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DYNAMIC SIMULATION OF PERFORMANCE AND COST OF HYBRID PV-CSP-LPG GENERATOR MICRO GRIDS WITH APPLICATIONS TO REMOTE COMMUNITIES IN DEVELOPING COUNTRIES

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ABSTRACT

Energy infrastructure in rural areas of developing countries is currently deployed on an ad-hoc basis via grid extension, public and private sector solar home system (SHS) service using photovoltaic (PV) panels, and community distributed generation systems, also called mini or micro grids. Universal access to energy is increasingly pursued as a policy objective via e.g. the U.N. Millennium Develop Goals (MDG), Sustainable Energy for All (SE4All), and U.S. Power Africa initiatives. Rational allocation of energy infrastructure for 1.6b people currently lacking access requires a screening process to determine the economic break-even distance and consumer connection density favoring topologically diverse energy technology approaches. Previous efforts have developed approaches to determine grid-connection break-even distances, but work on micro-grid and SHS break-even distance and density is limited.

The present work develops an open access modeling platform with the ability to simulate various configurations of PV, Concentrating Solar Power (CSP), and fueled generator backup systems with exhaust waste heat recovery. Battery and thermal storage options are examined, and typical meteorological year (TMY) data is combined with probabilistic and empirical load curve data to represent the appropriate physical dynamics. Power flow control strategy and infrastructure is optimized for a minimum tariff (USD/kWh) for cost recovery. Cost functions derived from manufacturers' data enable performance and economic assessment for a case study micro grid in Lesotho.

NOMENCLATURE

CSP Concentrated Solar Power
DNI Direct normal Insolation
HTF Heat transfer fluid
I Irradiance
ICT Information and Communications Technology
M Maintenance
O Operation
ORC Organic Rankine Cycle
T Temperature

Subscripts

amb Ambient
b Beam
col Collector
e electric
ex Exhaust
HTF Heat transfer fluid
SHS Solar Home System
su Supply
t thermal
WF Working fluid

INTRODUCTION

The IEA forecast of 37% growth in energy consumption from 2015-2040 is projected to occur largely (85%) in developing economies [1]. The 'Power Africa' initiative launched by the Obama administration has set a target for an additional 10GW of capacity to double access to energy in sub-Saharan Africa [2]. The United Nations, which calls for universal access to energy by 2030 in its Sustainable Energy for All action agenda, reports that approximately 55% of new connections will depend on micro grid and off-grid solutions, while calling for a doubling in the share of renewables in the energy generation mix [3]. According to Navigant research, revenue from micro grids (including off-grid, commercial, municipal and military) will increase from USD 10 billion in 2013 to over 40 billion annually by 2020 [4]. Micro grids with renewable energy generation thus have an important role to play at the intersection of energy access, economic development, and climate change, and there is a growing need for implementation best practices that include decision tools for determining where and how to optimally deploy micro grid infrastructure. The emergence of ICT solutions for 'Smart Grid' transactional and control functions is increasingly enabling the commercial viability of micro grids for remote and underserved communities, and, interestingly, the load following characteristic and high renewables fraction of these islanded micro grids presents a case where technology evolution driven by the need for energy access may provide the conceptual basis for engineering the macro grids of the future to include a high proportion of solar power.

There are many parameters that influence the go/no-go decision and engineering design approach for a micro grid project, and among these the relationship between capital and operating expenses, demand dynamics and local ambient conditions are of major importance. The site specificity and wide variation in these parameters makes a 'one size fits all' approach problematic and exacerbates the expense associated with evaluating individual opportunities, analyzing feasibility of a micro grid versus alternatives (e.g., grid extension, solar home systems), optimizing the technical design, and projecting financial metrics. In particular, the design and control of micro grids with multiple generation sources is a topic of renewed interest (see [5, 6]) in the wake of declining PV prices (<0.60 USD/W in 2014 [7]) and the cost and availability advantages of hybridization with, e.g., fossil fueled back up generators. Existing modeling packages such as HOMER can be used under license for basic micro grid planning [8], but due to their black boxed algorithms their effectiveness is limited to a few hard-coded configurations that exclude more flexibly optimized hybrid systems.

In this paper we present an open source code holistic methodology which, to a greater extent than previously shown, automates and accelerates the following tasks:

1. Identifying and assessing opportunities for micro grid deployment on the basis of planning documents, satellite mapping, estimated user demand and meteorological data
2. Rationally allocating infrastructure between a blend of possible generators - including Photovoltaics (PV), Concentrating Solar Power (CSP) and reciprocating generator sets operating on a range of available fuels
3. Including storage components, e.g., battery and thermal energy storage (TES)
4. Optimizing the control strategy for integrating energy flows
5. Designing for economic objective functions such as minimized capital cost or leveled electricity cost (LEC) within a user-defined project financial framework

This approach is exercised in a case study optimizing a hybrid micro grid for providing grid-quality (i.e. driven by user demand rather than scheduled or limited in power delivery) energy access to a remote, off-grid community in sub-Saharan Africa.

