Load predictions: vulnerability of micro-grids based on renewable energies due to increasing population and individual demand

Meike Kühnel1, Babak Ravanbach1, Benedikt Hanke1, Olga Weigel2, Ingo W. Stuermer3, Alister McMaster4, Sander Maebes5, Karsten von Maydell1

1DLR Institute of Networked Energy Systems, Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany
2Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Hamburg, Germany
3Lower Saxony Ministry for Environmental Affairs, Energy, Building and Climate Protection, Hannover, Germany
4Department of Economic Development, Environmental Affairs and Tourism of Eastern Cape, East London, Republic of South Africa
5Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, East London, Republic of South Africa

E-mail: meike.kuehnel@dlr.de

Abstract: Small-scale systems are vulnerable to changes. The development of solution strategies for changing conditions should therefore, be considered from the outset in planning. For planners and installers of mini-grids for rural villages without grid connection, first of all, the question of the expected electricity demand arises. So far, this is determined primarily by interviewing the population. However, studies have shown that there are still major differences between the power demand estimated and the real load after electrification. Reinforcing here is the inadequate assessment of load development through immigration and increased prosperity. On the basis of a currently developing mini-grid in the Eastern Cape of South Africa, we could show that a load increase of ~60% within 10 years is to be expected. The following possibilities were outlined as possible ways of counteracting the increase in load: (i) communicating with the population, i.e. on energy efficiency to raise awareness and understanding, (ii) early planning of capacity building and identification of key performance parameters to trigger the expansion based on local socio-cultural conditions and grid supporting qualities. An adequate database for the initial electrification and power development should also be established and available on open-source basis for researchers, developers, communities, and installers.

1 Introduction

ENGINEER is a sub-project of the 'pilot project for the construction and sustainable operation of local energy grids based on renewable energies in the Eastern Cape' funded by the Federal-State-Government-Project of the Federal Ministry for Economic Cooperation and Development Germany (BMZ) and the federal state of Lower Saxony, South African institutional funding is given by the Department of Economic Development, Environmental Affairs & Tourism (DEDEAT), the Eastern Cape Rural Development Agency (ECRDA) and implemented by the GIZ. Aim of the project is to demonstrate a solution for an economically and ecologically sustainable energy supply to rural communities and test it in Upper Blinkwater, a small non-electrified village in the mountains of Eastern Cape in South Africa. Upper Blinkwater is located 32.85°S and 26.56°E in a height of ~900 m above sea level and around 17 km away from the next main road (cf. Fig. 1).

Joint monitoring of institutional integration promotes the development of regulatory frameworks for so-called mini-grids and decentralised electricity supply scenarios. The village will be used as a ‘living lab’ by mainly South African universities and research facilities to study the development of power consumption, increasing loads, and the desired feedback on local prosperity in the long run. Monitored achievements of load development, necessary cost of operation and maintenance as well as integration in regulatory and institutional processes can be used to develop and define a political and institutional framework for future mini-grid installation and integration. Including retro-fitting structures and a growing renewable power generation plant into upfront considerations is essential for an economically sustainable and persistent mini-grid. An adaptive system will learn from the development of the villages' electric power consumption during the first years of electrification. A recommendation for further installation of renewable energy capacities such as micro wind turbines (M-WTs) and additional solar power will be triggered by the recorded demand development and additional onside data using the infrastructure of the generation side. This opens up a new look on business plans and the calculation of levelised cost of electricity (LCOE) and cost reflecting tariffs with a more fluently and dynamic behaviour reflecting real-life challenges.

2 Motivation

Energy use and the access to reliable electric power is an essential cause and facilitator of economic grows and a binding constrain for all sizes of business [1]. Reduction of the backlog in electrification is one of the main aspects of the anti-poverty campaign of South Africa, facing the fact of a poverty headcount ratio of more than 20% and 15.8% of the South African population without access to electricity [2]. In far off rural areas islanded mini-grids based on renewable energy generation offer both, access to electricity
to transfer a consumption scenario from one region to another. To the knowledge of the authors, there is up to now no reliable database for load pattern or standard load profiles of rural villages first electrification. However, literature shows significant differences between the widely used interview method and later consumption measurements. Estimated load profiles mismatch resulting demand by up to 300% [7, 8].

3.1.1 Past: binary approach to electricity access: In the past, electricity access was measured in a binary way. This typically means ‘having or not having an electricity connection’. Its focus on only one attribute, access to the grid, provides a simplistic and often distorted picture because it fails to determine how this access translated into reliable, affordable, and modern service. In addition, the traditional counting method is static and fails to account for evolving technology solutions [9].

