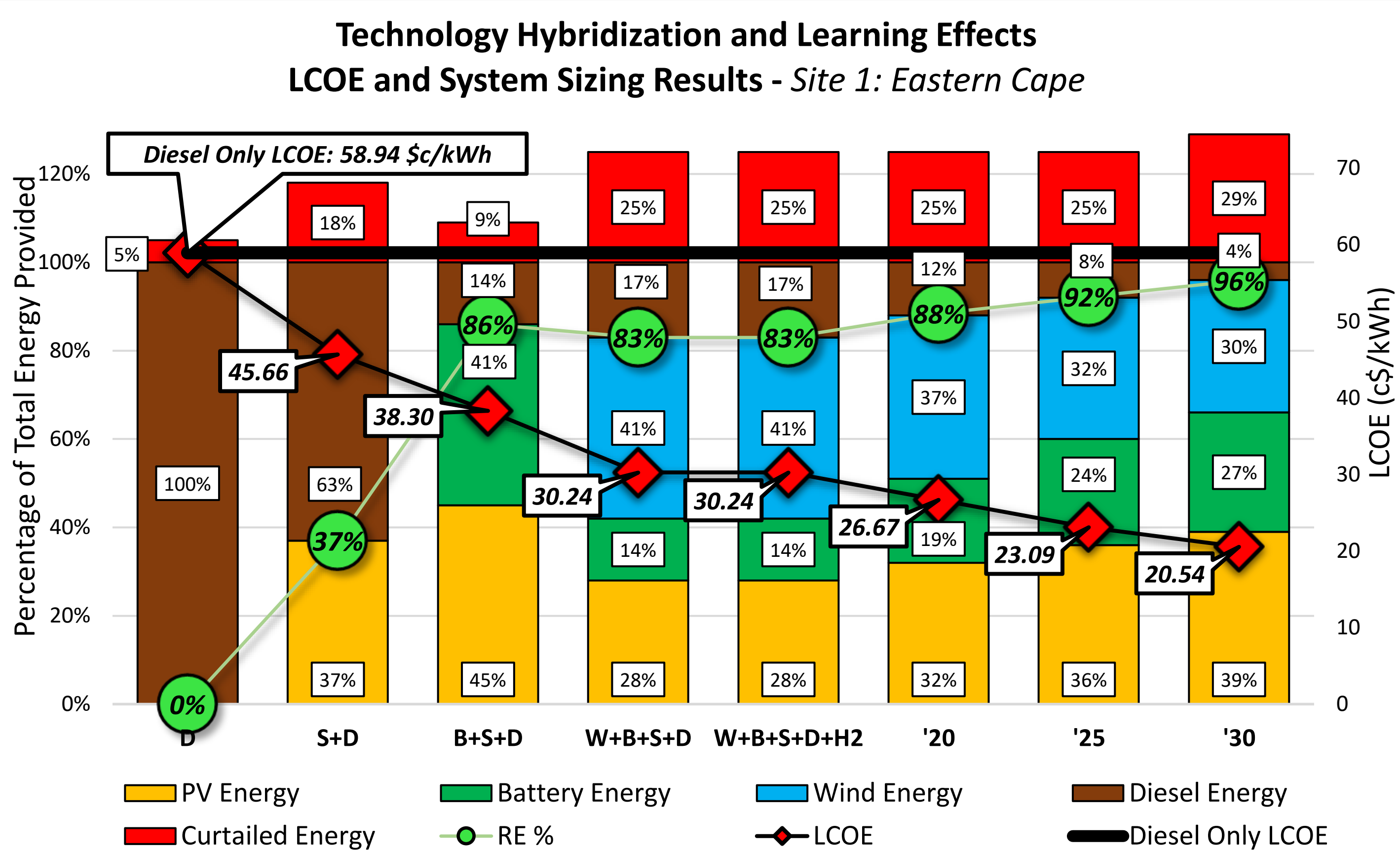

Figure 35: Effects of Technology Hybridization on System Cost, Energy Mix and RE shares. The 5% curtailed energy in the diesel only case is due to the generator having a minimum allowable load factor of 25%.