MICRO GRID OPTIMIZATION METHODOLOGY

While community-led systems are possible, the relatively high capital and technical requirements involved generally lead to micro grid deployments managed in the context of energy access project frameworks; these in turn may include government or NGO-sponsored or fully subsidized access, private sector investment with earned income revenue from sale of energy (per kWh or a flat service level tariff), or some combination of the above. Broad consensus on what constitutes access to energy is lacking, and although there are emerging international standards concerned with hybrid micro grids (IEC/TS 62257 and IEEE 1547), the design goal for such systems has not been standardized in practice in terms of quantity or timing. The World Bank has proposed a tiered scheme to describe increasing levels of energy service ranging from task lighting to economically meaningful loads [9], but a generalizable process for allocating consumers to tiers and sizing generation accordingly has not been established. In this paper, we avoid the foregoing questions by presenting a simplified framework for micro grid deployment that assumes returns to debt capital for any micro grid operator (government or private sector), revenue from service charges sufficient to maintain positive cash flow and achieve cost recovery, and a level of service at the connection nodes for islanded consumers comparable to the level of service for similar small communities served by the grid. We also assume a business model comparable to that of an electric utility with metering and electricity tariff on a currency per unit energy consumed (e.g. USD/kWh) basis, and note that a suite of ICT solutions exists enabling transactions via e.g., smart metering [10] and mobile money platforms (e.g., M-Pesa, Airtel Money).

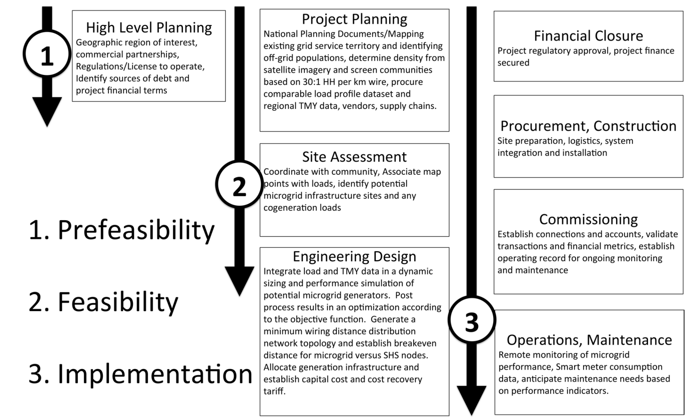

FIGURE 1. FLOW DIAGRAM OF THE MICRO GRID DECISION PROCESS

MICRO GRID DECISION PROCESS

Fig 1 shows a flow diagram outlining the process of identifying where and deciding whether and how to deploy a micro grid in the framework of an energy access project. Key steps in this process include the delineation of grid and off-grid service territory, by, e.g., utilizing national planning documents, energy service provider maps, satellite imagery, etc., and the identification of population centers of sufficient size and density to warrant further investigation. The expected trajectory and timeline for grid extension and community density indicate situations where micro grids are eliminated as an option: proximity to a soon to be extended grid and low household density favoring solar home systems (SHS). The thresholds for this may vary according to the micro grid proponent and would need to be assessed relative to the expected project payback period; in this study areas within 15km of grid service territory and household densities below a minimum of 10 per km of connecting wire are excluded. Once site selection criteria have been met, a detailed analysis of the hybrid micro grid design can proceed on the basis of load inference and position, and meteorological data. Insolation on a latitude tilt surface from e.g. NASA SSE datasets and direct normal irradiance (DNI) and temperature from TMY or local measurements are used to quantify the solar resource for PV and CSP generation and the ambient losses for thermal storage. As with HOMER or any other hybrid micro grid simulation tool, accurate dynamic modeling of the energy physics will only be useful in the context of appropriate load dynamics, which are often poorly characterized. In the following sections a methodology for constructing a dynamic load profile and allocating an optimal mix of generation and storage is described for a case study village in Lesotho, southern Africa.

