TEMPO – Techno-Economic Minigrid Planning and Optimization: A flexible open-source model applied for rural electrification in South Africa using hybrid mini-grids including hydrogen storage.

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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, approximately 1 billion people are living without access to electricity, with over 55% living in Sub-Saharan Africa (IEA, 2017). Furthermore, 85% live in rural areas, often with challenging terrain, low income and demand density; or in countries with severely limited electricity infrastructure, making grid extension unrealistic. Recent advances have made hybrid mini-grids combining several energy technologies into standalone electricity systems one of the most promising alternatives for electrification. It is estimated that up to 350,000 new mini-grids would be needed to reach universal access goals by 2030.

To evaluate hybrid renewable mini-grids among alternatives such as grid extension or stand-alone systems, a comprehensive, transparent, and flexible modelling framework is needed to determine the optimal electrification alternatives. Given the intermittent and location-dependent nature of renewable energy sources, the evolving costs and performance characteristics of relevant technologies, and the characteristics of technology interaction, detailed system simulation and demand modelling is required to determine the cost optimal combinations of technologies for each 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.

This framework, and through its computational implementation, attempts to explore and address three central issues:

1. The fundamentally unique and changing contexts surrounding every specific mini-grid,
2. The basic technology selection, component sizing, and costing problem,
3. The lack of transparency and flexibility of models aimed at bridging the *science-policy boundary*.

TEMPO - The Techno-Economic Mini-Grid Planning and Optimization 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 using a Particle Swarm Optimization (PSO) algorithm. 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* programming language coded into an interactive computing environment called a *Jupyter Notebook* are briefly described. TEMPO has been released open-source and is available under the MIT license[1].

The model was applied for the investigation of 15 hypothetical mini-grids sites[2] covering the spatial extent of un-electrified populations of South Africa and to validate and demonstrate the model's capabilities as a proof-of-concept. The effect of technology hybridization and future technology cost reductions on the expected cost of energy and the optimal technology configurations are demonstrated. The project included firstly the mapping of unelectrified households in South Africa furthest from the grid with the best potential for off-grid electrification. The project also included investigating the economic viability of hydrogen fuel cells and electrolysers as an energy storage medium for longer term storage. The modelling results showed that hydrogen storage was not an economical option with present day technology costs and performance. The model was then used to determine an approximate fuel cell and electrolyser break-even cost targets for each site every 5 years to 2030.

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 to this freely available and open source model 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.

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[1] Available at Github Repository: https://github.com/GregoryIreland/mini-grid-model

[2] Commissioned by the South African Department of Science and Technology (DST) and the South African National Energy Development Institute (SANEDI). Project report available at: bit.ly/ERC-DST-Mini-Grids-Report

1 INTRODUCTION

1.1 THE ELECTRICITY ACCESS CRISIS IN SUB-SAHARAN AFRICA

It is estimated that 1 billion people or roughly 15% of the global population, do not have any access to electricity (SE4ALL, 2017), with a further 1 billion with access only to highly unreliable, poor quality, illegal, or potentially dangerous supplies (UNDP, 2016). Access to clean, modern energy services is an essential requirement for sustainable development, and is underwritten by the United Nations Sustainable Development Goals (SDGs) and Sustainable Energy for All (SE4ALL) program (UNDP, 2017). Although difficult to measure, the potential direct and indirect positive impacts of clean rural electrification are numerous including: access to education, health care and refrigeration, clean drinking water, street lighting, communications technologies, mobile banking, and local productive and commercial uses of electricity (Cecelski & Glatt, 1982). By doing so using renewable energy technologies, this can be made possible without local or global pollution and environmental damage (ARE, 2017).

Of those without access, about 80% are in rural areas, with 55% of the total in Sub-Saharan Africa alone (REN21, 2015). In Africa the average population growth rate currently outpaces the overall electrification rate (SE4ALL, 2017). 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 (World Bank Group Independant Evaluation Group, 2016).

1.2 OPTIONS FOR ELECTRICITY ACCESS PROVISION AND THE SE4ALL 5 TIER FRAMEWORK

The UN SE4ALL program has developed a 5-tier household electrification access framework, 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 (Bhattacharyya, 2014), (SE4AL; ESMAP, 2015).

Electrification strategies for rural areas in developing countries can generally be classified as follows:

- Centralized Grid Extension
- Mini-grids or Hybrid Mini-grids; which are small power generation and distribution systems, normally between 10 kW and 10 MW[3] that provide electricity to multiple end-users, and
- Stand-alone Systems; which are small electricity supply systems, not connected to a distribution system, providing power to individual appliances, homes, community facilities or small productive uses.

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 (Bhattacharyya, 2014). 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 (IRENA, 2016). 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.

Solar home systems (SHS) 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 (World Bank Group Independant Evaluation Group, 2016). These stand-alone systems can be a highly effective temporary 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 (Practical Action, 2016). 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 and 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 (AEUEP, 2015).

If the demand and willingness to pay exists, mini-grids can be sized to provide full tier 5 electricity access. Mini-grids are modular and scalable and can be designed to be incrementally expanded to meet demand growth (AEEP RECP, 2014). 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 mineral extraction and processing (AEUEP, 2015). Mini-grids are thus considered the only *off-grid* electricity supply option able to provide full tier 4 or 5 good quality, high power, and reliable electricity economically.

The International Energy Agency (IEA) has estimated that 40% (IEA, 2014) 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 (SE4ALL, 2017).

[3] The Alliance for Rural Electrification defines a micro-grid as being from 1 to 10kW and a mini-grid as being between 10kW and 10 MW (www.ruralelec.org)

1.3 OFF-GRID RENEWABLE ELECTRICITY SUPPLY SYSTEMS

The *standalone* mini-grid concept is not new, with many isolated rural areas, islands, military bases, or remote industrial operations deploying decentralised generation technologies to generate electricity on-site where a grid connection is not available or is unreliable. These are connected to local distribution networks, forming a mini-grid, able to provide power to users independently (Bhattacharyya, 2014), (IRENA, 2015). Mini-grids interconnected within the main grids of developed countries are 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 (Navigant Research, 2017 Q2), (Parhizi, Lotfi, khodaei, & Bahramirad, 2015).

Recently, interests in multi-technology *hybrid renewable mini-grids*, used specifically for the purpose off-grid rural electrification have risen in popularity (IEA, 2014) (ARE, 2011), illustrated as in Figure *1*. These hybrid mini-grids incorporate various combinations of renewables, storage and conventional generators, often 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 system availability, and reducing the overall cost of energy compared to single technology systems (IEA PVPS, 2013).

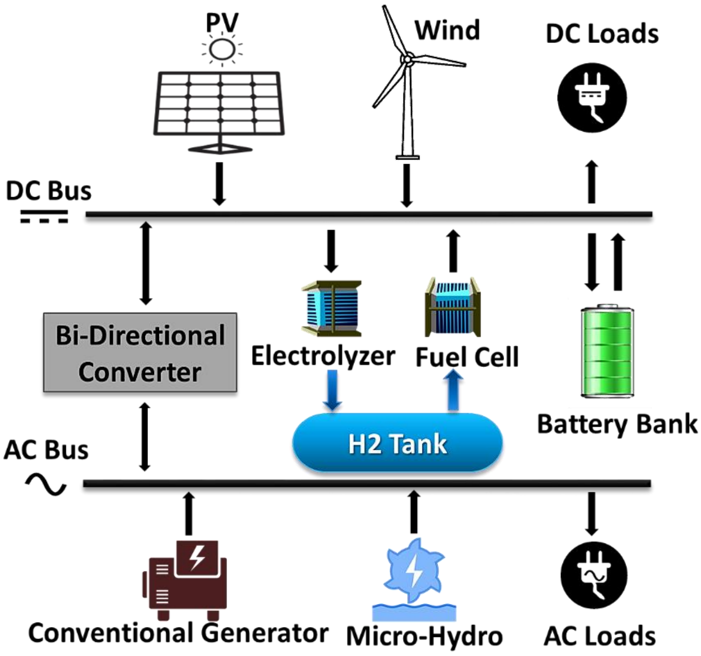


Figure 1: Simplified diagrammatic configuration of a Parallel Functioning Hybrid Mini-grid: AC and DC generators feed into a hybrid bi-directional inverter to integrate, control, and manage the operation of all connected technologies. Hybridized technologies in the figure above include solar PV, wind, hydro, and conventional generators (diesel, gasoline, natural gas, biogasification etc) with energy storage provided by batteries, hydrogen electrolysers, and fuel cells.

