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Rural electrification and capacity expansion with an integrated modeling approach

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Abstract: In developing countries, mini-grids are seen as an important option to improve electrification rates in rural areas. In order to be successful, mini-grids face issues of operation and sizing of generation capacities. Current studies on the optimal sizing of mini-grids do not include capacity expansion feedbacks regarding the operator's or investor's long-term economic performance on growth in electricity usage, e.g. gap between demand and supply impacting the operator's income. Using a System Dynamics model, this paper compares the impact from two capacity expansion strategies on rural mini-grid operator's long-term economic performance. The two capacity expansion strategies are: a strategy with minimized costs and a strategy where only diesel power is allowed. Research shows that a cost-minimized capacity expansion strategy might not be the most beneficial solution for the operator's long term financial performance. Specifically, the high investment costs prohibit the implementation of the cost-minimized expansion strategy. In addition, the diesel-only expansion strategy suffers from high operational costs, which creates long-term challenges as the share of diesel increase. Therefore, the timeline of the investments and when to implement different strategies is important, creating a benefit for a System Dynamics approach.

1. Introduction

Over one billion people lack access to electricity. Half of these people live in sub-Saharan Africa, mostly in rural inaccessible areas [1]. Increasing electricity access is an important step towards improving social, economic and environmental conditions [2, 3]. In order for rural communities to gain full benefits from electricity within the foreseeable future, reliable and well-managed off-grid solutions are needed [4-7].

One proposed off-grid solution are mini-grids. In the context of rural electrification mini-grids are often considered to be small independent generation and distribution systems supplying some hundreds to a few thousand customers. One benefit of mini-grids over other off-grid solutions, such as solar home systems (SHS), is that they are large enough to supply electricity to productive activities and small industries. Creating opportunities for productive use is considered as an important link between electricity consumption and rural development [8, 9]. Apart from positive effects on local economic development, a mini-grid's larger capacity also allows for more customers, and thereby, increases the benefits by economies of scale.

Despite their potential, mini-grids in rural electrification have resulted in various levels of success. One of the major challenges is their poor economic performance, preventing them to reach cost-recovery [10-13]. The difficulty of recovering costs can be linked with low customer electricity consumption [14], high capital costs [15], low utilization factor [10], inappropriate tariff schemes [10, 16], lack of promotion of productive uses of electricity and unreliable electricity supply [6, 10, 17, 18], as well as dispersed populations [19].

Furthermore, many mini-grids are operated by local organizations and relying on their generated income to cover operation and expansion costs [10, 20]. With a lack of financial resources, these small operators have more difficulties covering their expenses than large scale utility's.

The economic performance of mini-grid operators has previously been studied using different methods. Simulation tools such as HOMER [21] or optimization tools as DER-CAM [22] have been used to investigate the issue of matching initial generation capacity with electric load while minimizing costs. In addition, System Dynamics have been used to investigate the effects of feedback within electric utilities in developing countries [23, 24]. System Dynamics is a method based on control theory and systems thinking developed to analyze complex problems in social systems that are characterized by feedback and delays [25]. To the knowledge of the authors there has not been any study of integrating cost minimization for

capacity expansion and dispatch with System Dynamics for mini-grid operators in developing countries. Therefore, the purpose of this paper is two folded. First, it aims to fill the gap in rural electrification modeling by proposing a modeling approach consisting of both a cost-minimization model and a System Dynamics model, which are linked using a bottom-up load model. Second, the paper aims at applying the proposed modeling approach using data from two rural mini-grid projects in Tanzania.

The paper is structured as follows. First a brief literature review on rural electrification, optimization and simulation methods and System Dynamics is presented. Secondly, an explanation of the modeling approach is presented, where a more detailed description of each module is given. This is followed by a presentation of the input data used for the analysis, the key results and discussion, leading to the final conclusions.