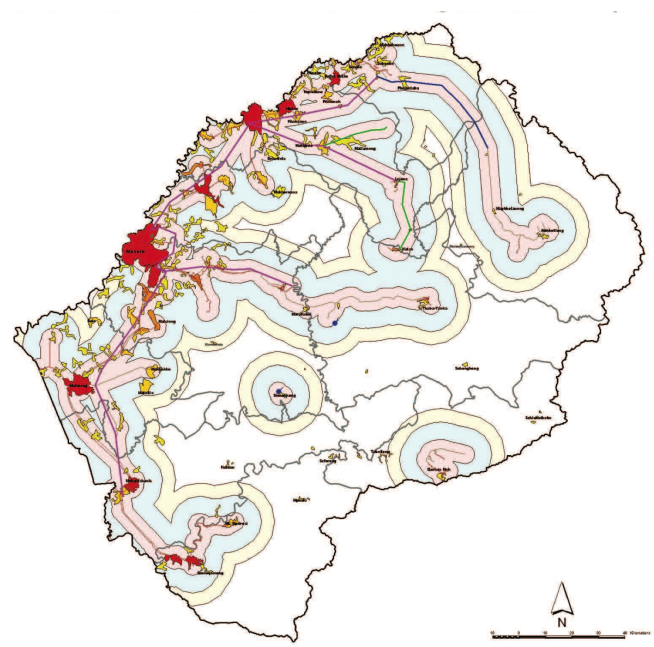

FIGURE 2. SERVICE TERRITORY, 15KM BUFFER ZONE, AND AREAS DESIGNATED FOR OFF-GRID SOLUTIONS IN LESOTHO [11]

Case study: Ha Nkau village, Lesotho

Following the process outlined in Fig. 1, the National Electrification Master Plan (NEMP) for Lesotho was consulted along with input from the government Department of Energy and the Lesotho Electricity Corporation (LEC). An excerpt from the NEMP is shown in Fig. 2, detailing the current and projected service territory for the LEC. Communities outside of the service territory were earmarked for off-grid solutions and a subset of these were analyzed using satellite imagery to map the settlements, locate building geoposition, determine the layout and calculate the density of the communities. Mapping services were obtained from Gridform and Developmentmaps [12, 13]. Integrating these inputs creates a pool of candidate communities for micro grid deployment, from which Ha Nkau (0° 2'3.84"S 28°1'58.68"E), a settlement of 84 households, 5 small businesses, a school, church and health clinic, is selected for a case study in this paper. During an onsite assessment conducted in November 2014, the building types (household, small business, clinic, school, etc.) were mapped, and the village leadership was consulted to estimate household consumption levels and assign number of persons per household. This data and the layout of buildings in Ha Nkau was processed using the ViPOR program [8] to identify a distribution network topology minimizing the connecting wire (Fig. 3). To connect Nkau's households, small businesses, and institutions requires approximately 5km of distribution wire, or about 18 connections per km.

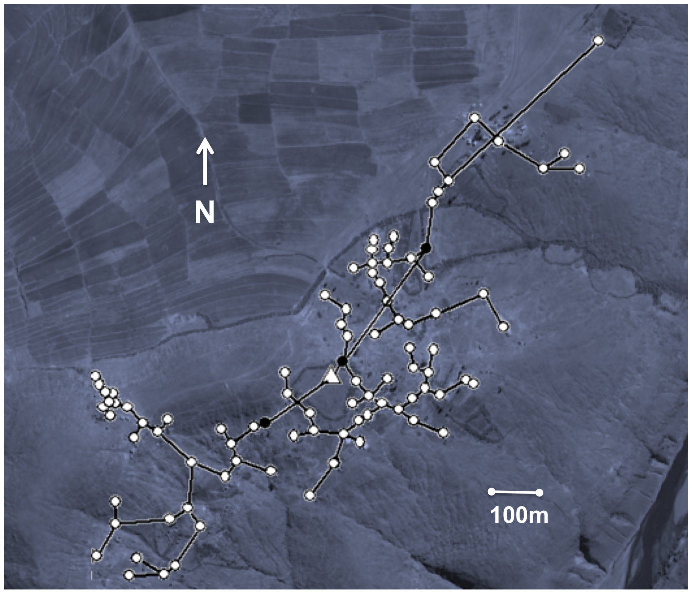

FIGURE 3. 92 CONNECTION MICRO GRID DISTRIBUTION NETWORK LAYOUT FOR HA NKAU, LESOTHO.

Modeling Methodology
PROBABILISTIC LOAD INFERENCE

Accurate anticipation of design loads is a critical determinant for optimizing micro grid infrastructure. In this study, the extent and timing of loads is derived from data for comparable on-Grid communities (in terms of geography, size, and demographics) to create a probabilistic distribution function at the household level, supplemented with load measurements taken previously at remote health clinics in Lesotho [14]. For this community micro grid study, high temporal resolution (5 minute) consumption data was drawn from the South African NRS load research dataset [15] and screened for proximity to Ha Nkau and similitude in community composition. Dipelaneng, a small farming community with 93 monitored households in the Mantsopa municipality of South Africa (located about 100km from Ha Nkau) serves as the model for household load distribution.