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 in real time. Failure to do so can cause system failure, or energy depletion. Regardless of the size of the system this can only be achieved using *3 different methods* (Katiraei, 2007), (Boait, 2014). 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 (Katiraei, 2007), (Boait, 2014).

Firstly, one can *vary the supply* of the generators in the system to meet the required demand. This is applicable 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). 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 (Boait, 2014). 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. (Welsch, Bazilian, & Howells, 2013), (Abdullah, 2009).

1.4 THE ENERGY ACCESS REVOLUTION OPPORTUNITY: LEARNING FROM TELECOMMUNICATIONS SUCCESS

In much of Sub-Saharan Africa (SSA), mobile telecommunications have effectively leapfrogged and rendered wired telecommunication infrastructure largely 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 (Welsch, Bazilian, & Howells, 2013). 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 (Willson & Wong, 2003).

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

(GSMA, 2014). 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 (GSMA, 2016).

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 (AEEP RECP, 2014). 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.

2 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 work 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 policy or investment recommendations to various interested stakeholders.

2.1 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"* (Schnitzer, 2014) 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 (Schnitzer, 2014), (Brent & Rogers, 2009). Additionally, if a diesel genset is included as an energy source in a hybrid system, the under-sizing 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 (Katiraei, 2007). The underutilization of installed capacity, lost curtailed energy, and decreased efficiency all increase the overall cost of energy provided by the system (Boait, 2014).

2.2 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 (AEEP RECP, 2014), (Cader, 2016).

The limitations of individual renewable energy technologies can be partly addressed by combining multiple technologies with complementary characteristics into *hybrid mini-grids* (ARE, 2011), (IEA PVPS, 2013). 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.

To demonstrate the techno-economic effects that multiple interacting technologies have on optimal hybrid component sizing, a systems effect diagram is presented in *Figure 2*. 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.

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 (Scamman, 2015), (Mohamad & Shabani, 2015). 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 least-cost combination of technologies for a hybrid mini-grid for each unique location and context.

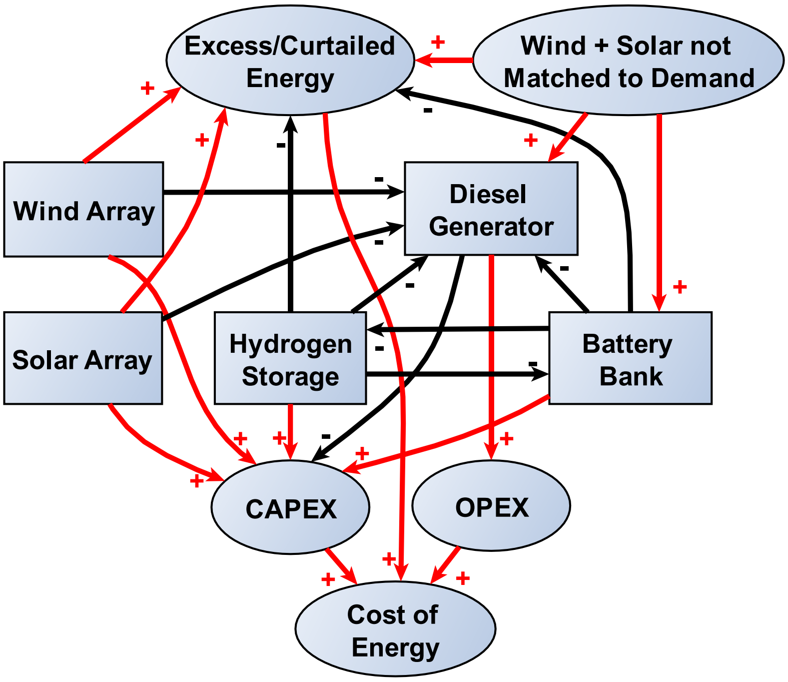


Figure 2: Mini-Grid Component Sizing Cost Dynamics: Simplified systems diagram illustrating the fundamental systems dynamics the various hybrid technologies have on the overall system sizing when minimizing the cost of energy.

2.3 MODEL TRANSPARENCY AND FLEXIBILITY

Many models face challenges concerning a lack of transparency, results reproducibility, the use of proprietary software and data, or high computational complexity from increased modelling resolution or larger application. All combined, this can result in the ineffective bridging of the *science-policy boundary* and limiting the ongoing future usefulness of systems created, ultimately reducing the potential impact and value of the modelling efforts and research outputs (Pfenninger, 2017; DeCarolis, 2012).

Modelling the future is inherently uncertain and enters into the realm of “post-science” or “post-truth”. Many models are also “black-boxes”, where the inner workings and input assumptions are not open to be reviewed or scrutinized (Pfenninger, 2017). Proprietary software is also often used requiring expensive license subscriptions while the data used may have been purchased or is confidential (HOMER, 2017; SolarGIS, 2017; pay-walls).

The assumptions made and possible scenarios modelled will invariably entail a level of subjectivity by those involved in the process. Therefore, without full input and data transparency and reproducibility, modelling results and policy suggestions may be disregarded or refuted by stakeholders with claims of bias or manipulation. This results in reducing credibility and confidence in results and may hinder non-technical or non-expert stakeholders from being able to make decisions for policy or deployment plans or garner public support.

3 TEMPO – THE TECHNO-ECONOMIC MINI-GRID PLANNING AND OPTIMIZATION MODEL

The mini-grid simulation and optimization model, TEMPO, 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 3 provides a diagrammatic illustration of the full model, with each functional sub-model block and their integration shown. 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.

3.1 MODEL DESIGN ATTRIBUTES

TEMPO 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 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 (Homer Energy, 2017), RETscreen (Natural Resources Canada, 2017) and DER-CAM (Berkley Lab, 2016) 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.