2. Literature Review

Mini-grids are becoming an important option for electrification of rural communities and can in some areas compete with grid-extension [26]. A frequently used energy source in off-grid mini-grids is diesel. Fluctuating and high diesel prices as well as negative environmental impacts have attracted alternative energy sources, e.g. hybrid and renewable based mini-grids. A range of factors have played a role in the increase of mini-grids. Mandelli et al. [27] identified five dimensions that have contributed to the increase in small scale systems in rural electrification: environmental, technological, economic, political and social. Ahlborg and Sjostedt [28] used a socio-technical system perspective to analyze different factors that led to the success of a locally operated and owned NGO led mini-grid in Tanzania. Even though complex, Sovacool [29] also found that community ownership is important for successful mini-grid implementation and operation.

Rural electrification is highly interdisciplinary and most of the research has been technology focused [27, 30]. One of the key technological and economic challenges in rural electrification are matching generation capacities with electric load [31]. As such it has been widely covered in the rural electrification literature (see [19, 32-40] for a few examples). Lanre et al. [32] used HOMER to study the most economical energy mix of solar PV, wind, batteries and diesel for six different rural regions in Nigeria. Their study used two groups of load profiles: social infrastructure and households. From their different system configurations

and local availability of energy resources, they found that a hybrid system consisting of PV/battery/diesel was the most economical choice.

Rohit Sen et. al [33] also used HOMER to identify the most economical energy supply option for a rural area in India. Their system was based on synthesized load profiles for two customer groups (households and local businesses) and had a peak load of 68 kW. Using data on local resources, they found that the most economical solution was a mixed energy system that mostly relied on hydropower and some biodiesel and solar PV. In addition, they conducted a sensitivity analysis of their system by allowing the future load to increase or decrease, and thereby, creating a link between their solution and future load developments. However, generation capacity matching studies have not taken into account the feedback and delays from key driving processes, which is important when considering long-run impacts [41]. For example, increased electricity consumption can lead to increased income levels [42]; customer acquisition costs decrease as system sizes increase; and unreliable electricity supply can negatively impact the use of electricity and decreases operator's economic performance [17, 23]. One method that considers feedback and delays is System Dynamics.

System Dynamics was initially used for urban and organization problems during the 1960s [43, 44]. Since then, the application has become much more widespread and there has been a considerable use of System Dynamics in the electric power and energy area [45, 46]. Quadrat-Ullah [47] found that the complexity in developing energy policies is well suited for System Dynamics. Consequently, Quadrat-Ullah used System Dynamics to study the issue of capacity expansion in Canada and found that considerable investments are needed in the future [48]. Similarly, Dimitrovski used System Dynamics to simulate market dynamics, including prices and capacity expansion in the Western US [49]. Important contributions to the electric power and energy sector have been made by Ford and Naill [45]. Amongst others, Ford analyzed the boom and bust cycles in power plant construction in California and found that they follow a similar pattern to commodity markets, with implications on reserve capacity [50].

Applications of System Dynamics on electrification challenges in the developing country context are less common. Using System Dynamics, Steele [23] investigated the causal relationship between electricity usage, reliability, and the Kenya Power and Lighting Company's (KPLC) economic performance. Steel found that during certain conditions, low power reliability resulted in a vicious loop, which led to reduced financial performance. Continuing on Steel's work, Jordan [51] developed a System Dynamics model of the national electric power system in Tanzania also considering issues of capacity expansion. Jordan concluded that it is important to consider electricity demand endogenously in electric power

systems when improvements from capacity expansion are large, which is often the case in developing countries. Similarly, Hartvigsson [52] developed a System Dynamics model focusing on the economic performance of mini-grid operators in Tanzania. However, none of the mentioned System Dynamics studies have considered capacity expansion and load variations for mini-grid operators in developing countries.

3. Modeling Environment

Most capacity optimization models rely on daily and/or seasonal load profiles in order to match generation with load. Since System Dynamics is used to model structures found in organizations and social systems it is well suited for aggregated variables, but it is not suitable for the fast variations found in daily load profiles. Therefore, in order to integrate a capacity optimization model with a System Dynamics model, a simple bottom-up load model is used. The proposed simulation and optimization approach therefore consists of three models: a linear bottom-up load model [53], a System Dynamics model of a mini-grid operator [52], and a cost optimization capacity investment model (in this case the Distributed Energy Resource and Customer Adaption Model, DER-CAM [54, 55]).