The generation of the simulated load profile for Ha Nkau makes use of load data and corresponding metadata stored in a database (e.g., MySQL), while a Load Curve Generator script in Matlab pre-processes data subsets to quantify adequacy and generate characteristic loads using a probabilistic distribution function (PDF). In this study household and clinic load data is utilized as additional load types are added through ongoing load monitoring data collection efforts. An assembler builds community level PDF load profiles from lower level profiles based on user input information (building type, persons) about the community nodes assessed during the site visit. The micro grid simulation model, described in the following section, receives an annual load profile

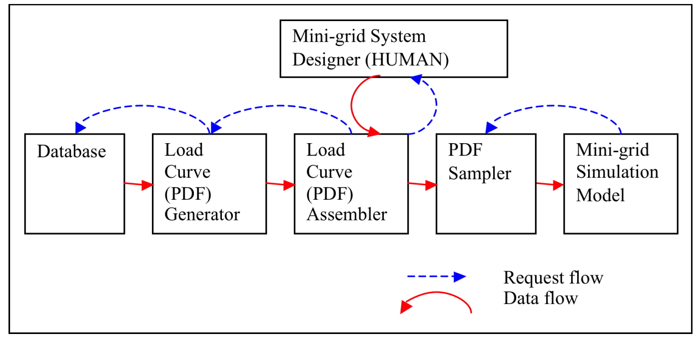

FIGURE 4. SYSTEM LEVEL DESCRIPTION OF THE LOAD-ESTIMATION PROGRAM

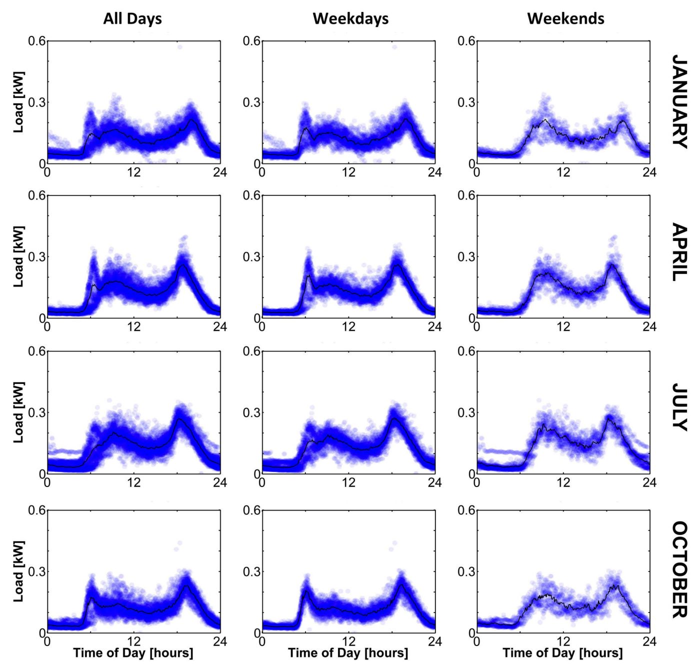

FIGURE 5. COMPARISON HOUSEHOLD LOAD DATASET FROM DIPELANENG, SOUTH AFRICA, SELECTED MONTHS BY QUARTER WITH WEEKDAY AND WEEKEND PROFILES

(differentiated by weekday, weekend and seasonally) at predefined timestep resolution (in this study, 10 minutes). The quarter-monthly and weekday/weekend household level load PDFs for Dipelaneng are shown in Fig. 5, and the constructed aggregate community level load profile for Ha Nkau (built in 10-minute time steps) is shown as a daily average in Fig. 6. The peak instantaneous load in the simulated load curve is 45kW, and the average daily consumption at the HH level is 2.85kWh day^{-1}.

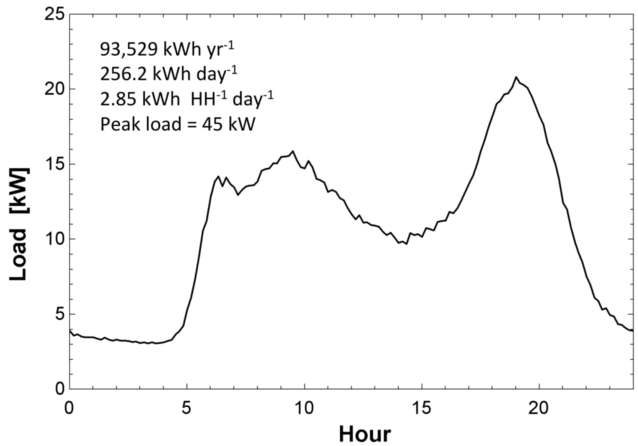

FIGURE 6. AVERAGE INFERRED DAILY LOAD CURVE FOR 84 HOUSEHOLDS AND HEALTH CLINIC (HA NKAU, LESOTHO)