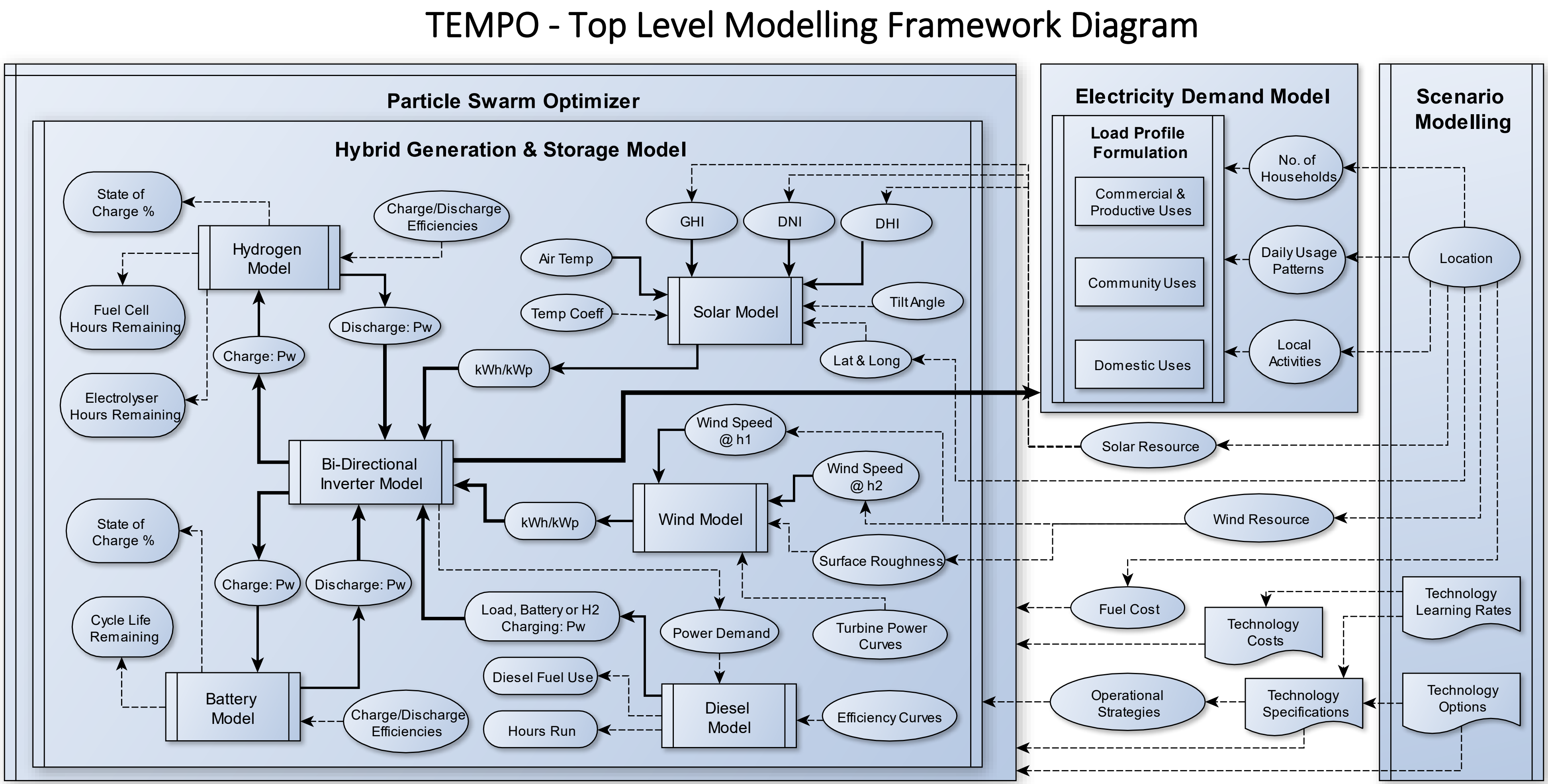


Figure 3: Full Mini-Grid Simulation, Sizing and Costing Model (Solid black lines indicate energy flows, dotted lines indicate data flows). Each functional block of the model and their respective integration is illustrated above. The modular and open source nature of the blocks in the model allows for 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 (yEd, 2017).

3.2 COMPARISON OF LEAST-COST ALTERNATIVES

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 (Short, Packey, & Holt, 1995). 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. 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.

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 (Short, Packey, & Holt, 1995):

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

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

3.3 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 (Eberhart & Kennedy, 1995), (Zhang, Wang, & Ji, 2015).

Many other optimization algorithms are capable of efficiently finding solutions to this multi-dimensional and non-linear optimization problem (Gamarra & Guerrero, 2015). The PSO algorithm was chosen mainly due to its attributes of simplicity, versatility, customizability, competitive performance, and computational scalability – these are described below.

The basic process of the Particle Swarm Optimization algorithm is described below (Valle, 2008):

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:

$$\boldsymbol{v_p^{t+1} = w * v_p^t + c_1 * rand_1 * (Pbest_p^t - x_p^t) + c_2 * rand_2 * (Gbest^t - x_p^t)},$$

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 4* 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.

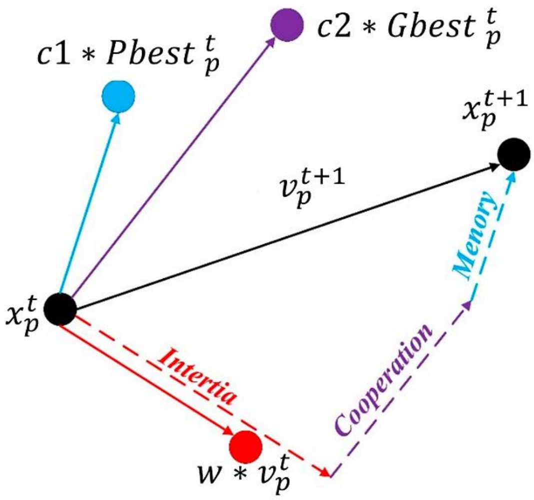


Figure 4: Particle swarm vector update diagram for a single particle in a 3-dimensional solution search space (diagram adapted from (Yu, Wang, Niu, & Hu, 2016)*)*

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 (Valle, 2008), (Zhang, Wang, & Ji, 2015):

- **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 (Valle, 2008). Population based algorithm allowing for Multi Objective Optimization (MOO) using Pareto Dominance or other methods (Wang & Singh, 2009), (Fadaee & Radzi, 2012), (Sharafi, 2014).

- **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 (Valle, 2008), swarm size and number, (Liu, Chen, & Yuan, 2015), particle mutation (Jimenez-Fernandez, Salcedo-Sanz, Gallo-Marazuela, Gomez-Prada, & et.al., 2014), fuzzy-logic (Moghaddam, Seifi, & Niknam, 2012), and chaotic randomization (Liu, Wang, Jin, & et.al., 2005) among many others (Valle, 2008), (Zhang, Wang, & Ji, 2015).

- **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).

3.4 Model Framework Coding Implementation

3.4.1 Open-Source Project Code and Notebook Hosting: Python & Jupyter Notebooks:

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 (Python, 2017) coded into an interactive computing environment called a *Jupyter Notebook* (Project Jupyter, 2017). 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*

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

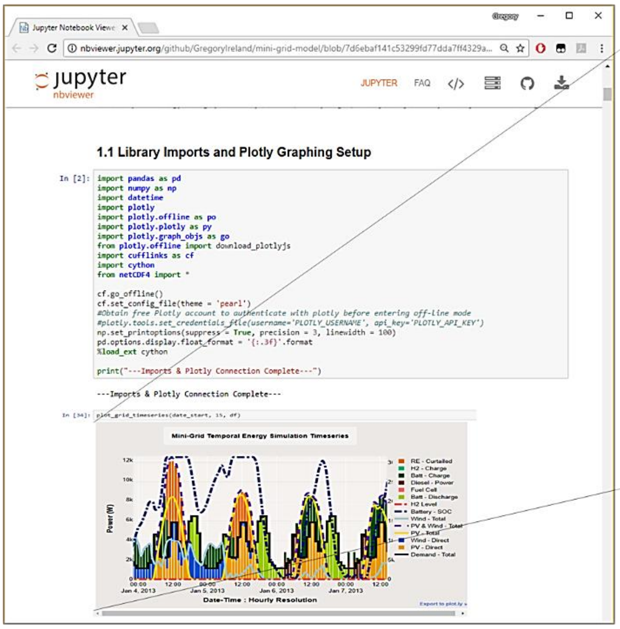
(Use the above link for the correctly rendered notebook with included visualisations)

The Github repository that will host the code and ongoing applications of the model will be hosted and maintained at:

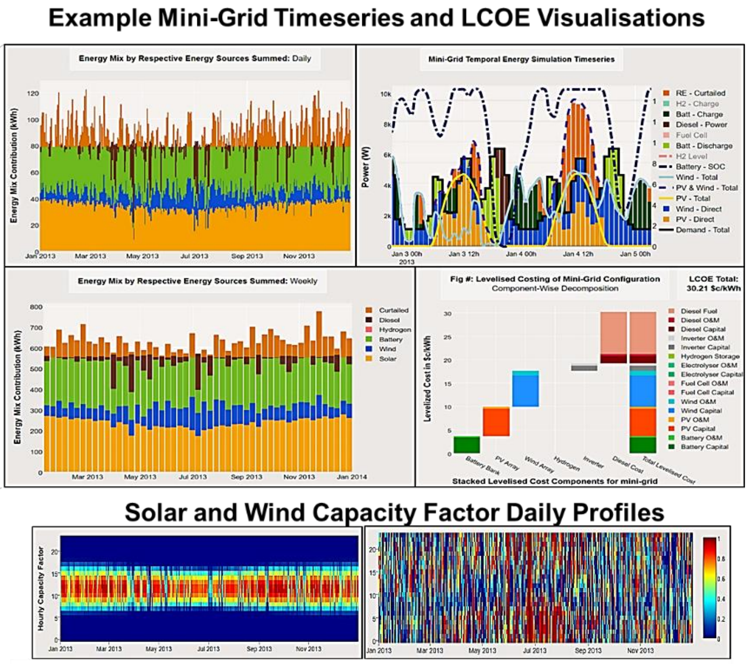
https://github.com/GregoryIreland/mini-grid-model

The Notebook and Github repository is the entire reference for any of the model's computational or algorithmic implementation details. 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.