Critical *technology hybridization results* demonstrated in the figure above for Site 1 in the Eastern Cape are:

- Reduction in the energy cost at this location by roughly **50%** from **USD 58.94 c/kWh** for the diesel only case, down to **USD 30.24 $c/kWh** with the inclusion of all hybrid technology choices.
- Renewable energy shares economically included in the system increase first from **0% to 37%** with the inclusion of solar, **up to 86%** with the inclusion of batteries, and (in this case) a slight *decrease* to **83%** with the inclusion of wind. (The combination of wind and solar resources for this site economically justified wind backed up with diesel to address intermittency rather more batteries)
- The amount of **curtailed energy *increases* to 25%** in these cases, as the combinations of solar and wind which reduce the most diesel usage also cause significant excess energy at other low demand times.
- The inclusion of **hydrogen fuel cell** and **electrolyser** technologies at **present day costs is not an economic storage option**. The optimizer chooses the exact same system configuration as without H_2.

Primary results of technology *cost reduction projections to 2030*:

- Using the technology cost projections as described above, the LCOE is estimated to **drop by roughly one third**, from **USD 30.24c /kWh in 2015** to **USD 20.54c /kWh in 2030**.
- The relative energy mix of each year's optimal system configuration evolves to progressively **include more solar energy and less wind energy**, explained by the differences in their respective learning rates
- The amount of energy that is provided to **the load via the batteries doubles**, due to the expected cost reductions of li-Ion batteries.
- The amount of diesel needed is also reduced, allowing the **renewable energy share** of the system to **increase from 83% in 2015 to 96% in 2030.**

Following on from the example above, the evolution of the LCOE and optimal combination of energy sources due to technology cost reductions are demonstrated from 2015 to 2030 for sites 1,2, 10 and 15 in Figure 36. Circled in Red is the lowest **renewable energy share** of all sites modelled for **Site 10 in 2015 at 77%,** and the highest share **for Site 15 in 2030 at 98%.**