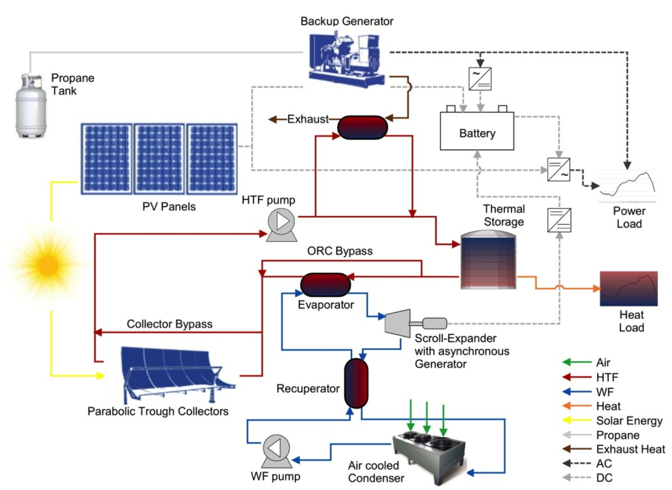

FIGURE 7. HYBRID MICRO GRID INCLUDING PV, CSP AND LPG WITH BATTERY AND THERMAL ENERGY STORAGE

DYNAMIC SIMULATION METHOD

Figure 7 illustrates the power plant topology in a fully integrated hybrid configuration of PV, CSP, ORC, and LPG generation considered in this study. A hybrid micro grid invokes the concept that a portfolio of generators is able to leverage the strengths of certain generator types against the weaknesses of others. For example a genset has a low first cost but high operating costs and emits CO_2, while for PV is the reverse is true; solar is intermittent while gensets have a high capacity factor; chemical battery storage is more expensive than thermal energy storage, but CSP is more costly than PV; the presence of a chemical battery mitigates the part load penalty for gensets, etc. The task of the model, implemented in Engineering Equation Solver (EES), is to determine which combination of generators, in what size of installed capacity, under which operating control strategy, is able to meet variable demand at a minimum cost (i.e., cannot be undersized and should not be oversized). The simulation of energy flows for the generation portfolio starts from the assumption that the micro grid is designed to meet 100% of projected loads (drawn from the PDF in 10 minute time steps), and because only fuel-based generators have a close to 100% availability each simulated configuration includes a backup generator at a minimum, with other energy equipment blended into the mix in a parametric sweep of the design space. For each unique configuration, the model proceeds through each time step and allocates the output of an available generator or combination of generators to meet the load. The generators include PV modules (modeled at latitude tilt and temperature compensated), Parabolic Trough Collectors (PTC), packed bed thermal energy storage (TES), organic Rankine cycle (ORC), electrochemical batteries, and an LPG fueled generator with optional exhaust gas waste heat recovery. To reduce computational time, representations of complex components have been implemented as functions derived from fitted data from either detailed model output or experimental measurements. The physics based models or experimental datasets used are described fully in [14, 16–18]. The source code used in this study is available online at web.mit.edu/mso/www/uGRID.zip.

TABLE 1. RANGE OF TECHNOLOGIES REPRESENTED IN MICRO GRID DESIGN SIMULATIONS

Generator	Source	Storage
PV	Solar	Battery
ORC	CSP	TES
LPG Genset	Fuel	Battery
Inverter	Storage	Battery

The power plant equipment represented in the model is listed in Table 1, and the operating states of the micro grid corresponding to the permutation of generators, along with the major control linkages guiding the operating strategy, are illustrated in Fig 8. Additional features of the hybrid micro grid dynamic simulation include waste heat recovery from the exhaust of the genset (in the case where an ORC is present) and generator 'smart' charging of the battery bank to preserve its capacity for solar storage, by means of a shutdown triggered by assessment of the battery state of charge with respect to prediction of the pre-dawn load energy residual.