Interactive Model Outputs and Jupyter Notebook Implementation



Section of the Python Jupyter Notebook used for the implementation of the model code and case study application. Shown is some Python import code and a visualisation of the mini-grid simulation timeseries using the open-source Plotly library. The full notebook can be easily viewed and downloaded allowing the model to be easily shared, peer-reviewed, understood, or modified in parts.



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). These graphics were created using the open-source Plotly visualisation library.

Table: Summary of model framework design choices and benefits.

Design Choice	Benefits
Open-source with Input data from publicly accessible sources	• Completely free and open to be used and contributed to by researchers, developers, governments or NGOs • 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 sources and assumptions are open for results reproduction through verification and peer-review
Coded in Python with 'Jupyter Notebooks'	• High level, flexible, and widely understandable coding language • Interactive development environment with powerful data-rich analysis and visualisation possible • Python has many packages allowing functionality expansion and easier integration with other models • Reproducible computation and independent handling of code blocks is possible • Jupyter notebooks support multiple languages and are easily shared and collaborated between researchers
Simple & Modular components	• Simpler to expand or modify model functionality and manage in parts • Model is coherent and understandable to a wider audience • Individual contributions of varying detail can be made to specific sections without specialist knowledge
Optimization Algorithm: Particle Swarm Optimization (PSO)	• Meta-heuristic algorithm allows non-linear optimization and modifications to objective function • "Embarrassingly Parallel" computation possible for individual particles, allowing scaling of scope or detail • Population based algorithm allows multi-objective optimization using Pareto dominance principle

4 Proof of Concept and Practical Application of the Model: Rural Electrification in South Africa using Hybrid Renewable Mini-Grids with Hydrogen Fuel Cells and Electrolysers

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*. Undertaken with the South African National Energy Development Agency (SANEDI) commissioned by the South African Department of Science and Technology (DST) (Hughes et al., 2017). There are two policy-relevant contexts for exploring the potential for mini-grids with hydrogen fuel cells in South Africa. Firstly, South Africa has committed to providing universal access to electricity by 2030 through the New Household Electrification Strategy (NHES), aligned with the goals and objectives of the UN's SE4ALL program (DoE 2016). Secondly, the development of fuel cells using domestically-produced platinum group metals, has been a focus of South African technology research and development policy for some time. Various other policy questions could also be investigated using the model, including mini-grids in the central grid planning process, related skills development and research foci, or impacts on demand for key non-PGM domestic minerals critical in various sustainable energy technologies such as manganese, vanadium, chromium, titanium, cobalt, gold, nickel and others.

Despite significant progress in electrification over the past two decades, around 14 % of households (2.17 million) in South Africa currently un-electrified (www.energy.gov.za). Even though the National Electrification Programme (NEP) achieved a high number of rural connections between 1994 and 2002, rural electrification only really became a key focus after 2002. This shift brought about an associated increase in connection costs, a decline in connection rates and the need to provide additional transmission infrastructure, or alternative forms of supply. The current estimate is that 150 thousand of the unelectrified households in rural areas lie more than 0.5 km from the nearest MV substation, and more than 3km is around 40 000 households (Hughes et al., 2017)

4.1 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 coverage of a wide spatial distribution of different solar and wind resources across South Africa (ERC, 2017).

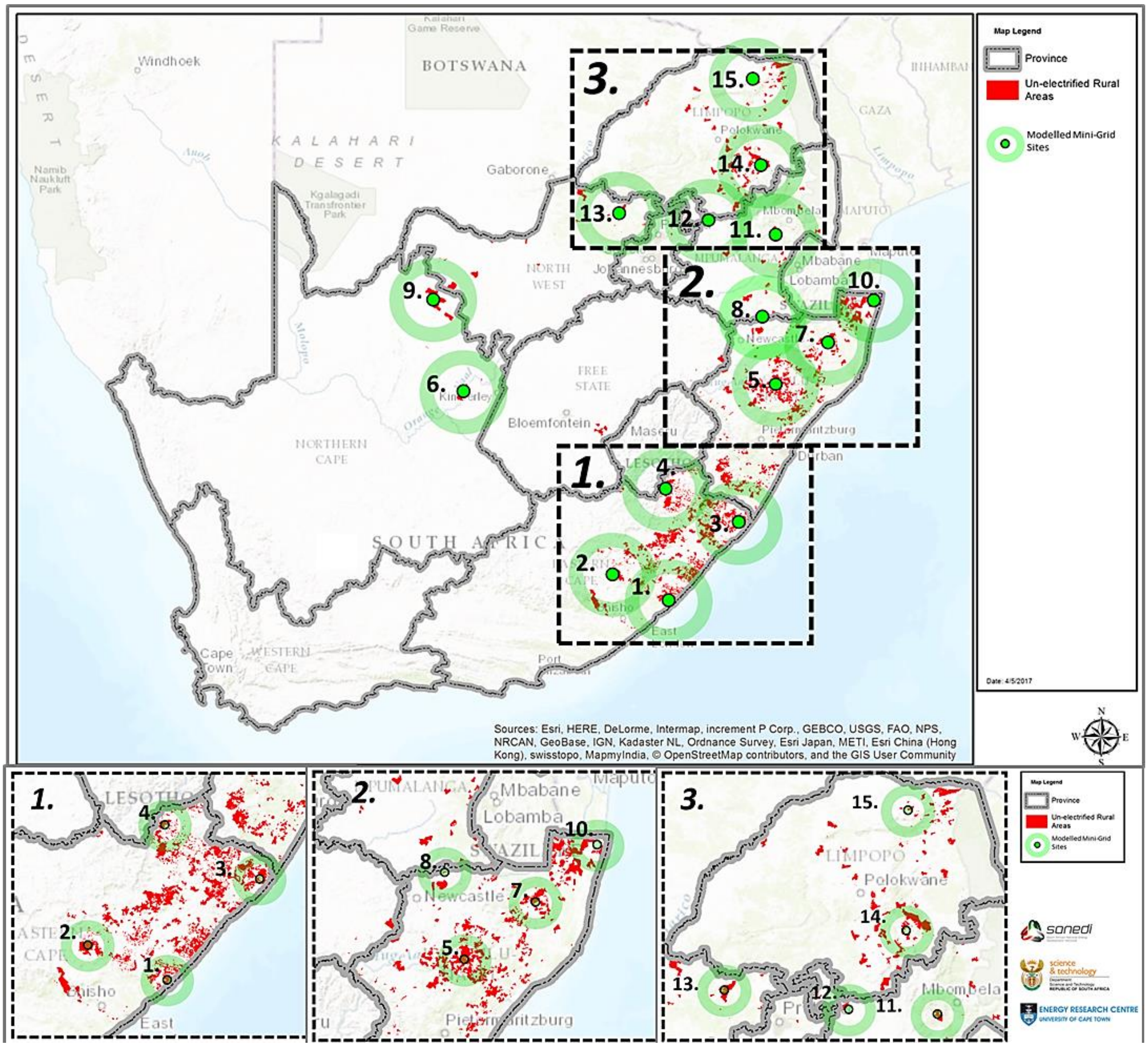


Figure 5: Maps showing the distribution of the 15-modelled representative hypothetical mini-grid sites covering the spatial extents of remaining unelectrified areas in South Africa. Details for the data and methodologies used to identify and map these areas see (ERC, 2017)

2015 US Dollars **8.2% discount rate** **13:1 ZAR/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) *Y2030: 1,165*	Turbine[3]+ Tower[4, 5] (40m) (30% of total CAPEX) 1,910 + 820 = 2,730 (DC) *Y2030: 1,355*	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]		*Fuel: 1.5 USD/litre*	---	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: Complete Mini-grid Component Cost and Performance Data Matrix

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20. Kestrel, 2017. e400nb Technical Specifications. Available: http://www.kestrelwind.co.za/assets/documents/e400nb.pdf. (Accessed 32st January 2017).

4.2 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. Figure 6 shows the composite community demand profile, which will be serviced by the mini-grid being modelled with a laundry, 2 shops, and water pumping and purifying system. Further details on the demand profile formulation can be found in Ireland (2017) and Hughes et al. (2017).