3.1.2 Present: SE4ALL multi-tier framework (MTF): The SE4ALL MTF redefines energy access to fill the gaps in the binary access measurement. It acknowledges that energy access is a spectrum of service levels (or tiers) consumed by households, productive engagements, and community facilities. It also focuses on the quality of the energy service [9]. With all its advantages the MTF may fall short in handling the following scenarios: real-time and high-resolution consumption/generation data, integration of renewable energy systems, growing demand and evolving customer behaviour, ever-improving appliances, and introduction of new products. Furthermore, as a standardised method, the MTF neglects regional differences based on social-cultural aspects.

Based on this, two approaches were used to estimate the load profile for the mini-grid. With the help of a survey of the villagers, the current consumption of energy carriers such as paraffin, gas, batteries, and wood, individual financial situation, and budget for electric energy as well as expectations regarding power supply and electric applications was evaluated. The second approach used for the identification of future power and energy demand is based on the MTF. TIER 0 (no access to electricity) to TIER V (full developed power grid access) of the MTF define minimal requirements for power supply, quality, availability and costs per household from street lights only, solar home systems to a mini-grid and grid or grid-like level supply quality and quantity.

All stakeholders and funding agencies from local authorities such as the responsibles municipalities over to regional entities such as the ECRDA and the DEDEAT of Eastern Cape towards German stakeholders such as the GIZ and Lower Saxony Ministry for Environmental Affairs, Energy, Building and Climate Protection agreed on a targeted supply quality of with a grid-like quality compared to the supply quality of ESKOM the national power company. Main points of argument are

• As stated in the introduction a good quality of electric power and energy supply is considered one main driving factor for economic development.
• Energy access is considered a fundamental right in South Africa.
• The mini-grid must not be perceived as a second-best solution in public perception.
• A high rate of acceptance and identification of villagers with the mini-grid to protect the installation from vandalism and theft.

The basic parameters for TIER IV (grid-like quality) and TIER V (grid quality) from WORLD BANK Group [9] are listed in Table 1.

3.1.3 Future: data-driven load profiles: Mini-grids provide energy services tailored and optimised for a certain consumer load profile. For renewable hybrid mini-grids, the fluctuating nature of resources adds more complexity to the challenge of maintaining the energy balance. Therefore, having access to accurate load profiles is indispensable for the initial design and optimisation during the operation. Standard urban household load profiles are quite useful and essential in the field of energy research, and there has already

Table 1 Multi-tier matrix for measuring access to household electricity supply [9]

| Unit       | TIER III | TIER IV | TIER V |
|------------|----------|---------|--------|
| min. peak  | kW       | 0.2     | 0.8    | 2      |
| capacity   | kWh      | 1.0     | 3.4    | 8.2    |
| min        | h/d      | 8       | 16     | 23     |
| availability | h/evening | 3     | 4      | 4      |
| reliability| disruptions | NaN1  | max. 14 | max. 3 |
| —          | per week | —       | —      | —      |
| —          | max. SAIFI² | NaN    | 730    | 156    |
| —          | max. SAIDI³ | NaN    | 6240 min | —      |
| voltage    | NaN      | grid standard | — | —      |
| affordability | NaN      | max. 5% income | — | —      |

1NaN: not a number.
2SAIFI: annual system average interruption frequency index.
3SAIDI: annual system average interruption duration index.

power grid equivalent quality level and an economic solution for the responsible authorities.

The general design and technical composition of various stand-alone power supply networks have been relatively well investigated. Various scientific papers analyse the optimal energy supply scenario for rural areas. The focus here is primarily on the best balance of different generation and storage capacities and technologies (renewable and fossil) as well as energy management systems and mini-grid controllers (cf. [3–6] etc.).

Main challenges for planners, developers, and engineers of mini-grids are the appraisal of a residential load profile of former un-electrified areas and the matching with highly fluctuating renewable energy resources. The adjacent increase of the load caused by economic growth, new demands for electric appliances, and a growing village size triggered by the availability of electricity adds further challenges and uncertainties.

Successful implementation of mini-grids requires the right technology, access to financing and consumer-friendly payment system, an appropriate regulatory environment, social facilitation, institutional implementation, environmental impact evaluation, human capitalisation, and training, as well as implementing a robust, reliable, and sustainable monitoring and evaluation framework (MEF).

In this study, we present the vulnerability of micro-grids to an increase in electrical load. Various approaches to load balancing and proposals based on early retro-fit considerations for micro-grid planners are addressed.

3 Methodology

A promising mini-grid design requires careful estimation of the expected power and energy requirements, the identification of suitable generation and storage technologies, as well as good knowledge of the local rules and regulations governing power generation, distribution, and sales.

To illustrate the problem of growing electricity demand due to the migration or increased consumption due to increasing prosperity, the focus of this study is in particular on the load assessment, the socio-cultural background, and the MEF used. The technical layout developed and optimised for the village and resulting system components are presented as far as necessary for the problem. Economic parameters and the integration into a local electricity tariff system are also considered taking the local circumstances into account.