HOMER, which has frequently been used in rural electrification studies includes a wide range of tools, but there is a limited ability to integrate HOMER's output and input with other software, such as MATLAB and Vensim. Furthermore, the simulation approach used by HOMER does not qualify it as a true optimization tool, and therefore, it is of limited usability for complex situations when optimal investment decisions and dispatch are needed. Both these limitations can be addressed by DER-CAM, making it an ideal candidate for this study. Each model used in this approach serves a specific purpose. The bottom-up load model generates daily electric load profiles with an hourly resolution, calculated based on power availability and average customer income. Power availability is defined as the fractional reserve capacity, e.g. if the power availability is less than 0, there is a lack of capacity. Based on the generated load profiles, DER-CAM determines the cost-minimized energy mix and dispatch of available energy sources. Capacity expansion is evaluated at each time step and if power availability drops below 5%, DER-CAM generates a new capacity expansion strategy. The new energy mix is then implemented in the System Dynamics model. This results in multiple capacity evaluations and expansions during the simulation time. The System Dynamics model simulates feedback between the operator's economy and number of

customers, power availability and number of customers and electricity demand, as well as between electricity demand and local economic growth. Due to the complexity in terms of feedback from having a dynamic electricity price and due to the tariff schemes used in the analyzed villages, the model considers a fixed electricity price. The three models are linked together by relying on each other's outputs as inputs. Table 1 illustrates the links between inputs and outputs. For example, DER-CAM requires load profiles and current generation as inputs, and outputs new capacity investments, new generation profiles, and operational costs. DER-CAM's outputs are used as input by the System Dynamics model and the load model. Since each model is developed using a different software (DER-CAM is developed in GAMS, the System Dynamics model in Vensim and the bottom-up load model in MATLAB), a modeling environment was setup in MATLAB. MATLAB was chosen since it allows for communication with Vensim using the VenDLL library; the load model was developed in MATLAB and MATLAB allows for straightforward data exchange with DER-CAM.

Table 1 A schematic view of the modelling setup consisting of DER-CAM (GAMS), MATLAB and Vensim. The table shows the links between the model inputs and outputs.

MATLAB					
Load Model (MATLAB)		DER-CAM (GAMS)		System Dynamics (Vensim)	
Input	Output	Input	Output	Input	Output
Average Income	Load Profile Electricity Demand Power Availability	Load Profile	O&M Costs Capacity Expansion Costs Generation Profile	Electricity Demand Power Availability O&M Costs Capacity Expansion Costs	Average Income
# Customers					# Customers
Power Availability					
Generation Profile					

3.1 System Dynamics Model

The purpose of a System Dynamics model is to link system structure to a problematic behavior [56]. Therefore, an important step in System Dynamics modeling is to define the investigated problem and propose a dynamic hypothesis [25]. The model in this paper aims at

describing the problematic behavior of mini-grids low financial performance. With this in mind, the dynamic hypothesis is presented in Figure 1. Based on the dynamic hypothesis, a stock and flow model was developed using the iterative process proposed by Sterman [25]. The model is developed based on experiences, interviews and data collected from two mini-grid projects in south-western Tanzania (from here on referred to as community A and community B).

The model is divided into 5 sectors: customer expansion, mini-grid economics, local market and economy, capacity expansion, and population. Among others, it captures the feedback between electricity consumption, average income, power availability, and the operator's financial balance (working income). Using a simplified causal loop diagram, the main causal loops are presented in Figure 1. The stock and flow model used in our work [52] includes 20 stocks, roughly 70 variables, and 48 constants. The full list of stocks, variables, and constants can be found in the appendix.

Figure 1 Causal loop diagram of the driving feedback processes in the System Dynamics model (Please note that loops can be nested. For example, B2 and R2. Details of the feedback loops are shown in Table 2.)

Figure 1 shows closed feedback loops named R1 to R3 for self-reinforcing loops, and B1 to B2 for self-balancing loops. R1a and R1b represent the feedback between electricity usage and economic growth. R1a represents gain from increased productivity amongst small and medium sized enterprises (SME), and R1b represents impact from increased income on local demand. R2 is the reinforcing feedback loop due to reduction in individual connection costs as the grid is expanding (a larger grid reduces the average distance to a point of connection). The loops R3a and R3b represent the feedback from the financial balance on electricity usage

via either number of customers (R3a) or power availability (R3b). B1 represents the balancing effect reduced power availability has on electricity usage. B2 represents the increasing expenses as the number of customers is increasing, e.g. the operator's expenses increase as the mini-grid grows. B3 represents the balancing effect that increase in generation capacity has on financial balance. Table 2 shows a full list of the variables included in each feedback loop.