In the limiting, non-hybrid case, the generator supplies

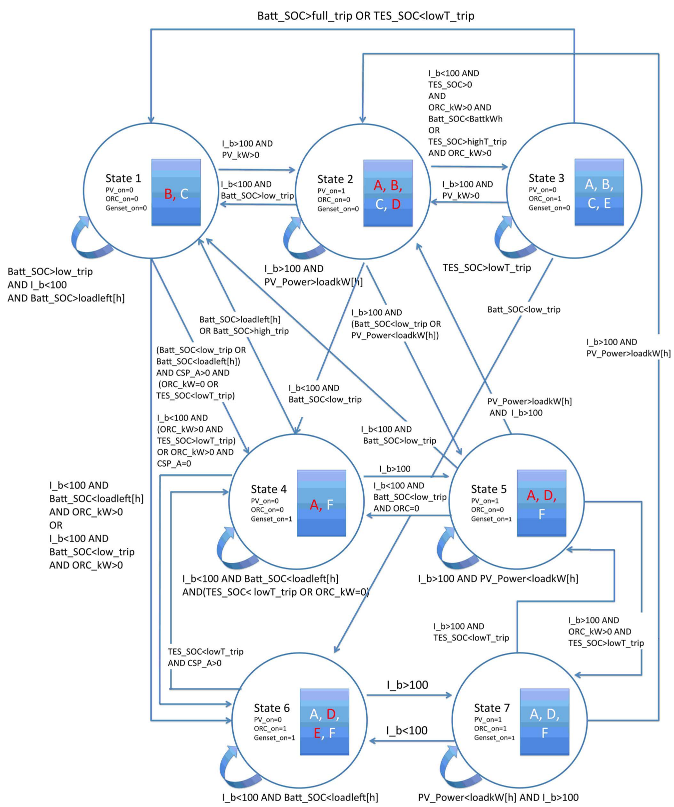

FIGURE 8. STATE TYPE DIAGRAM FOR SIMULATION AND CONTROL ALGORITHM. A: BATTERY CHARGING, B: BATTERY DISCHARGING, C: INVERTER ON, D: TES CHARGING, E: TES DISCHARGING, F: GENSET ON. RED LETTERS INDICATE OPTIONAL OPERATIONS PROVIDED THE NECESSARY COMPONENT IS INCLUDED IN THE SYSTEM

100% of the load year round, and the effect of adding in other generators is to reduce the fuel consumption, possibly even to zero in configurations with ample storage capacity. The output of the model is a time series of data including the load profile, solar dynamics (DNI) and ambient temperature, the state of charge of the battery bank and TES (if simulated), input to storage from PV, CSP, ORC, or LPG Genset, and the respective contributions to the load from the inverter or generator. The calculated fuel consumption (kg year^{-1}), load profile integral (kWh year^{-1}), and initial capacity allocation is post-processed in a cash flow analysis. The capital costs of equipment are obtained via debt of variable interest and tenure, and the operating and maintenance costs are derived from the dynamic simulation output (fuel) and manufacturers' cost functions. A parametric sweep of potential configurations creates a matrix of outputs, and an iterative method is used in post-processing to calculate the minimum tariff necessary to maintain positive cash flow during the project period while servicing debt and operating and maintaining the

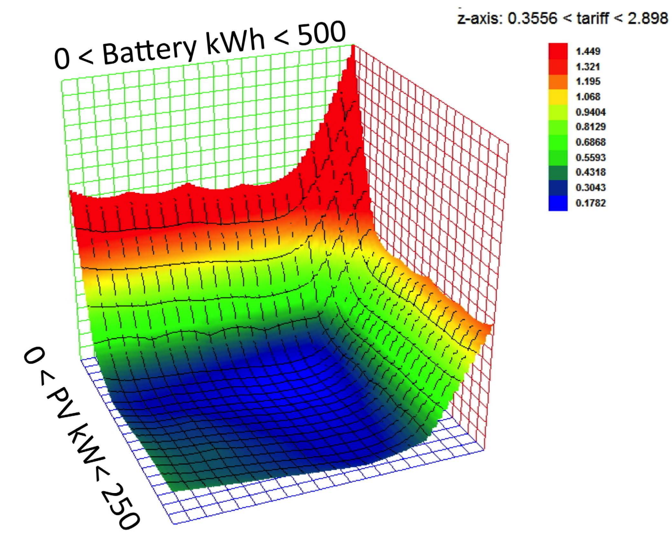

FIGURE 9. MINIMIZED COST RECOVERY TARIFF SURFACE WITH RESPECT TO PV AND BATTERY INSTALLED CAPACITY

micro grid, including periodic battery replacement. The configuration with the minimized tariff can be investigated further and sensitivity analysis performed for cost functions, financial model assumptions, installed capacity, etc.