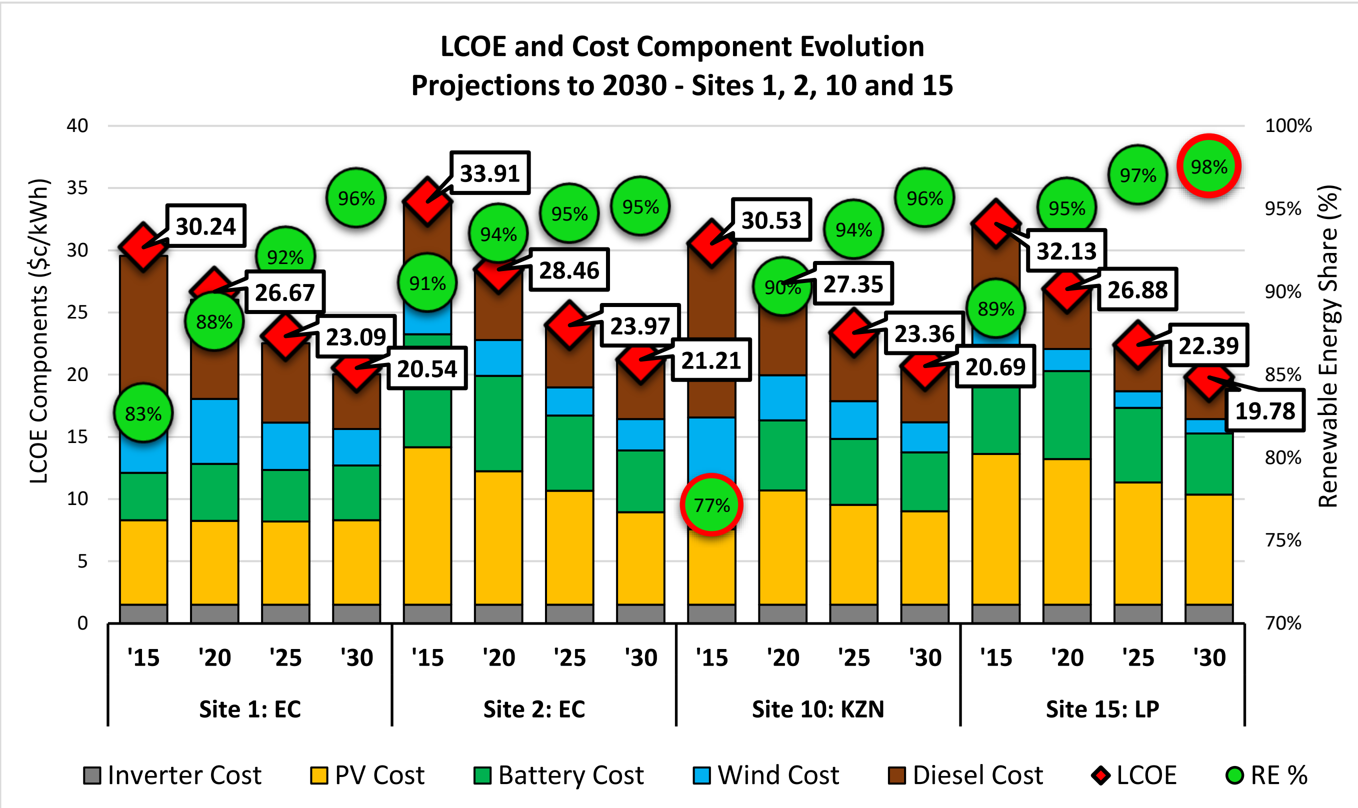

Figure 36: Levelized Cost and Renewable Energy Share for Sites 1, 2 10 and 15 from 2015 to 2030. Circled in Red is the lowest renewable energy share of all sites modelled for Site 10 in 2015 at 77%, and the highest share for Site 15 in 2030 at 95%.

5.4 Hydrogen Technology Cost Targeting

Using currently available technology costs for the included hydrogen technologies, the system optimization does not select any hydrogen technologies as an economic contribution to the system. However, significant cost reductions for PEM hydrogen technologies are possible through the scaling up of their production [84], [95], [96]. Therefore, to determine at what cost the hydrogen technologies would become an economic choice for inclusion in the system configuration, the modelling below is carried out to determine a cost target economic breakeven curve from 2015 to 2030 for both PEM fuel cells and electrolysers.

Hydrogen storage is considered to reach economic breakeven if either 20% of the energy is cycled and served through the hydrogen system, or a minimum of a 2.5kW Fuel cell is installed in the optimal system configuration.

Two scenarios are presented. Firstly, a base case where the system is unconstrained to determine the most economic system based on any combination of technologies and its resulting energy mix. Secondly, a scenario is included to potentially increase the value that hydrogen storage may give to the system, by requiring the mini-grid to provide at least 98% of its energy through renewable resources.

5.4.1 Unconstrained Baseline System Optimization

Leading up from the discussion in this chapter, the results of the hydrogen technology cost targeting are presented here, shown in Figure 37 below. The unconstrained base case is run with the following specifics:

- All available technologies are available for selection in the sizing optimization.
- Diesel is included and has no constraints on usage to meet otherwise unserved load most economically.
- 100% of energy is served by the system, either through renewables or diesel backup.