3.1 Load profile estimation of un-electrified villages

The development of a robust energy consumption scenario for rural, less developed, villages after initial electrification is still a major challenge for developers. Individual consumption behaviour, financial capacities, and specific needs influence the resulting load profile on a great amount, especially on small-scale mini- and micro-grids. Socio-cultural differences also make it more difficult
been a significant scientific contribution to this subject. In contrast, there has been relatively little effort to deal with load profiles of rural mini-grids using renewable energies. In particular, the development of private electricity consumption after initial electrification has been neglected so far.

3.2 Power system design
The following framework was for the grid and generation design identified based on funding, the intention of granting agencies, and the admired location of the mini-grid:

- robust, well-known technology, application proven
- easy to maintain
- high share of renewable energies
- high availability of power with a grid-like supply quality
- capital investment within the fund given budget
- local supplier
- local technicians for installation, operation, and maintenance
- local recycling option
- option for future main grid connection and end of line support by the generation system
- possibility for retro-fitting depending on demand evolution

The simulation software HOMER [10] has been used to identify the optimal supply strategy within the given boundaries.

3.3 Levelised cost of electricity (LCOE)
Even though ENGINEER is a social development project, fair cost calculations are necessary to assure the dissemination and replicability of the system. Calculation of true cost is essential for other municipalities to see mini-grids as an option for the electrification of rural villages. Nevertheless, regulations in South Africa and the obligations of municipalities differ from other countries and influence the cost and return of investment calculations for public and private power suppliers.

Access to energy is a fundamental right in South Africa and power tariffs in South Africa are regulated and approved by the National Energy Regulator South Africa (NERSA). Electricity tariffs are therefore highly regulated in particular for the poor, indigenous, and low-income communities, and must be approved by NERSA. Furthermore, households with an income <2000 ZAR/month benefit from a free allowance of at least 50 kWh/month. This must be provided by the responsible municipality by electric power or, if the household is not connected, by other energy carriers such as paraffin or gas as a supplement.

For the area of Raymond Mhlaba Municipality approved tariffs for domestic consumption are

- 0.8821 ZAR/kWh for the first 50 kWh and
- 1.1199 ZAR/kWh for the next 300 kWh

in a month. Saving of cost for the provision of supplemental energy carriers is included for the municipal grid owner. All capital cost [capital expenditure (CAPEX)] of this South African mini-grid is covered by different South African and German funds. For replicability reasons, LCOE was calculated with and without CAPEX. Depreciation is excluded from the LCOE, as well as the interest rate. The cost of diesel is assumed to be constant as highly volatile diesel prices have been proven unpredictable.

3.4 Monitoring and evaluation framework (MEF)
The aim of the latest phase of the project is to design a systematic approach to develop a sustainable MEF for photovoltaic (PV) hybrid mini-grids by integrating cutting-edge technologies and smart methods in a scalable platform of replicable solutions towards connecting the mini-grid with diverse stakeholders with enhanced observability of both generation and consumption profiles.

A sustainable MEF can facilitate the flow of essential data to various stakeholders, including governmental organisations, utility operators, consumers, research institutes, investors, universities, and local authorities to manage, evaluate, and optimise the system.

The measured and collected data can be used to generate ‘standard or reference’ load profiles for rural households or communities. These profiles are for mini-grid researchers and developers active in sub-Saharan Africa. The MEF is aimed at providing the following advantages: real-time generation/consumption monitoring, accurate, high-resolution load profile generation, observation/analysis of the demand evolution, on-going design optimisation, and seamless data access to all stakeholders.

3.5 Development of key performance indicators (KPIs)
To monitor, evaluate, and optimise the mini-grid, a set of KPIs is developed through a technical workshop with all the stakeholders. A hybrid approach is used to develop the KPIs including a measurement-based approach, considering the installation of hardware components to measure energy and contextual data required for KPI calculation, and a model-based approach by defining the configuration parameters and mathematical formulas required for KPI analysis (i.e. system average interruption duration index). The mechanisms, equipment, and software to support the MEF should be well-thought-out and designed in the early stages of development. The identification of a number of key indicators to evaluate, compare, and aggregate global data on renewable energy mini-grid systems is the main challenge.

Through recent smart grid technology developments, it is becoming easier to monitor and track the production of each component of hybrid systems. Smart metering enables enhanced and cost-effective monitoring and management of all the assets on a grid thus improving resource efficiency. Smart metering, remote asset monitoring, and pay-as-you-go technology frameworks have significantly improved mini-grid operational efficiency.

4 Results
4.1 Load profile
The estimated load profile is based on the expectations of villagers regarding needed or aspired electrical applications, their available budget for the payments, and limitations of power systems capacity.

4.1.1 Wealth and available budget: Over 90% of Upper Blinkwaters population have an income below the South African poverty line of 2000 ZAR/month. Sources of income are mainly social grand, child grant, disability grant, and pension. The self-assessment of villagers regarding their individual monthly budget for electrical power yielded a mean amount of around 150 ZAR/month with a range of at least 50 ZAR/month (two households) to 250 ZAR/month (two households) at most. Three households did not provide information on their budget.