Table 2 Details of feedback loops shown in Figure 1

Feedback loop	Included Variables
R1a	Customers Average Income – Electricity Usage – SME Productivity – SME Revenue – Customers Average Income
R1b	Customers Average Income – Local Economic Demand – Local Economic Production – SME Revenue – Customers Average Income
R2	Economic Balance – Number of Customers – Individual Connection Cost – Operator Expenses – Economic Balance
R3a	Economic Balance – Number of Customers – Electricity Usage – Operator Income – Economic Balance
R3b	Economic Balance – Installed Generation Capacity – Power Availability – Electricity Usage – Operator Income – Economic Balance
B1	Electricity Usage – Power Availability – Electricity Usage
B2	Economic Balance – Number of Customers – Operator Expenses – Economic Balance
B3	Economic Balance – Installed Generation Capacity – Operator Expenses – Economic Balance

3.2 Load Model

The load model is a linear bottom-up appliance diffusion model [53]. It models electricity demand by simulating the occurrence of appliances, e.g. lightbulbs, TVs and stereos.

Appliances are then aggregated to obtain load profiles and electricity demand for the mini-grid. The growth in electricity demand is determined by the growth in the occurrence of each appliance. The load model used in this study assumes that appliance occurrence is a linear function of income.

Each appliance is associated with a standard daily load profile. The appliances and their corresponding standard daily load profiles were obtained by conducting an appliance inventory and measurements in community A and are shown in Figure 2. At the time of the data collection, the mini-grid supplied about 270 customers. The load-profiles were verified against measurements, and therefore, implicitly include coincidence for the 270 customers. The measured coincidence factor including the 270 customers was 0.5 and was kept constant during the simulation. According to P. Boait et al. [57] changes in the coincidence mostly

occurs when the number of appliances and/or customers are low. As long as the number of customers and/or appliances are relatively large, the usage of a constant coincidence factor should be a good estimation. Household load profiles are shown in green and commercial load profiles are shown in blue.

Figure 2 Standard load profiles from appliances obtained by doing an inventory on appliances and measurements in community A. Each figure represents the standard load profile for a single appliance. The top four graphs (green) show household appliances and the bottom four graphs (blue) show SME appliances.

The appliances were identified via interviews and are therefore case specific. Community A and B are situated on the Tanzanian highlands and temperatures are generally cool. This explains the lack of otherwise common appliances such as fans [27].

The occurrence of each appliance is a function of a diffusion rate with a corresponding saturation limit. The diffusion rate determines how sensitive the occurrence of an appliance is to changes in income. The saturation limit is the maximum occurrence of a specific appliance. Equation 1 describes the load profile for appliance i .

$$\Gamma_i = I \cdot \delta \cdot StdLP(t)_i \quad (1)$$

I is average income, δ is diffusion rate, $StdLP_i$ is the standard load profile for appliance i in hour t . In order to obtain the system's total load profile, the appliance load profiles are aggregated. Equation 2 describes a generic expression for the total load profile.

$$\sum_{j=1}^m \sum_{i=1}^n U_j \cdot \Gamma_i(t) \cdot f \quad (2)$$

m is the number of customer groups, n the number of appliances in each customer group and U_j the number of customers in customer group j . Similar to Sen et. al. [33] this paper uses two customer groups: households and SMEs. Due to sensitivity to power availability, customers are assumed to respond negatively to supply disruptions. Customer's response is expressed by the logistic function f with power availability (PA) as a variable, shown in Equation 3. The response is similar to that used by McRae [58].

$$f = \frac{1}{1 + e^{-k \cdot (PA - PA_0)}} \quad (3)$$

The parameter k influences the steepness of the logistic function and the parameter PA_0 is the value of sigmoid's midpoint (e.g. when f is reduced to 50% of its initial value). Initial values for k and PA_0 were estimated and are shown in Table 3. Due to uncertainties in k and PA_0 a sensitivity analysis has been performed and is presented in section 5.2.