CASE STUDY RESULTS: HA NKAU, LESOTHO

Using DNI and ambient temperature data from the Lesotho Meteorological Services (collected at Moshoshoe Airport), the load PDF derived from the NRS dataset for Dipelaneng, and the household numbers obtained via satellite images and site survey, a one year dynamic simulation was run for 612 configurations of PV kW, ORC kW, CSP collector area, TES kWh$_t$ and Battery kWh$_e$ on 48 server instances using the Amazon EC2 cloud over a 24 hour period. These 612 simulations were each post processed under 9 cash-flow model scenarios varying interest rate and loan tenure from 5-15% and 5-15 years respectively. While some configurations including CSP and ORC approached optimal, the highest performing system for supplying electricity service (no cogeneration) to Ha Nkau households and clinic and meeting the objective function for the minimized tariff (0.35 USD/kWh) under the most patient capital scenario (5% return over 15 years) for the case study conditions features a PV array of 100kW and battery storage of 200 kWh. Variation in cost recovery tariff as a function of PV and battery installed capacity is shown in Fig. 9. Excerpts from the optimized micro grid configuration illustrating system state and power flow indicate the level of detail in the dynamic simulation output (Fig. 10).

The projected capital cost of the micro grid power plant, distribution network and balance of system is approximately 235k

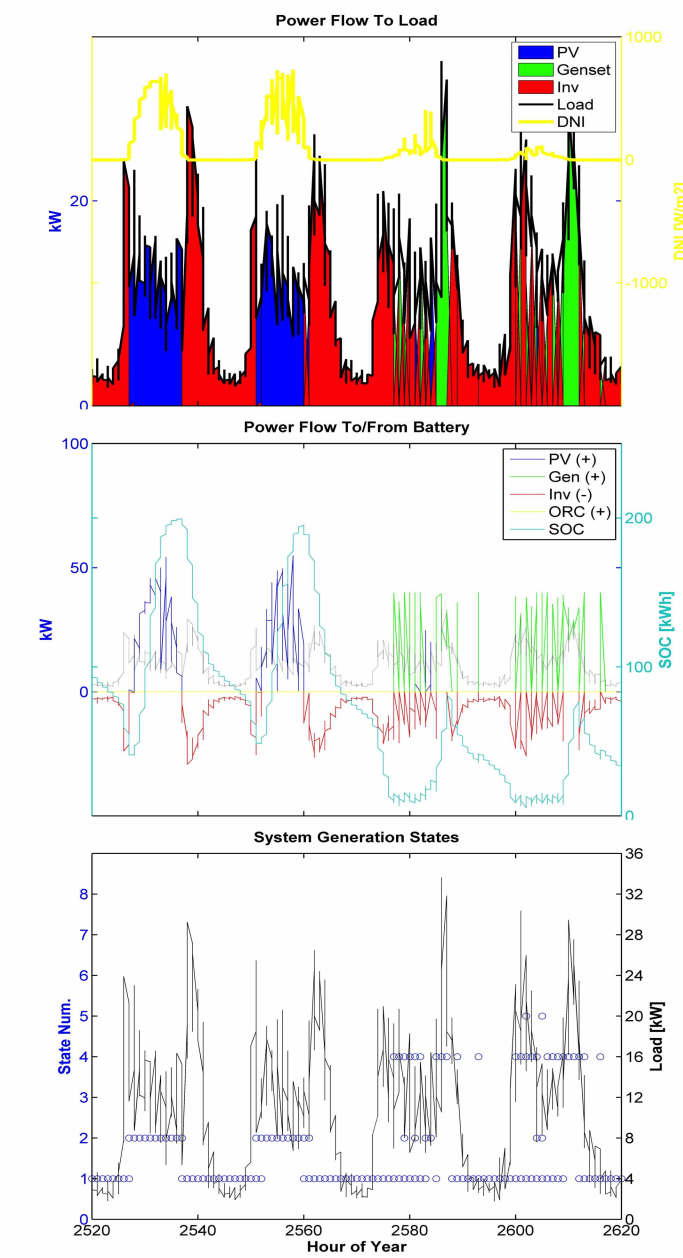

FIGURE 10. HA NKAU SIMULATION EXERPT SHOWING SYSTEM STATE (CORRESPONDING TO FIG. 8) AND OPERATIONAL DYNAMICS

USD, with specific costs of 4.7 USD kW^{-1} nominal capacity (inverter or genset) and roughly 475 USD per capita. A breakdown of component costs is shown in Fig. 11, and the cash flows for the micro grid project developer are illustrated in Fig. 12, for the patient capital scenario achieving cost recovery and slow returns to capital at a tariff of 0.35 USD kWh^{-1}.