4.1.2 Favoured electrical applications: Upper Blinkwater consists of 67 households, no businesses, or public building or further infrastructure such as street lights. All 67 households were interviewed in April 2017. Among other issues, a focus was on their household structure, financial situation, energy consumption, and aspired electrical applications. The survey was designed by the German Project partner and conducted by municipality officials. When asked about the need for electrical applications, the focus was clearly on refrigerators, kettles, electric stoves, televisions, and radios followed by lights, phone charger, microwaves, and street lights (cf. Fig. 2).

4.1.3 Estimated load profile: For the estimation of the Upper Blinkwater load profile, 55 of the 67 households were considered. The other 12 houses are not within the vicinity of the mini-grid. These far off lone-standing houses will be supplied with an isolated solar home system that is not part of this study. In the first year of energy access, a mean daily consumption of 3.85 kWh per household is assumed, assuming a slight distribution regarding the energy consumption per household caused by the different
opportunities, the available budget for electricity, and the free allowance for the poor population of South Africa. Although the individual household budget is very limited first power consumption is not expected to be extremely low, as old and energy in-efficient electrical applications are available due to second-hand use of appliances from relatives living in bigger cities. Ten years of load development was calculated including some system losses (e.g. theft) and an increase of connections and wealth (see Table 2 and Fig. 4).

An increase in load is driven by an increase in population. The number of plots is expected to rise from 55 to 78 in ten years. An increasing amount of electrical devices as well as an increase in prosperity reinforces this effect and lifts the mean annual individual consumption from around 1.4 to 2.1 MWh (cf. Table 2). Based on the individual household income and budget for electricity a tier distribution III/IV/V of 6/43/6 is assumed, after ten years the distribution is expected to shift to 0/43/35.

Within the first ten years of the project runtime, the total electricity consumption of the village is expected to double with a median demand of 18 kW and a maximum peak demand of 85 kW (cf. Fig. 3b). The distribution throughout the day is not expected to change with years passing by. The increase in electricity consumption, whether due to migration or increased individual consumption, fits the data from the Habaswein project in Kenya. In this implemented hybrid mini-grid, an increase in load of ~20% was measured within 2 years [11].

4.1.4 Data-driven load profile generation and analysis: The MEF provides the opportunity to streamline the flow of real-time energy data (generation, consumption, and storage) from the system to generate accurate and high-resolution data-driven load profiles for rural households or communities. These profiles are used for studying and analysing the evolution of demand and making on-going design optimisation. The following features have been considered as the base requirements for the MEF system:

(i) Data collection (economic, automatic, accuracy, resolution, compatibility etc.)
(ii) Data transfer and storage (economic, reliable, automatic, wireless etc.)
(iii) Accessibility of data (cloud-based and online view via internet and remote access)
(iv) Security of data (secure servers, authenticated etc.)
(v) Scalability (envisioning the growing demand and size)

4.2 Development of KPIs

In the first step, the main features of MEF and the integrated components are specified. Two types of data sources, energy (i.e. generation, consumption, storage, power quality etc.) and non-energy (i.e. revenues from prepaid electricity meters) are defined as the base to parameterise the mini-grid system. In the next phase, KPIs are categorised into five domains including: technical, operational, financial, social, and environmental according to the specific needs of each stakeholder. In the last step, a data flow scheme is designed and the appropriate metering and telecommunication technologies and software modules are integrated.

Table 2 Load development during ten years considering losses, increase in wealth, and numbers of consumers

| Item                  | Unit    | Item | Item | Item | Item | Item | Item | Item | Item | Item | Item |
|-----------------------|---------|------|------|------|------|------|------|------|------|------|------|
| project time          | year    | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
| no. connections       |         | 55   | 57   | 59   | 61   | 63   | 66   | 69   | 72   | 75   | 78   |
| tier III consumers    |         | 6    | 3    | 2    | 1    | 0    | 0    | 0    | 0    | 0    | 0    |
| tier IV consumers     |         | 43   | 47   | 48   | 49   | 50   | 50   | 49   | 48   | 46   | 43   |
| tier V consumers      |         | 6    | 7    | 9    | 11   | 13   | 16   | 20   | 24   | 29   | 35   |
| summed consumption    | MWh/year| 73.6 | 80.4 | 87.3 | 94.2 | 101.1| 110.1| 120.8| 131.6| 144.1| 158.4|
| kWh/day               |         | 201.5| 220.3| 239.2| 258.0| 276.8| 301.5| 331.0| 360.5| 394.8| 433.9|
| losses                | kWh/day | 10.1 | 11.0 | 12.0 | 12.9 | 13.8 | 15.1 | 16.5 | 18.0 | 19.7 | 21.7 |
| total load            | kWh/day | 211.6| 231.4| 251.1| 271.0| 290.7| 316.6| 347.5| 378.5| 414.5| 455.6|
A hybrid approach is used to develop the KPIs; a measurement-based approach, considering the installation of hardware equipment to measure energy and contextual data required for KPI calculation, and a model-based approach by defining the configuration parameters and mathematical formulas required for KPI analysis.