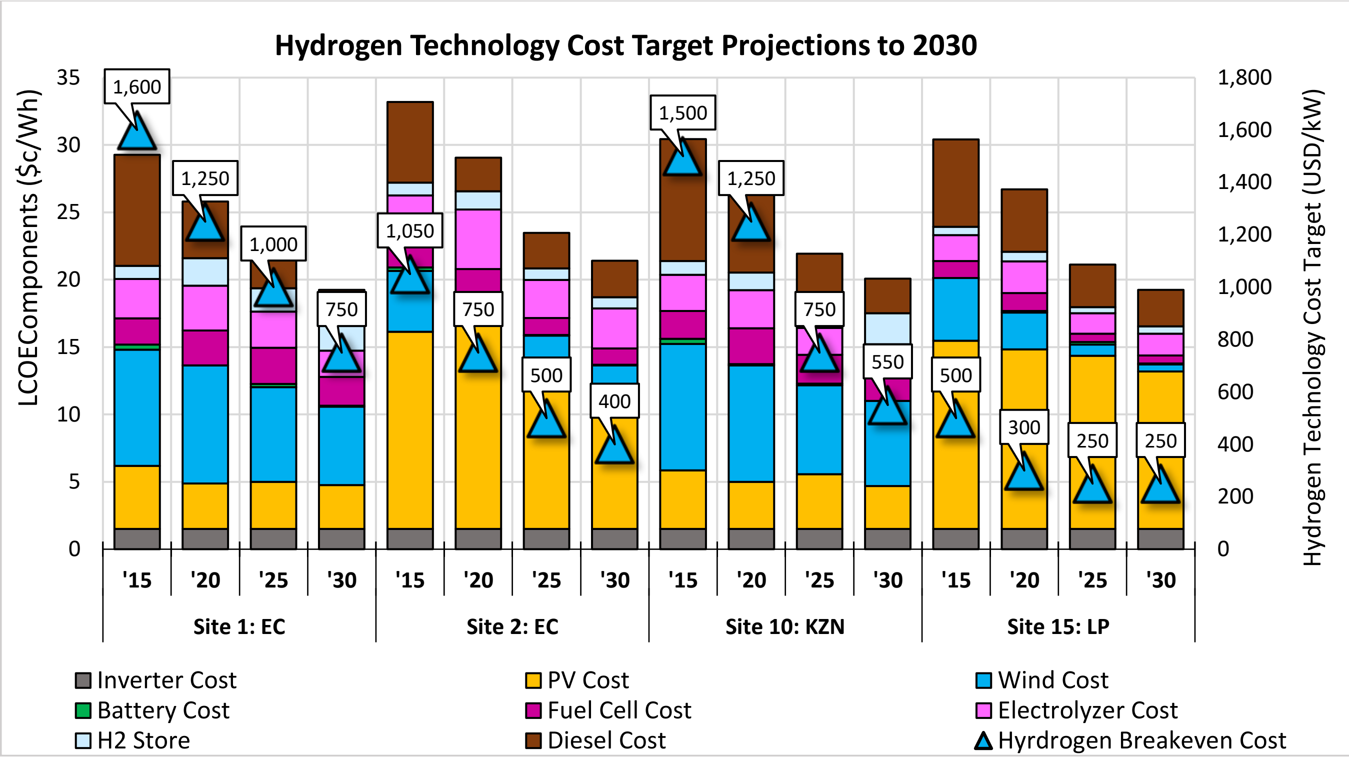

Figure 37: Hydrogen Cost Target Points to 2030 for Sites 1, 2, 10 and 15

Figure 37 above demonstrates the significantly different price points between sites at which hydrogen technologies become an economic technology choice. The areas here with the most favourable conditions are sites 1 and 10, lying on the coast of the Eastern Cape and Northern Kwazulu-Natal. The least favourable sites, are those further north and west into South Africa, which have both more consistent, and higher overall amounts of sunshine, with generally lower wind resources – site 15 largely represents this trend. Site 2 includes similar energy shares of solar and wind resources to that of site 15, however having a more seasonal and intermittent solar resource in the Eastern Cape, it supports hydrogen technologies at a higher price point.

5.4.2 98-100% Renewable Energy Share Requirement Scenario

Meeting the final percentages of system load with only renewable energy can significantly increase the sizing requirements of the system, and hence the cost of energy. This is due to the system needing to be sized for the absolute worst case renewable energy collection period in the year, usually needing both significant storage capacity, while still often curtailing energy due to the need to oversize the system for this expected worst case. In this scenario, the system is constrained to be forced to be sized large enough **to be able to meet 98% of its energy demands using renewable energy sources only**.