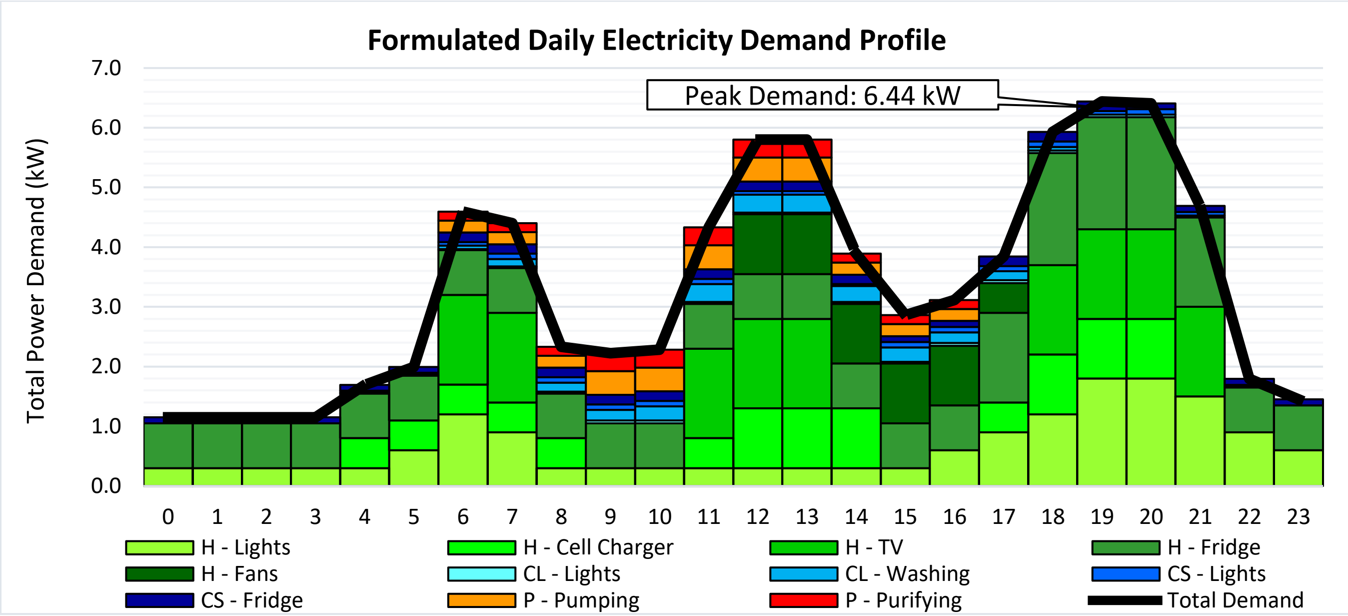


Figure 6: Bottom-Up Formulated Composite Daily Demand Profile: of a hypothetical 100-household community mini-grid including domestic, commercial and community electricity demand. H – households, CL – commercial laundry, CS – commercial shop, P – productive/pumping/purification.

4.3 METEOROLOGICAL DATA

Time synchronized data for both solar and wind from 2013 are used for each of the 15 sites, retaining local solar and wind daily and seasonal meteorological correlations. The details surrounding the data-sets used are described below with an overall summary shown in *Table 1*. 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 timeseries data are used in this application.

The satellite modelled solar data used in this application of the model has been obtained from the NASA MERRA-2 satellite measurements (Reinecker et al, 2011) made available by Pfenninger (2016). This data has a spatial resolution of 0.50° latitude and 0.66° longitude and a temporal resolution of one hour.

The windspeed timeseries data used is sourced from a project between the Fraunhofer Institute, the Council for Scientific and Industrial Research (South Africa) (Fraunhofer & CSIR, 2016), and the Wind Atlas of South Africa (WASA) project (WASA, 2017). 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. The windspeed timeseries data is run through the implemented wind generation model using the turbine power curve to determine average hourly capacity factors. Power outputs for each 15-minute interval are calculated and summed to increase accuracy due to the non-linear cubic power law of wind energy and the turbine's non-linear cut in and maximum power speeds.

Solar and wind maps are used to verify the chosen years of simulation with the long term modelled annual averages where coverage is available. The solar maps used are those produced by SolarGIS (ESMAP, 2017), the wind maps are from WASA and Fraunhofer-CSIR.

Annual average values in these atlases are not suitable for use directly in system sizing calculations but *can be used as an important indicator of the overall amounts and spatial distributions of resources.* Solar resources are shown to gradually increase towards the north west of the country, while very good wind resources are less uniform with high site specificity, but with good wind sites still covering very large areas of South Africa.

Table 1: 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	5km x 5km	250m x 250m
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)

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 detailed site specific layout analysis and local insular resource prospecting. This is typically done including on-site measured data to determine the expected system performance more accurately.

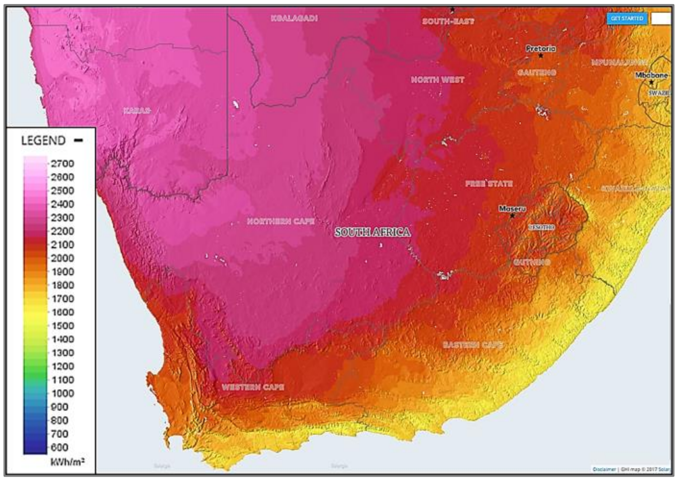


Figure 7: Solar atlas of South Africa covering South Africa showing long term Global Horizontal Irradiation (GHI) averages and their distribution (ESMAP & World Bank, 2017)

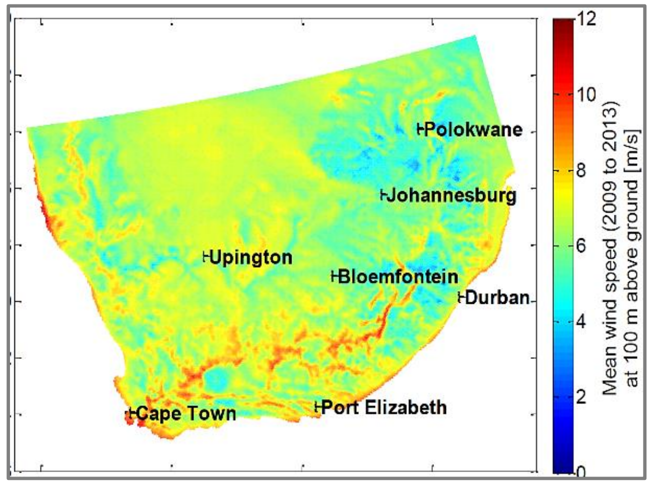


Figure 8: Wind Speed Averages from the Extrapolated Fraunhofer and CSIR Dataset covering South Africa with a 5 x 5km Resolution (Fraunhofer & CSIR, 2016)

5 RESULTS

The results of the application of the techno-economic mini-grid modelling of the 15 representative mini-grid sites are presented below. 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.