4.2.1 Data types and KPI domains: Two types of data sources, energy (i.e. generation, consumption, storage, power quality etc.) and non-energy (i.e. revenues from prepaid electricity meters) are defined as the base to parameterise the mini-grid system. In the next phase, KPIs are categorised into five domains including:

- Technical
- Operational
- Financial
- Social
- Environmental

Interpretation: It explains the indicator and how to interpret it, e.g. inverter voltage output and its corresponding unit in volt and the relevant upper and lower expected limits.

Measurement: It shows how this indicator shall be measured correctly and the method.

Baseline: It indicates the base value in year 0 and forms the references for year n + 1.

4.2.2 Data flow scheme: The developed data flow scheme is displayed in Fig. 5. All energy data is collected by the master inverter and forwarded via gateway and wireless modem to the data aggregation unit. Consumption and power quality data measured by the smart meter at household connections points are forwarded wireless towards the data aggregation unit. The data transmitter and mobile booster passing all data, including data from the mobile vending system to the main data storage for processing, monitoring, and evaluation.

The collected data will be used to identify further key performance parameters to develop an objective standardised trigger for retro-fitting of mini-grids. Normal load profiles for first electrification and evolution pathways are to be developed, too.

4.3 System design and performance

The final design for tendering consists of 75 kW_{peak} PV power. South Africa is part of the so-called ‘sunbelt’ countries and according to the data of a typical meteorological year Upper Blinkwater experiences mean irradiance of 210 W/m² (maximum at 1.4 kW/m²) and a summed energy of 1836.6 kWh/m². The huge solar potential and strong spatial variability of wind potential especially in rough and hilly environments were the many driving factors for the decision. Wind, on the other hand, has a very strong spatial dependence both in the main wind direction and in the distribution of wind forces. Therefore, a wind turbine-based energy system requires a preliminary wind measurement campaign that cannot be replaced by an existing wind atlas. Running water and biomass energy were rejected due to the weather and environmental conditions at Upper Blinkwater. Around 280 kWh lithium ion battery storage will be installed on the DC side of the system. The higher capital costs of lithium ion batteries are compensated by a higher usable capacity, less degradation, respectively, higher lifetime and better performance in hot climates. Furthermore, South Africa has a young emerging lithium ion battery economy and is an of the leading countries developing an lithium ion recycling strategy [12].

An additional 40 kW diesel generator for back up and times of very high peak load will add support on the AC site of the grid. Three converters of 20 kW each will be used to form the grid, feed DC power to AC grid, and enable battery charging from the diesel generator.

All converters are supposed to be able to work bi-directional, as inverter and rectifier, and offer grid forming abilities. The grid will be formed by one of the inverters, leaving two inverters to take over in case of a technical failure. A simplified model of the system setup is shown in Fig. 6. Illustrated is also a potential retrofit connection of a M-WT either on the DC side of the power generation or on the AC bus. A research group of South Africa Wind Energy Project (SAWEP), Council for Scientific and Industrial Research (CSIR), and the Wind Atlas South Africa group is analysing the most beneficial wind retro-fitting for the mini-grid system. The higher capital costs of lithium ion batteries are compensated by a higher usable capacity, less degradation, respectively, higher lifetime and better performance in hot climates. Furthermore, South Africa has a young emerging lithium ion battery economy and is an of the leading countries developing an lithium ion recycling strategy [12].

An additional 40 kW diesel generator for back up and times of very high peak load will add support on the AC site of the grid. Three converters of 20 kW each will be used to form the grid, feed DC power to AC grid, and enable battery charging from the diesel generator.
This surplus energy can be used to create and support business models. Thus, the villagers' survey revealed the need for a larger cooling facility to collect and cool the proceeds of gardening such as fruit and vegetables for future sale. In the first year, a median of 106 kWh/d is available for further use.

The system response to a winter day with reduced solar irradiance is shown in Fig. 8a as an example of the system response on difficult days. The battery state of charge (SOC) during morning hours is high enough (SOC = 64%) to fulfil the forecast electricity demand of Upper Blinkwater. During daytime, solar irradiance starts to supply the demand and manages to even charge the batteries up to their overcharge protection limit. Demand after sunset is easily supplied by the battery system which ends the day with a lower SOC (SOC = 51%). The diesel generator does not have to be used under these conditions, but the usable potential of the excess energy is also comparatively low.

4.3.2 Ten years of system performance development: Excess energy, without further businesses, will be reduced significantly from around 30% down to 6% (cf. Fig. 7b). On average days, no excess energy would be available for further use. On 37 days of the tenth year, >10 kWh/d is available.