For this 98-100% Renewable case: The remaining 2% of load could be served by an included backup diesel generator, constrained only to be allowed to meet the exceptional cases of low combined renewable energy availability. It would also be possible to exclude the diesel generator from the system, but **relax the system requirements to allow 2% of the energy to remain unserved. This could then be considered a system supplying 100% of its energy from local renewable sources.**

Including this constraint can be justified for multiple reasons, among others, as listed below:

1. Energy autonomy, avoidance of fuel price volatility and protection from fuel supply disruptions
2. Avoidance of additional logistics, security, safety and spillage risks of diesel fuel
3. Elimination of local emissions and noise from diesel generators
4. Strategic or political commitment to 100% renewable energy resources

The same cost target determination modelling exercise is carried out as above, with this additional constraint for the 98% renewable energy case, and is shown below in Figure 38 in comparison to the unconstrained case.

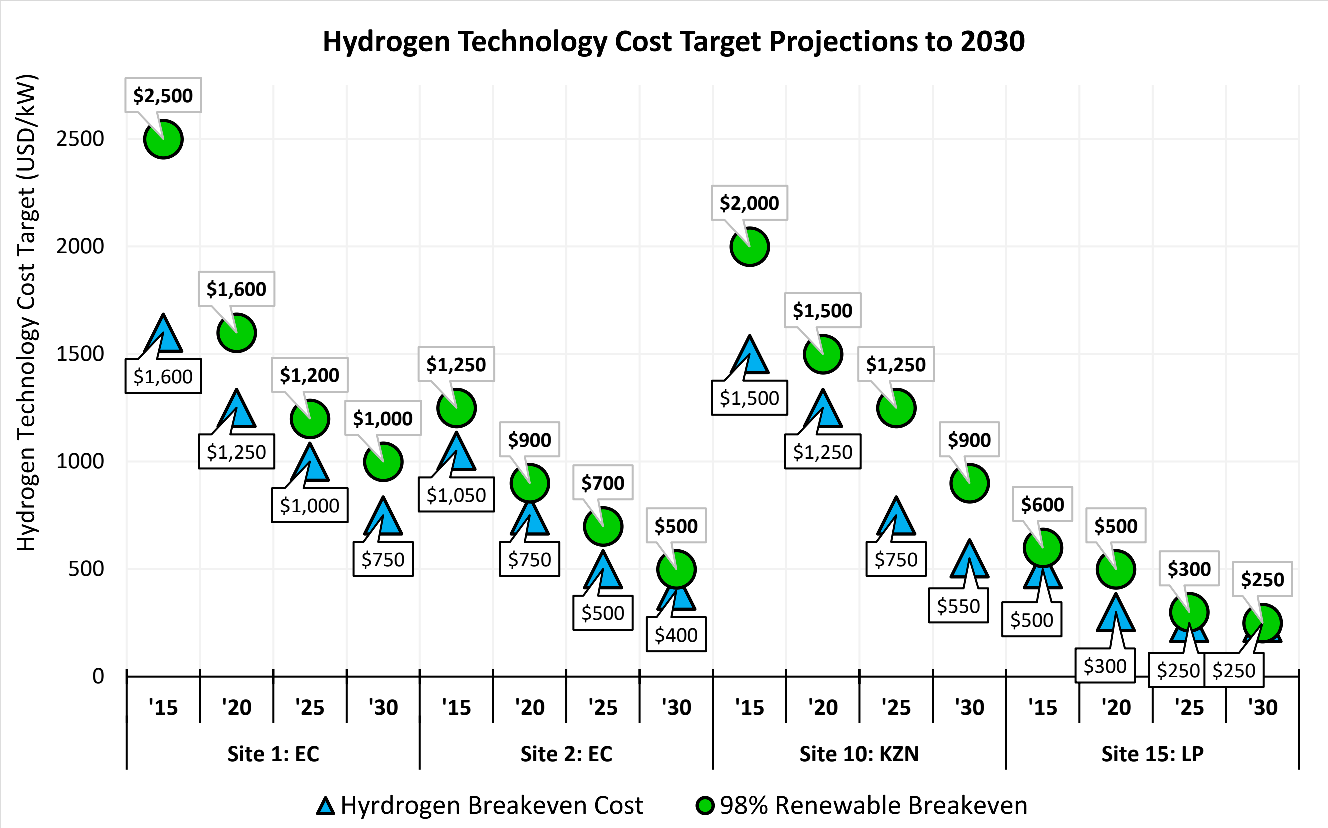

Figure 38: Hydrogen Technology Cost Targets Compared with 98% Renewable Energy System Constraint.