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. The sites that are presented in more detail below are as follows:

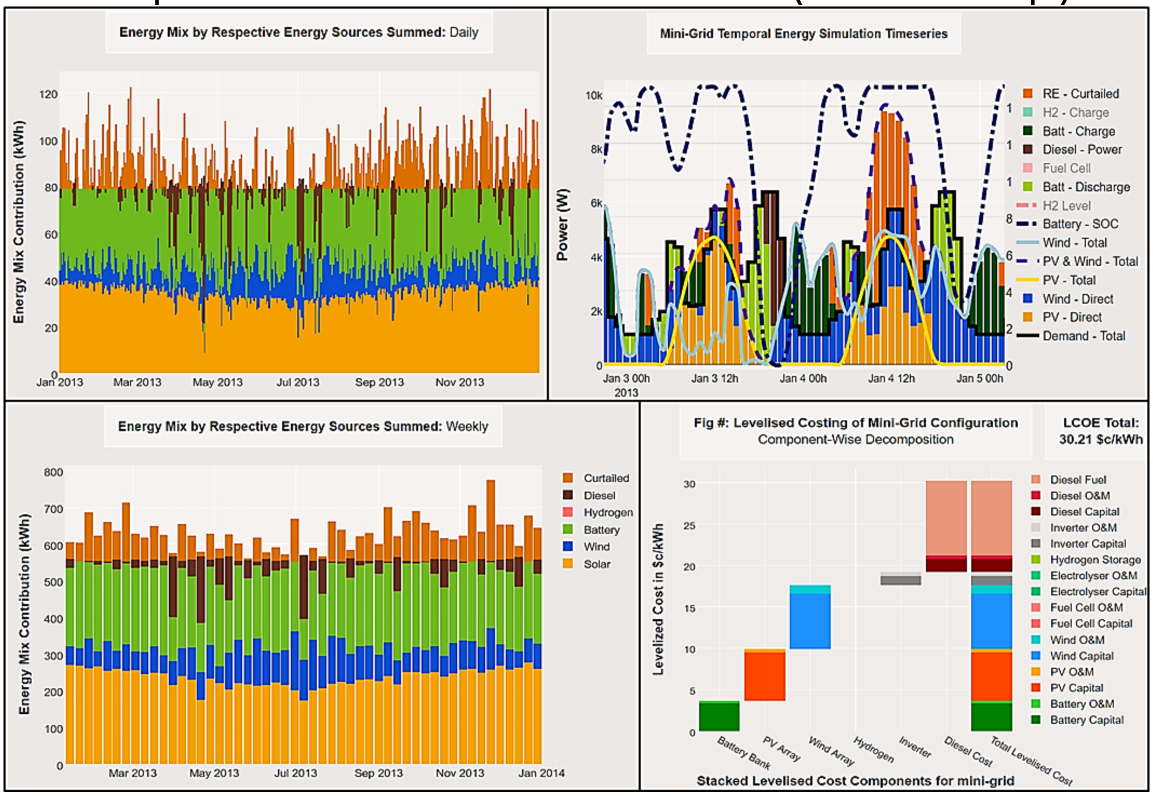
1. **Site 1: EC** Southern Coastal Extent of Un-electrified areas in the Eastern Cape
2. **Site 2: EC** Central Eastern Cape on the North-Western Extent of the un-electrified Eastern Cape
3. **Site 10: KZN** North Eastern Coastal tip of South Africa in Empangeni, Kwazulu-Natal
4. **Site 15: LMP** Northern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

5.1 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.

Figure 9 below shows several data visualisation outputs available from the developed mini-grid model. These figures are all accessible directly from within the Jupyter notebook and can be used to assist the modeler in understanding the data itself (exploratory visualisation) and can also be used to display important results to other stakeholders (explanatory visualisation). Shown below for Site 1 in the Eastern Cape are annual timeseries for the optimal energy mix, the ongoing dynamic hourly operation of the mini-grid, and the levelized cost components. Shown at the bottom of the page are the daily resource distributions of the solar and wind resources.

Example Mini-Grid Timeseries and LCOE Visualisations (Site 1: Eastern Cape)



Solar and Wind Capacity Factor Daily Profiles

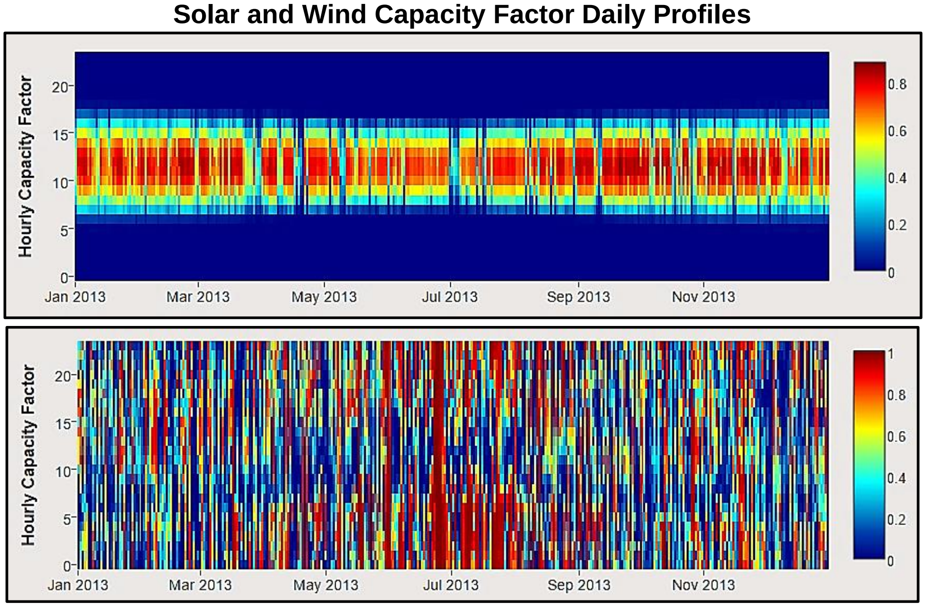


Figure 9: Example Data Visualisation Outputs available from within the implemented Jupyter Notebook. The top left two plots show the variations in the energy mix provisions at a daily and weekly resolution over the year. The top right shows the mini-grid's dynamic operations timeseries as above, and the bottom two plots show the daily profiles (vertical direction) of the solar and wind power capacity factors over the year (horizontal axis)

5.2 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 10* 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.

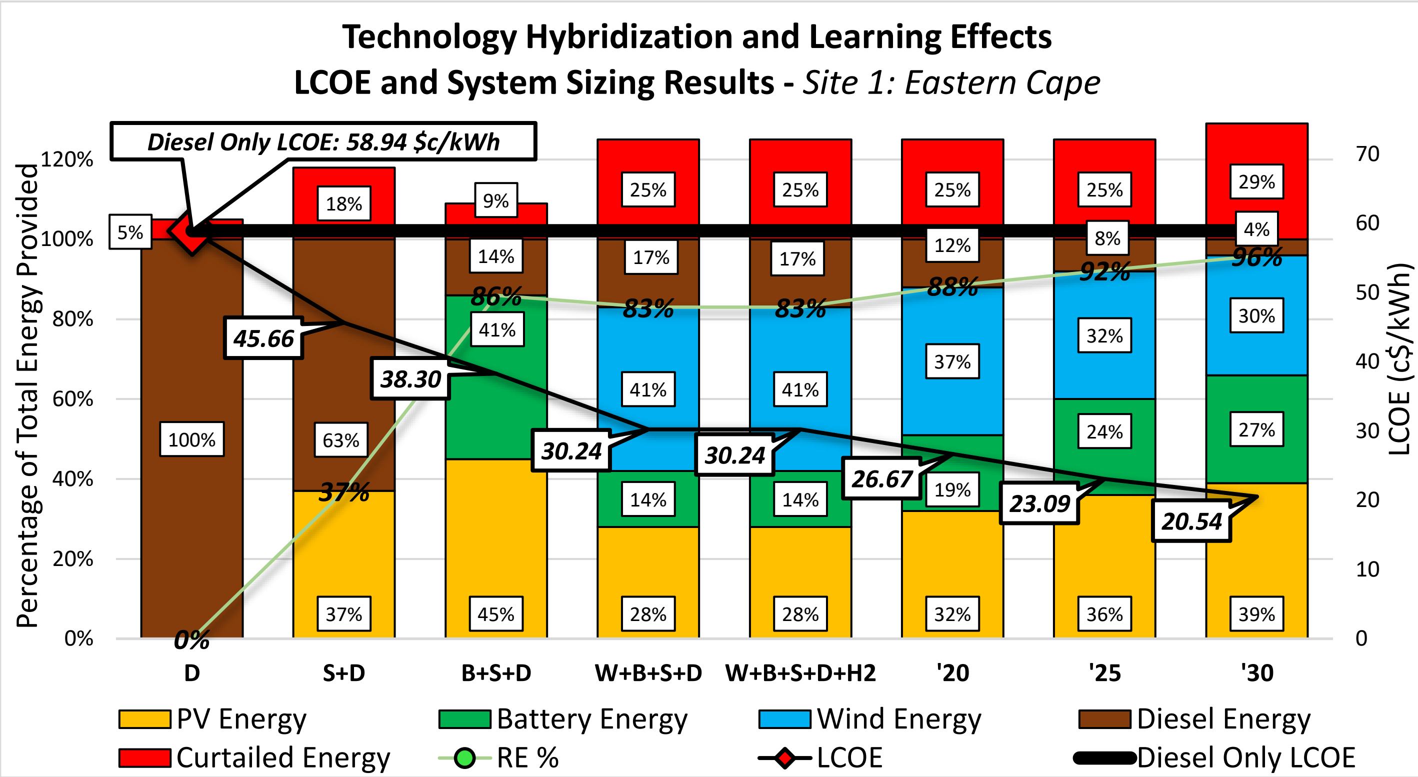


Figure 10: Effects of Technology Hybridization on System Cost, Energy Mix and RE shares. The 5% curtailed energy in the diesel only case is due to the generator having a minimum allowable load factor of 25%.