The amount of unmet load will increase slightly to about 1% (cf. Figs. 7d and 9). During 130 days, the demand at 6 pm is missed by 5.1–42 kW. The median unmet power of the whole year is still zero whilst the median of unmet power during the 130 days

---

Fig. 7 Daily distribution of excess power during the first and tenth year. The median excess power is indicated with a bold line. The distribution of the maximum of demand, unmet load and excess power of the first and tenth year is displayed in the lower row

(a) First year: excess power is available from noon to 5 pm up to a median peak of 34.1 kW. (b) Tenth year: there is no excess electricity available on average days. (c) First year: the maximal unmet load is <1 W. (d) Tenth year: the maximum of excess power with 34 kW and unmet load with 42 kW are in the same range and the demand increased to a maximum of 83 kW.

Fig. 8 System response during the day with the highest amount forecast unmet load in the tenth year. The left graph displays the very same day of the first year. The estimated power consumption of the village is shown in the upper graph. PV and diesel power output is shown in the second graph. Battery SOC is shown in graph three, charge and discharge power in the fourth graph. The bottom graph displays unmet load and excess electricity of that day in kW

(a) First-year system response, (b) Tenth-year system response
is in the order of 9 kW, respectively, 10% of the peak demand. This equals a maximal unmet energy demand of 51 kWh/day with a mean of 5.1 kWh/day or a median of 0 kWh/day. With empty batteries and no solar power, the diesel generator is covering the electricity demand during day time. At the time of peak demand, however, the capacity of the diesel generator is no longer sufficient, so that almost 40% of the total demand cannot be covered.

Increasing load raises the use of fossil fuel from around 610 to 25,000 litres in the tenth year to fulfil the villagers’ needs without further installation of renewable generation capacity (cf. Fig. 10). This corresponds to an increase of four while the share of renewable energy reduced by 2.4 from 98.5% down to 62.7%.

For representation, the day with the highest amount of unmet load of the tenth year is displayed in Fig. 8b. The demand during morning hours and low PV power will be satisfied by the installed diesel generator, as the SOC of the battery bank is already very low. The summed energy supplied by the PV system corresponds to around 54% of the daily maximum. This is still enough to supply electricity during the daytime and charge the batteries a bit. The electricity requirement in the evening, however, cannot be covered with the maximum power of the diesel generator. A total amount of 51.4 kWh with a maximal power of 25.8 kW will not be met in this scenario. The corresponding day of the first year with the same environmental conditions is shown in Fig. 8a. In contrast to the tenth year, in these days morning during the first year, the batteries are not fully discharged and thus able to meet the electricity demand. At sunrise, the village is supplied by the PV system, which also charges the batteries to their maximum capacity. Therefore, even the evening electricity requirement can be completely covered by renewable energies. A small amount of around 1.8 kWh excess energy needs to be curtailed.

On such a cloudy day with low PV power, the generation system cannot cover the high peak demand even though the total amount of unmet load and missing annual capacity is only around 1%. Another strategy to charge the battery system with the diesel generator would be able to cover this problem introducing an even higher diesel consumption. A combination of high demand with low PV power results in a maximum degree of capacity utilisation of the diesel generator. There is a lack of around 10 kW generation power to cover the full demand.

4.4 Levelised cost of electricity (LCOE)

The calculated LCOE covering ten years of project time are around 2.4111 ZAR/kWh. This includes a dense operation and maintenance schedule to ensure a very high quality of power supply, training for administration and technician, cost of diesel (13.3 ZAR/l), replacements costs and spare parts. The share of fossil fuel cost of the diesel generator on the LCOE increases strongly during the project time (cf. Table 3). The estimated cost of energy substitutes such as paraffin (including cost of transportation) per household within the Raymond Mhlaba Municipality area of responsibility is around 5 ZAR/kWh if equalised to 50 kWh.

5 Conclusion

The designed generation system is able to cover the estimated demand. All parameters given by the ‘MTF’ of the WORLD BANK Group are successfully covered. However, a cost reflecting tariff on the basis of LCOE would be too high to be approved by the legislation agency NERSA. The main driving factor in the long term for increasing LCOE is fossil fuel consumption caused by increasing energy demand. Discussions with all stakeholders revealed three possible strategies as countermeasures.

Owing to the remoteness of the village to the existing national grid and future planned extension (closed planned substations are located in about 60 km range and will be developed in 6–8 years) and geographical challenges including protected nature areas isolating the site a renewable hybrid mini-grid solution was proposed to meet the electrification challenge for the community of Upper Blinkwater. With the feed-in ability, the mini-grid generation capacity can be used after a future connection to the main grid for the benefit of power supply and power grid stability.