In the above, the effect of the 98% renewable energy requirement can be seen in contrast to the previous results as the economic breakeven cost targets are raised across the board. The difference between the two cost target curves can be seen to start relatively large, but the difference narrows for systems built later in time, reducing the competitive advantage of hydrogen storage. This is due to the future cost reductions of solar, wind and batteries causing the system to progressively choose very high renewable energy shares as the more economic choice, regardless of system constraints.

5.5 SUMMARY TABLE OF ALL 15 SITES RESULTS FOR 2015 AND 2030

Shown in the table below are the results of all 15 sites, for the end case years of 2015 and 2030. Shown are the optimal LCOEs, relative energy mixes and hydrogen technology cost targets for the base case and 98% renewable energy case. Minimum, maximum and mean values for each metric are also given for each year. The intermediate years of 2020 and 2025 are excluded here for the sake of brevity.

Table 8: Summary Table of Modelling Results from all 15 Sites Across South Africa

Site No.	Year	LCOE (\$c/kWh)	RE Share (%)	Solar (%)	Wind (%)	Battery (%)	Diesel (%)	Curtailed (%)	H_2 Target (\$/kW)	H_2 98 RE Target (\$/kW)
1.	'15	30.24	83	28	41	14	17	25	1,600	2,500
	'30	20.54	96	39	30	27	4	29	750	1,000
2.	'15	33.91	91	41	14	37	8	11	1,050	1,250
	'30	21.21	95	40	16	39	5	17	400	500
3.	'15	29.58	79	22	45	14	19	28	1,750	2,125
	'30	20.35	96	34	35	27	4	30	1,000	1,000
4.	'15	30.28	86	39	23	26	12	15	1,150	1,500
	'30	19.70	95	42	19	35	4	19	600	600
5.	'15	33.72	86	40	21	28	11	15	950	950
	'30	21.47	95	43	13	39	5	15	250	250
6.	'15	29.71	85	38	29	20	13	19	1,300	950
	'30	19.33	98	44	14	40	2	13	250	<250
7.	'15	33.34	84	37	25	25	13	16	950	600
	'30	21.27	96	41	18	37	4	18	<250	250
8.	'15	32.98	85	41	17	29	13	12	950	950
	'30	20.99	96	45	12	40	3	18	450	525
9.	'15	28.01	87	37	32	19	12	19	950	1,300
	'30	18.61	97	42	24	31	3	19	250	600
10.	'15	30.53	86	33	17	21	11	8	1,500	2,000
	'30	20.69	97	37	8	34	2	9	550	900
11.	'15	34.42	77	45	8	41	6	7	600	600
	'30	21.07	96	46	7	44	3	10	250	250
12.	'15	33.73	93	47	0	49	4	7	600	600
	'30	20.36	97	47	0	51	2	11	<250	250
13.	'15	33.66	94	46	1	48	5	5	600	600
	'30	20.29	97	47	0	51	2	10	<250	<250
14.	'15	33.89	95	38	0	40	4	5	950	600
	'30	19.81	97	43	17	38	2	16	<250	<250
15.	'15	32.13	89	40	22	24	14	13	500	500
	'30	19.78	98	45	11	41	3	11	250	250
Min	'15	S9: 28.01	77	22	0	14	4	5	500	500
	'30	S9: 18.61	95	30	0	27	2	9	<250	<250
Max	'15	S12: 34.42	95	47	45	49	19	28	1,750	2,500
	'30	S5: 21.47	98	47	35	51	5	30	1,000	1,000
Mean	'15	32.01	87	38	20	29	11	14	1,027	1,135
	'30	20.36	96	42	15	38	3	16	455	531
Std Dev.	'15	2.00	5	6	13	11	4	7	367	617
	'30	0.78	1	5	9	7	1	6	239	286