Key *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 that without H_2.

Key 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 11*. 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%.

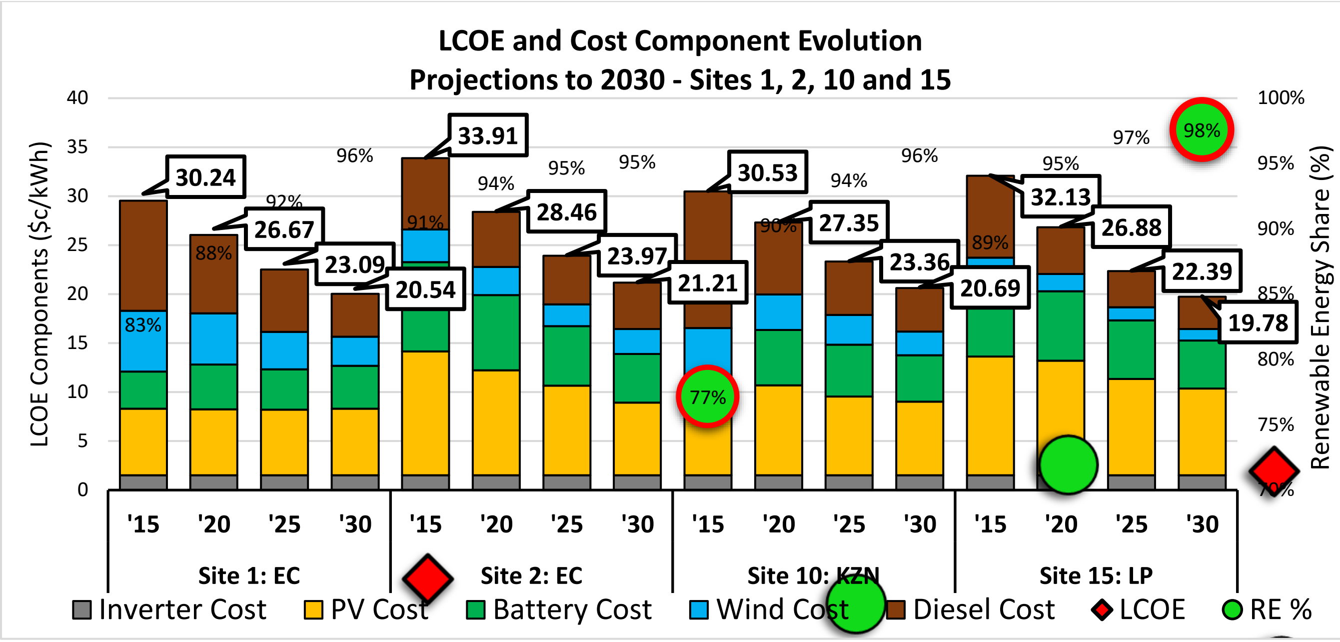


Figure 11: Levelized Cost and Renewable Energy Share Evolution for Sites 1, 2 10 and 15 from 2015 to 2030. Circled in Red is the lowest renewable energy share of all sites modelled for Site 11 in 2015 at 77%, and the highest share for Site 15 in 2030 at 95%.

5.3 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. 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.

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.

5.3.1 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 12 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.

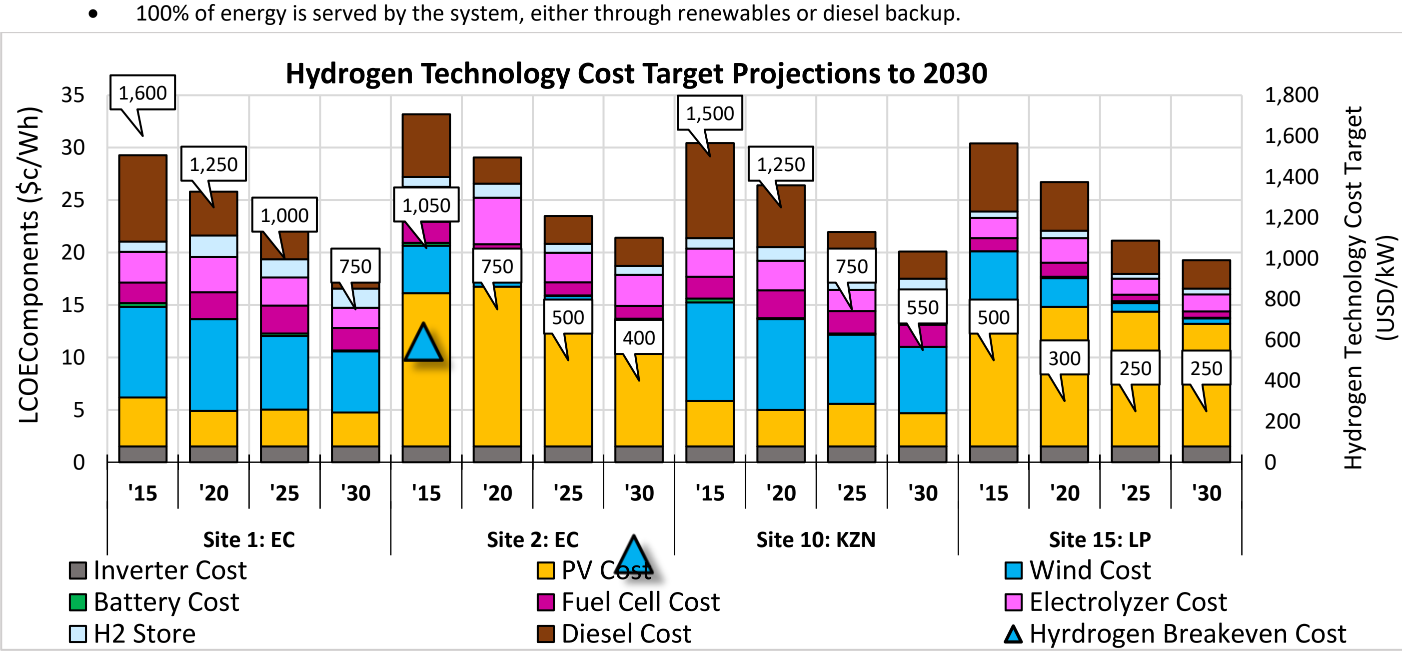


Figure 12: Hydrogen Cost Target Points to 2030 for Sites 1, 2, 10 and 15

Figure 12 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.

5.3.2 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 13* in comparison to the unconstrained case.