Table 3 Initial values for the modified logistic function parameters, k and PA_0 .

Customer group	k	PA_0
SME	30	0.26
Household	20	0.36

3.3 DER-CAM

The capacity expansion problem is handled using the Distributed Energy Resource and Customer Adoption Model (DER-CAM) [54, 55]. DER-CAM is a state-of-the-art decision support tool developed by the Lawrence Berkeley National Laboratory, Berkeley, California, and is extensively used to address the problem of optimally investing and scheduling distributed energy resources under micro-grid settings. The model is formulated as a Mixed Integer Linear Program (MILP), and the key inputs to DER-CAM are customer loads, market tariffs (including electric prices), techno-economic data of generation and storage technologies (including capital and operation and maintenance costs, efficiency, and other operational constraints). Key outputs of DER-CAM include site-wide energy costs, the optimal installed onsite capacity and optimal dispatch of selected technologies, and load management measures.

The purpose of DER-CAM is to find the optimal combination of technology adoption and operation to supply all energy services required by the site under consideration, while optimizing the energy flows to minimize costs and/or CO₂ emissions. In its standard operational mode, DER-CAM considers both electricity-only, heating (electric or gas) and cooling (electric or gas) loads. Due to non-existence of heating and cooling loads in rural communities, only electric loads are considered. As DER-CAM is used for investigating the impact of cost-minimized capacity expansion strategies on operator's economic performance, CO₂ emissions are not taken into consideration.

4. Model data

The proposed modeling environment is used to investigate the impact of cost-minimized capacity expansion strategies on an operator's financial balance. The comparison is done by comparing the results using two different capacity investment strategies. The first strategy uses the cost-minimized energy mix and dispatch from DER-CAM and the second strategy uses an energy mix and dispatch that only relies on diesel. The comparisons are done by simulating the operator's financial performance over a 20-year time frame. This timeframe enables the model to capture the dynamics of equipment replacement and electricity demand. The models are run iteratively with a time-step of one week using the following procedure. During each iteration, the System Dynamics model outputs average income and number of customers, which the load model uses to generate a load profile, power availability and electricity demand. The goal of the mini-grid's operator is to make sure that the reserve capacity never falls below 5%. If the spare capacity falls below 5%, DER-CAM is used to

generate a new capacity expansion and operation strategy, which is implemented in the System Dynamics model. Furthermore, in order for the operator to implement a capacity expansion strategy the operator must contribute 30% of the initial investment. The remaining investment is covered by a loan.

All three models require initial data sets. The System Dynamics model requires socio-economic data about the mini-grid, DER-CAM requires techno-economic data on costs and lifetime, and the load model requires data on diffusion rates and saturation limits. Data for the System Dynamics model were collected from the two rural electrification projects, community A and community B [52]. Data from the two projects are used interchangeably since a full dataset was not available from either of the projects. Table 4 contains initial values for the main stocks in the System Dynamics model.

Table 4 Initial values for the main stocks in the System Dynamics model

Stock	Initial Value	Unit
Operator's accumulated profit	10 000	USD
Number of SME customers	80	dmnl
Number of household customers	400	dmnl
Average weekly household income	20	USD/week
Average weekly SME income	30	USD/week
Electricity consumption households	8.4	kWh/week
Electricity consumption SMEs	29	kWh/week
Installed generation capacity	100	kW (hydropower)
Population (assuming an initial family size of 4.1 [59])	10 000	people

Table 5 shows techno-economic data used for DER-CAM's optimization that include capital costs, fixed annual maintenance costs, variable maintenance costs and lifetime. The fixed and variable maintenance costs also include operations costs, but exclude fuel costs (applicable only to diesel). As DER-CAM is a mixed integer optimization model, generation options were selected in the following sizes; diesel: 10 kW, 25 kW and 50 kW; hydropower: 50 kW, 100 kW and 200 kW; PV: any multiple size of 1 kW; wind: 25 kW; and battery: any multiple size of 1 kWh. Data on solar insolation and wind speeds were collected from the World Bank

Renewable Energy Resource Mapping project in Tanzania [60], and are presented in the appendix. Furthermore, no limitation was put on hydropower availability.