6

CONCLUSIONS AND FUTURE WORK

"The purpose of computing is insight, not numbers" – Richard Hamming

6.1 CONCLUSION

Renewable energy based hybrid technology mini-grids present one of the most promising options for rural electrification throughout Sub-Saharan Africa. However, for off-grid renewable mini-grid electrification to be successful in addressing the UN Sustainable Development Goals and Sustainable Energy for All initiative, committed to by the global community, many questions will still need to be answered in an ever-changing technological, economic, social, and political landscape.

However, determining the appropriate situational applicability of hybrid technology mini-grids is non-trivial, and requires a comprehensive modelling framework to adequately address this challenge. Presented in this research is an attempt to explore this challenge, provide a model designed to be fully flexible in its application to this problem, and to demonstrate the application of the developed model implementation in a particular case study.

Every mini-grid implementation has its own unique context, and to determine if a mini-grid is the most economically optimal solution in comparison to grid extension or individual solar home systems, a host of complex interacting variables must be appropriately accounted for throughout the modelling exercise.

Firstly, the choices of selection, configuration, and component sizing of energy technologies, which are expected to supply the lowest overall cost of energy need to be addressed. The hybridization of multiple complementary technologies is shown to give significant cost benefits, while allowing the economic inclusion of higher shares of renewable energy in the system. However, each added technology option adds additional sizing decision variables and technology characteristic interactions. This challenge is further amplified with the inclusion of the continually evolving costs and performance capabilities of technologies, and the inherently uncertain task of estimating likely projections of their future values.

This mini-grid configuration selection task must also be undertaken within the context of locally influencing variables on the ground at the intended mini-grid site, as well as the wider social and political context in which the project would be implemented. Primary variables on the ground include: the expected overall community electricity requirements and their varying demand profiles, the overall availability and local climactic characteristics of available renewable energy resources, the distance and terrain over which grid extension costing would need to be determined. Also relevant are national electricity infrastructure expansion plans, locally applicable subsidies/taxes, as well as the unknown total rates of usage uptake and behavior, or social perceptions and acceptability of new technologies.

The ultimate goal of undertaking a modelling exercise to discover valuable insights for the specific applicability of this opportunity, would be to provide credible and transparent input into the creation of politically actionable and economically optimal national electrification policy and deployment plans, and to provide guidance for further industry or academic research focus. If the modelling results are to successfully bridge the "science-policy boundary", the technical implementation of the model itself needs to exhibit several important characteristics.

To achieve this, it is essential that the results are firstly reproducible, including public access to input data, assumptions, and modelling softwares. Their technical implementations themselves also need to be open and transparent, which includes ensuring their simplicity wherever possible, to remain intelligible to non-subject matter experts, and allowing on-going peer review or collaboration within the scientific community. Furthermore, if the developed technical model implementation is itself to remain relevant and useful in answering ever-changing and yet unknown research questions, it needs to be flexible, customizable and computationally scalable if one is to require the inclusion of new variables, increase the modelling resolution, or apply it to very large datasets, without requiring a full model redesign or complex reintegration of different parts of the model.

In accordance with these model design philosophies, presented in this research is a model designed to be fully flexible in its application by aiming to be reproducible, transparent, simple, customizable, and computationally scalable. It is programmed as modular code blocks in Python, using Jupyter Notebooks and will be released as an open source collaborative project. All input data and used software in the model are free and available in the public domain. Finally, the meta-heuristic and population based Particle Swarm Optimization algorithm used for component configuration and sizing optimization exhibits the capability to be fully computationally scalable using parallel processing techniques, applied to highly non-linear objective functions, and can be easily modified to perform multi-objective optimization.