5.1 Reduction of energy demand

Access to electrical power introduces a pull effect on the population. This will increase the number of residents in Upper Blinkwater. Ignoring this situation will cause energy fraud and illegal connections to the grid. Usage of smart meters with the ability to curtail power supply of plots can be used to stabilise the grid and prevent blackouts. SCADA systems can help with the interaction of customers and support load balancing [13]. The comparison of the consumption communicated by smart meters with the monitored generation enables the identification of energy losses due to technical failure, illegal connections, and energy fraud. A social facilitator will be able to communicate, sensitise, and educate the villagers about the power supply and network stability. In this way, village cohesion is used to involve the villagers in securing the power grid and infrastructure by the generation of an ownership feeling.

Table 3 Share of O&M, cost of diesel, vending and replacements during a project time of ten years

| Year | 1, % | 2, % | 3, % | 4, % | 5, % | 6, % | 7, % | 8, % | 9, % | 10, % |
|------|------|------|------|------|------|------|------|------|------|-------|
| diesel | 4 | 7 | 10 | 14 | 19 | 23 | 28 | 35 | 39 | 44 |
| O&M | 68 | 64 | 61 | 57 | 54 | 52 | 48 | 41 | 40 | 37 |
| replacements | 23 | 24 | 24 | 24 | 23 | 21 | 19 | 19 | 17 | 15 |
| vending | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
A sophisticated SCADA system, which is not part of this study, will be implemented to optimise the systems’ behaviour and interaction with community members. An overshot of first consumption will be prevented by the use of prepaid metering. The available power per plot will be reduced in times of very high demand if necessary to prevent blackouts. A facilitation manager is in contact with the villagers to raise awareness and educate on energy topics such as efficiency and time of use.

Another option would be intraday load forecasting [14]. However, these methods require a larger network and a larger storage capacity. Owing to the higher number of consumers, the individual influence on grid stability is significantly reduced. The use of gas stoves to reduce the peak load in the evening is emphasised and supported by a first free batch of funded devices.

However, the possibilities to prevent an increase in demand are very low, especially since an increasing demand is also a sign of the desired increase in prosperity. Moreover, countermeasures that restrict the autonomy of South Africans are not an option due to the complex social, cultural, and historical background of South Africa.

5.2 Increasing generation capacity

The generation system is designed for the first-year demand with some additional capacity for a growing and prospering society. Considering the negligible diesel consumption in the first year and the high surplus energy, a larger design of power generation at the beginning of electricity consumption seems unsuitable. An initial calculation for a mini-grid with the electricity requirement of the tenth year from Upper Blinkwater and a share of renewable energy of +90% results in an unknown storage requirement of 430 kWh with a PV power generation of 161 kW. The summed overproduction after ten years would be nearly 1360 MWh. Degradation of system components, as well as potential loss, of components due to theft or vandalism must be considered in the economic feasibility analysis of an initial overcapacity. Furthermore, there is the possibility that a connection to the national grid may occur sooner than expected that electricity consumption may develop differently than predicted or that even unknown social development may change the general conditions within ten years. These aspects could make a premature investment in power generation capacity unprofitable or even wasteful.

Moreover, the immense upfront investment costs would reduce the chances of replicability to other municipalities or communities without external funds. The definition of key performance parameters to trigger retro-fitting of the generation system is a possible countermeasure. Considerations of measured demand profile and mini-grid system behaviour facilitate the selection of the best power generation technology.

5.3 Adequate framing of a mini-grid

LCOE of mini-grids is generally higher than those of a main and existing distribution grid with cross-subsidisation of generation.

A high backlog in electrification and the high cost of extending the distribution network to small and remote locations relocate the considerations also economically to the benefit of mini-grids. For a public, non-commercial mini-grids owned by municipalities we propose to change the view, from an isolated, independent generation and distribution facility towards a small part of the whole municipal distribution system, just with a gap in between the lines. This allows municipalities to fulfil their supply mission in rural areas. At the same time, a non-discriminatory electricity tariff for the poor population can be guaranteed.

All in all, a small-scale system is vulnerable to changes. The development of solution strategies for future changed conditions should, therefore, be considered from the outset in planning. A sustainable MEF can bridge the gap between the design and operation in the long run. In the case of the presented project, a monitoring system for the mini-grid in Upper Blinkwater provides practical insights into the technical requirements for sustainable, decentralised energy supply and the necessary framework conditions for other regions. Indirectly, other rural areas in South Africa should benefit from the monitoring results, as they should serve as a template for the development of further mini-grids.

6 Outlook

Future work in Upper Blinkwater will focus on monitoring the power system, consumption, and grid parameters and determination of general load profiles for the first electrification of rural villages to close the gap between interview-based demand assumptions and later electrification. Identification of key performance parameters to trigger retro-fitting in advance on the basis of reliable load profiles.

Together with SAWE and the renewable energy group of CSIR (South Africa) a strategy is currently being developed to integrate M-WE into the mini-grid. Particular emphasis is placed on supporting the network under development. Especially since wind turbines with the highest energy gain may not offer the best grid support. Mini-grids provide energy services tailored and optimised for a certain consumer load profile. For renewable hybrid mini-grids, the fluctuating nature of resources adds more complexity to the challenge of maintaining the energy balance. Therefore, having access to accurate load profiles is indispensable for the initial design and optimisation during the operation.