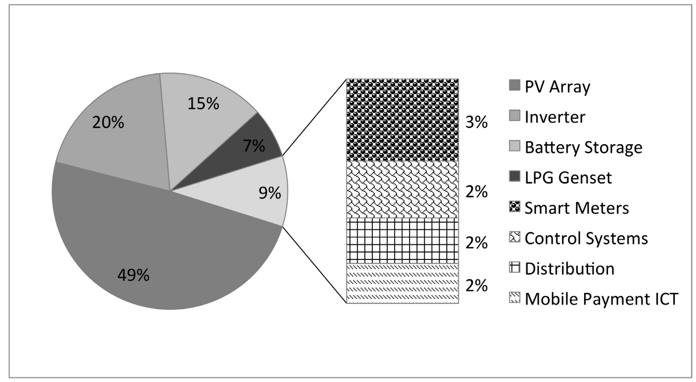

FIGURE 11. COST BREAKDOWN FOR HA NKAU OPTIMIZED MICRO GRID INFRASTRUCTURE

Note that configurations including CSP and ORC with TES were simulated and while the results of this exercise do not indicate their use for Nkau when the micro grid is optimized for electricity service only, cogeneration loads at, e.g., Nkau health clinic, not considered in this study but analyzed in earlier work [14], would tend to drive the optimized generation mix towards CSP. The results described above are also nominal to the extent that economic policy and demand elasticity, not considered in this study, would influence the optimal configuration. Data on the income differential between Dipelaneng, RSA and Nkau, Lesotho is not readily available, but the 0.35 USD kWh^{-1} cost recovery tariff is approximately 3x higher than the tariff in Dipelaneng. Assuming a long run price elasticity of demand of -0.32 from [19], the appropriate size and cost of a micro grid for Nkau may need to be reduced by as much as 53%. Including income differences could further modify the capacity required, however including these factors involves iteration of the design process to converge on a tariff that internalizes, e.g., subsidy mechanisms, uniform tariff policies, and demand elasticities. These data would be used in practice to further refine the design prior to establishing a micro grid project.

CONCLUSION

A holistic process for planning and implementing micro grids is proposed considering political and techno-economic factors such as grid extension, population density, and cost of capital, geographic variability in meteorological inputs (DNI and ambient T), and load inference using probabilistic distribution functions derived from comparable, already electrified communities. The rational allocation of installed capacity considering multiple potential generation sources is optimized via a dynamic simulation of micro grid energy flows and a project framework considering 100% availability, unconstrained consumer demand, and minimized tariff for cost recovery and positive cash flows

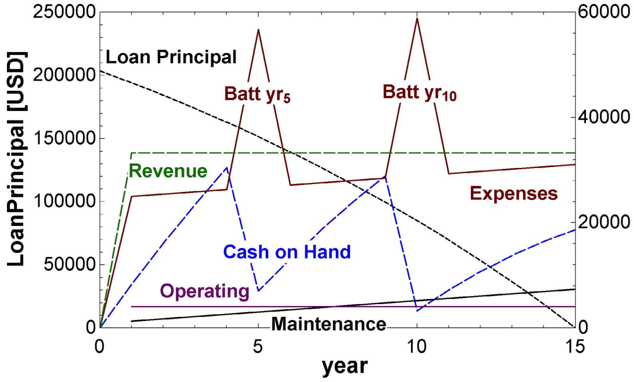

FIGURE 12. CASHFLOWS FOR HA NKAU MICRO GRID OPERATOR WITH 0.35 USD KWH^{-1} TARIFF AND 15 YEAR 5% PAYBACK PROJECT FINANCE

under a range of returns to capital.

A case study applying this methodology to Lesotho selects for a remote community Ha Nkau (84 households), locates and ascribes household and institutional (health clinic, school) loads within a distribution network topology, creates an aggregate community probabilistic load distribution (45kW peak), and simulates nominal micro grid configurations satisfying the objective function at 0.35 USD kWh^{-1} under favorable project finance terms. The output of this process is an engineering design template for optimized infrastructure meeting variable demand of approximately 256 kWh day^{-1}, consisting of a 100kW PV array and 50kW inverter, 200kWh of battery storage, and a 50kW backup generator, with an projected capital outlay of 235k USD, or around 470 USD per person. These results are nominal to the extent that further iteration of the design process could be envisioned to include, e.g., demand elasticities, subsidies, and regulation of tariffs. The computational effort deployed is substantial (requiring cloud based parallel processing on 48 instances over 24 hours), however the use of statistical load dynamics and the automation of these analyses mitigates need for labor intensive applications engineering for micro grid design on a case by case basis, and potentially improves the optimal sizing of equipment. Future work will explore the validity of this approach in practice, integrate cogeneration thermal loads at, e.g., health clinics, and quantify the advantages of hybrid PV-CSP-LPG power plants across a range of geographies and community compositions.

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