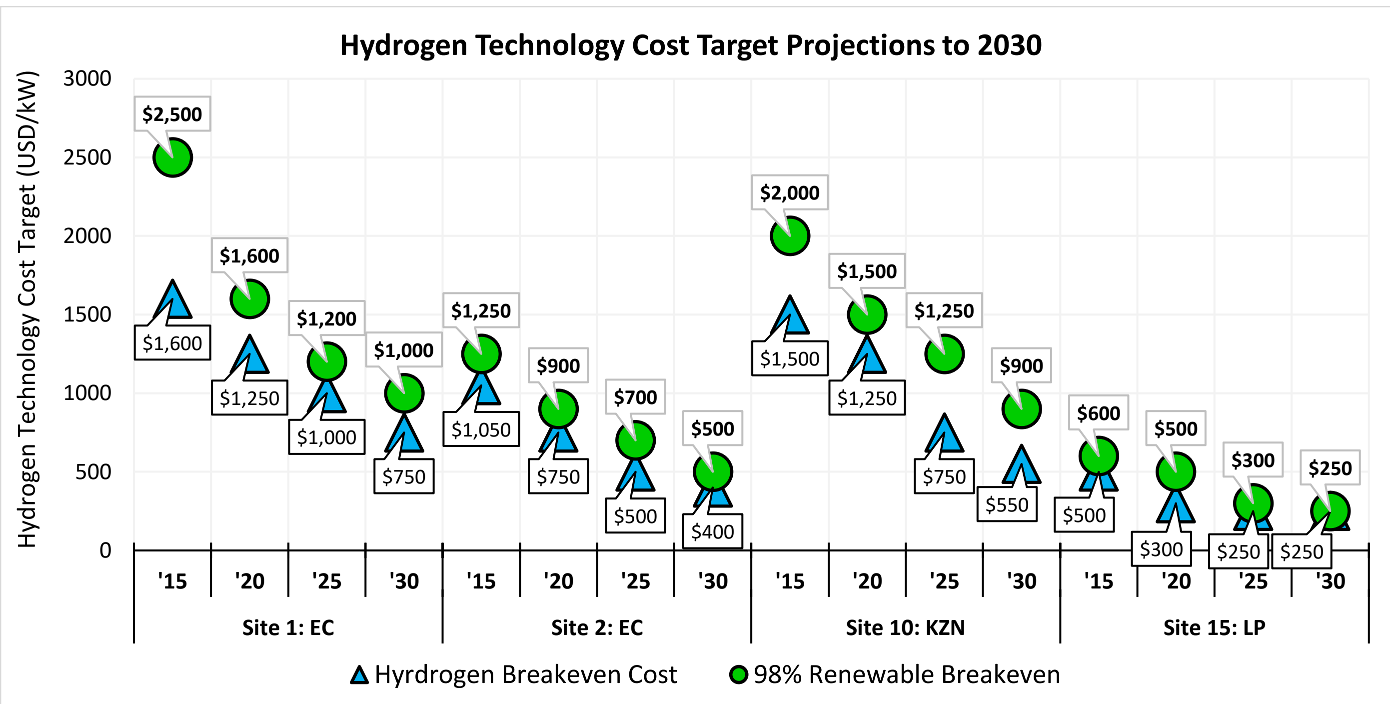


Figure 13: Hydrogen Technology Cost Targets Compared with 98% Renewable Energy System Constraint.

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.

5.4 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.

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	29.58	82	32	41	13	14	17	1,600	2,500
	'30	20.1	96	40	33	23	4	20	750	1,000
2	'15	33.9	91	47	15	30	8	8	1,050	1,250
	'30	21.21	95	47	18	31	4	14	400	500
3	'15	29.58	79	24	48	11	17	21	1,750	2,125
	'30	20.35	96	37	37	22	4	25	1,000	1,000
4	'15	30.27	86	42	26	20	12	11	1,150	1,500
	'30	19.7	95	48	20	28	4	15	600	600
5	'15	33.72	86	43	23	22	12	10	950	950
	'30	21.47	95	50	14	32	4	12	250	250
6	'15	29.7	85	41	31	16	12	14	1,300	950
	'30	19.34	98	51	15	32	2	11	250	<250
7	'15	33.34	84	40	27	20	13	10	950	600
	'30	21.28	96	47	19	31	3	14	<250	250
8	'15	32.99	85	45	19	24	12	8	950	950
	'30	20.98	96	51	14	32	3	14	450	525
9	'15	28.01	87	40	34	15	11	13	950	1,300
	'30	18.62	97	49	20	29	2	11	250	600
10	'15	31.56	86	45	23	21	11	8	1,500	2,000
	'30	19.76	97	53	11	34	2	9	550	900
11	'15	30.52	77	29	41	11	19	17	600	600
	'30	20.69	96	43	27	26	4	17	250	250
12	'15	34.41	93	52	8	34	6	5	600	600
	'30	21.07	97	52	9	36	3	9	<250	250
13	'15	33.13	94	52	10	33	5	5	600	600
	'30	20.1	97	54	6	38	2	7	<250	<250
14	'15	33.72	95	56	0	40	4	5	950	600
	'30	20.37	97	57	0	41	2	8	<250	<250
15	'15	32.11	89	46	19	26	9	6	500	500
	'30	19.73	98	51	13	34	2	9	250	250
Min	'15	**28.01**	77	18	0	11	4	5	500	500
	'30	**18.62**	95	28	0	22	2	7	<250	<250
Max	'15	**34.41**	95	38	36	40	19	21	1,750	2,500
	'30	**21.47**	98	38	28	41	4	25	1,000	1,000
Median	'15	32.11	86	43	23	21	12	10	1,027	1,135
	'30	20.35	96	50	15	32	3	12	417	531

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

6 Conclusions and Future Work

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, many questions remain unanswered in ever-changing technological, economic, social, and political landscapes. However, determining their appropriate situational applicability in comparison to centralized or standalone options is non-trivial and requires a comprehensive modelling framework to adequately address this challenge. Presented in this paper is an attempt to explore this challenge, develop an open-source model designed to be flexible in its application to this problem, and to prove the concept and demonstrate its practical application to a specific research question.

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. The hybridization of multiple complementary technologies in mini-grids 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 by continually evolving costs and performance capabilities of technologies, and the inherently uncertainty of estimating likely projections of their future values.

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. 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.

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 further innovation and collaboration with other stakeholders, it is hoped that valuable insight can be learned and shared to affect positive change and accelerate the implementation of politically actionable and economically optimal electrification plans, while also providing direction for future research areas, and understanding global technology development implications.

6.1 Key Focus Areas for Future Model Development

The research and model presented 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. It is impossible to include every aspect, variable, or topic within the practical limitations of an initial implementation and proof of concept. Several primary areas identified for future research focus are briefly described below:

Improvements and capability expansion of the model software implementation:

- Model front-end & open source access/collaboration
  - Open source access and management of code-base, including documentation and version control (eg. Github)
  - Graphical user-friendly interface and non-technical user readiness/capability with user manuals
- Integration with spatial Geographic Information Systems (GIS) and other related models:
  - Advanced localized demand modelling and load growth scenarios
  - Geographic spatial analysis with large GIS data sets – such as OnSSET (http://www.onsset.org/)
  - Satellite image recognition for village layout, demand density and night-light detection
- Highly optimized computational efficiency & parallel programming
  - Parallel Programming of optimization algorithm and multiple scenarios
  - 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, etc.
  - Energy benefit of services (different weighting to end-uses clinics, schools, productive etc)

System Configurations/Alternatives modelling:

- Full community energization and potential energy system integrations - not only electricity
  - Thermal uses, water systems, biogas, hydrogen CHP,
  - Inclusion of micro-hydro or biomass gasification, biodiesel etc. for local renewable generation options
- 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
- Demand side management, smart-grids & energy efficiency
  - Load prioritization, classification and flexible control

- Model Predictive Control (MPC) energy management and operational strategies including resource uncertainty and prediction with DSM
    - Use of super-efficient appliances
- Additional technical component modelling details inclusion
    - Battery, fuel cell and electrolyser characteristic curves for different load factor efficiencies
    - Spinning reserve requirements with higher temporal resolution
    - DC and DC+AC microgrids and integration with Telecommunications signal towers

Social and Economic

- Differentiated benefit weighting of energy provision for individual end-uses, demand feedback linkage to income generating activities
- Local employment, social acceptance, user inclusive design
- Impacts on global mineral and metal demands needed for new energy technologies, especially storage
- Environmental Impacts: Carbon, NOx & PM emissions, battery and hydrogen safety, fuel spillage.
- Health Benefits: Energy provision enabling better healthcare services
- Education: access to lights and ICT, teachers
- Smart-grid enabled targeted subsidies for individual priority high impact end-uses

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

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