Standard urban household load profiles are quite useful and essential in the field of energy research, and there has already been a significant scientific contribution to this subject. In contrast, there have been relatively fewer efforts to address rural load profiles connected to renewable hybrid mini-grids, especially for rural communities with no access to electricity after gaining a reliable grid-quality service, as the load profiles would evolve over time. It is the great willingness and support of other political and local stakeholders such as the Eastern Cape Rural Development Agency (ECRDA), NERSA, Department of Energy (DoE), and the CSIR.

7 Acknowledgments

The authors would like to thank the Lower Saxony Ministry for Environmental Affairs, Energy, Building and Climate Protection, the Department of Economic Development, Environmental Affairs and Tourism of Eastern Cape and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH as well as the Federal Ministry for Economic Cooperation and Development (BMZ) for the given trust and support within this project. Special thanks also to the Raymond Mhlaba Municipality for the readiness and support of an in South Africa still unusual approach. Also, to be mentioned is the great willingness and support of other political and local stakeholders such as the Eastern Cape Rural Development Agency (ECRDA), NERSA, Department of Energy (DoE), and the CSIR.

8 References

[1] CDC Group plc.: ‘Development impact evaluation, evidence review what are the links between public, economic growth and job creation? CDC in partnership with the overseas development institution’, January 2016
[2] WORLD BANK GROUP: ‘Poverty & equity data portal of the WORLD BANK group’, Available at http://povertydata.worldbank.org/poverty/country/ZAF; accessed August 2018
[3] Mandelli, S., Barbieri, J., Moreu, R., et al.: ‘Off-grid systems for rural electrification in developing countries: definitions, classification and a comprehensive literature review’, Renew. Sustain. Energy Rev., 2016, 58, pp. 1621–1646, https://doi.org/10.1016/j.rser.2015.12.338
[4] Nema, P., Nema, R.K., Rangnekar, S.: ‘A current and future state of art development of hybrid energy system using wind and PV-solar: a review’, Renew. Sustain. Energy Rev., 2009, 13, pp. 2096–2103, https://doi.org/10.1016/j.rser.2008.10.006
[5] Luna-Rubio, R., Trejo-Pere, M., Vargas-Vázquez, D., et al.: ‘Optimal sizing of renewable hybrids energy systems: a review of methodologies’, Sol. Energy, 2012, 86, pp. 1077–1088, https://doi.org/10.1016/j.solener.2011.10.015
[6] Sinha, S., Chandel, S.S.: ‘Review of software tools for hybrid renewable energy systems’, Renew. Sustain. Energy Rev., 2014, 32, pp. 192–205, https://doi.org/10.1016/j.rser.2014.03.035
[7] Hartzviggson, E., Ahlgen, E.O.: ‘Comparison of load profiles in a mini-grid: assessment of performance metrics using measured and interview-based data’, Energy Sustain. Dev., 2018, 43, pp. 186–195, https://doi.org/10.1016/j.esd.2018.01.009
[8] Blodgett, D., Duenhauer, P., Louie, H., et al.: ‘Accuracy of energy-use surveys in predicting rural mini-grid user consumption’, Energy Sustain. Dev., 2017, 41, pp. 88–105, https://doi.org/10.1016/j.esd.2017.08.002
[9] Bhatia, M., Angelou, N.: ‘Beyond Connections – Energy Access Redefined, Executive Summary of the conceptualization report’. ESMAP Technical Report, 088/15, World Bank, Washington, DC, 2015. Available at https://openknowledge.worldbank.org/handle/10986/24368 (License: CC BY 3.0 IGO)

[10] HOMER Energy Pro.: Available at https://www.homerenergy.com/products/pro/index.html

[11] Micangeli, A., Giovanni Santori, S., Del Citto, R., et al.: ‘Energy production analysis and optimization of mini-grid in remote areas: the case study of Habauwein, Kenya’, Energies, 2017, 10, Article ID: 2041, doi: 10.3390/en10122041

[12] Knights, B.D.H., Saloojee, F.: ‘Lithium battery recycling – keeping the future fully charged, green economy research report, research and policy development to advance a green economy in South Africa’ (Department of Environmental Affairs Republic of South Africa and Greenfund and Development Bank of South Africa, 2015)

[13] Palma-Behnke, R., Ortiz, D., Jiménez-Estévez, G., et al.: ‘A social SCADA approach for a renewable based microgrid – the Huatacondo project’. IEEE, Guangzhou, China, July 2019, doi: 10.1109/PES.2011.6039749

[14] Sidorov, D., Tao, Q., Muftahov, I., et al.: ‘Energy balancing using charge/discharge storage control and load forecasts in a renewable-energy-based grids 38th China control conference 2019’, arXiv:1906.02959