To demonstrate the functionality of the developed model's implementation, a case study is undertaken using the model to investigate mini-grids within the South African context using a sample of 15 representative sites covering the spatial extents of unelectrified rural areas. Described here, are the full set of modelling assumptions and data inputs used in the application, relating to the overall system design, formulated 100-household representative community demand profile, component performance and cost projections, and the details of the meteorological data used to simulate the local performance of solar PV and wind generation technologies.

The results of the application of the techno-economic mini-grid modelling of the 15 sites are presented and explained. Demonstrated in the results are the cost and renewable energy penetration rate improvements gained by technology hybridization, these trends are shown to continue to 2030 with technology learning. As energy storage using hydrogen fuel cells and electrolysers is found to be uneconomical at current market prices a hydrogen technology future cost target curve is determined for each of the sites going to 2030. The results also demonstrate the overall differing system technology configurations and changing value provided by hydrogen as a storage choice in the different renewable energy resource contexts across South Africa.

Through continued modelling exercises and collaboration with diverse rural electrification, mini-grid development, and research stakeholders, it is hoped that valuable insight can be learned and shared to effect positive change, and accelerate the implementation of politically actionable and economically optimal electrification pathways, while providing direction for future research areas.

6.2 FUTURE WORK

The research and model presented here are essentially defined surrounding the intention of ongoing future work. It is also emphasized that many yet unknown research questions will still need to be answered in an ever-changing technological, economic, social, and political landscape. As mentioned in the scope definition in Chapter 1, it is impossible to include every aspect, variable, or topic within the practical limitations of a master's dissertation. Several primary areas identified for future research focus are briefly described below:

System Configurations/Alternatives modelling:

- Inclusion of micro-hydro or biomass gasification, biodiesel etc. for local renewable generation options
- Full community energization and potential energy system integrations, not only electricity
    - Thermal uses, water, biogas, hydrogen CHP
- Main Grid Extension Costing, Interconnection, and Parallel operation
    - Grid expansion costing details and local distribution grid layout planning/costing
    - Inclusion of grid electricity as parallel supply option and Stochastic inclusion of grid un-reliability
- Additional Technical Component Modelling Details Inclusion
    - Battery, fuel cell and electrolyser characteristic curves for different load factor efficiencies
    - Spinning reserves requirements with higher temporal resolution
- Demand Side Management, Smart-Grids & Energy Efficiency
    - Load prioritization, classification and selective control
    - Model Predictive Control (MPC) energy management and operational strategies including resource uncertainty and prediction with DSM
- Integration with Other Related models:
    - Advanced localized demand modelling and load growth scenarios
    - Geographic spatial analysis with large GIS data sets

Sensitivity Analysis and Robustness of Optimal Configuration to Uncertainty:

- Various future technology cost and performance evolution scenarios
- Including disruptive technologies or alternatives. Flow, lithium air etc.
- Local demand growth scenarios
- Extreme Weather/Resource Variability Scenarios

Improvements and capability expansion of the model software implementation:

- Model Front-End & Open source access/Collaboration
    - Open source code access, management, documentation and version control (eg. Github)
    - Graphical user-friendly interface or commercial readiness/capability of model beyond code
- Highly optimized computational efficiency & parallel programming.
    - Parallel Programming of PSO
    - Cluster Applications, Multi-core processors, graphics card implementation (GPU)
    - Increased Temporal Resolution of simulation and spatial resolution and extent of mapping
- Multi Objective Optimization
    - Pareto front tradeoffs for all variables using population based PSO algorithm
    - Capital cost vs operational cost vs emissions vs maintenance requirements
    - Energy benefit of services (different weighting to clinics, schools, community, productive etc)

Social and Policy:

- Opportunity cost of non-electrification and rural market building
- Local employment, social acceptance, user inclusive design.
- Environmental Impacts: Carbon, NOx & PM emissions, battery and hydrogen safety. Fuel spills.
- Health Benefits: Energy provision enabling better healthcare services.
- Education: access to lights and ICT, teachers
- Electricity & equipment theft
- Energy Subsidies & Smart grid energy service targeted subsidies

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