Table 5 Investment and maintenance cost and life time data used in DER-CAM

Energy source	Capital costs (\$/kW)	Fixed Maintenance Costs (\$/kW/year)	Variable Maintenance Cost (\$/kWh)	Life time (years)
Diesel [61]	640	0	0.05	15
Hydropower [62]	5000	90	0.0042	50
Photovoltaic [39]	2200	0.17	0	25
Wind power [63]	2600	65	0	25
Energy Storage (Battery, \$/kWh) [19]	300	1.5	0	3 ¹

Table 6 shows data on appliance diffusion rates, saturation limits and average number of identified appliances from community A. Appliance saturation limits were estimated from data collected on appliances from community A (see [53] and [18]) and from [66]. Diffusion rates were calculated using the average number of appliances and average income (see Table 4 and 6) for each customer group. Average income and number of appliances were obtained from 47 interviews with mini-grid customers.

Table 6 Diffusion rates, saturation limits for each appliance and average number of identified appliances obtained from interviews.

Appliances	Diffusion rate [appliances/USD]	Saturation Limit [# appliances]	Average number of appliances identified through interviews from Community A
Light bulbs (household)	0.39	14 [66]	8.6
Stereo (households)	0.02	2	0.5
TV (households)	0.004	2[66]	0.8
DVD (households)	0.03	1	0.6
Light bulbs (SME)	0.03	4	1

¹ Battery lifetime is heavily affected by battery management, usage and environmental factors. M. Amutha and V. Rajin [64] reported battery lifetime ranging from 2.44 to 8 years (with an average on 5.5 years) for mini-grid purposes in India. J-Lujano-Rojas et al. [65] investigated lead-acid batteries in hybrid and microgrids and found that capacity quickly degraded after 3 years. As the modeling approach includes the feedback from power availability, battery lifetime is chosen to be conservative to reduce the impact of degrading battery capacities on electricity supply.

Stereo (SME)	0.013	1	0.4
Large loads (e.g. electric machines, welding equipment) (SME)	0.002	0.2	0.5
Other (SME)	0.008	1	0.17

5. Simulations

Figure 3 shows the accumulated profit (left graph) and power availability (right graph), on a weekly basis for the two strategies. The distinct drops in the accumulated profit are associated with increases in generation capacity (sudden expenditures) and are therefore linked to the increases in power availability. As seen in both graphs, the two solutions show similar behavior during the early phase. Initially the operator has resources and there is available capacity in the system. This drives an increase in number of customers and thereby also electricity demand (seen in Figure 4), which initially reduce power availability. When the cost-optimized capacity expansion strategy is used (continuous blue line in Figure 3), the operator's accumulated profit increase faster than the strategy relying on diesel-only (dotted orange line in Figure 3). The cost-minimized energy mix from DER-CAM mostly consists of hydropower, which has a high investment cost. The increase in accumulated profit can therefore be explained by the operator saving resources and reducing costs by not performing multiple investments as with the diesel strategy. The high investment cost associated with the hydropower expansion generates a long delay, and therefore, creates a mismatch between demand and generation. The mismatch between demand and generation reduces power availability and thereby negatively impacts total electricity demand and the operator's income. This behavior creates a viscous loop between power availability and profit that ultimately prevent the operator from implementing the hydropower capacity expansion.

Figure 3 shows results for accumulated profit (left) and power availability (right). The cost-minimized strategy is shown in continuous lines (blue) and the diesel-only strategy is shown in dotted lines (orange).

When the diesel-only strategy is used, the investment costs are lower (diesel is characterized by a low investment cost but high operating costs), making it possible for the operator to increase generation capacity faster. The faster implementations reduce mismatch between demand and supply and improve power availability when compared to the cost-minimized strategy, which is seen in the right graph in Figure 3. However, due to the high operational cost of diesel, the margin between income and expenses is lower, leading to lower accumulated profits, which is apparent from the left graph in Figure 3. As the share of diesel increase in the system, the margin between income and expenses decrease. Towards the end of the simulation, the margin is not adequate to allow the operator to collect enough profit in order to continue increasing generation capacity.

Figure 4 shows results for total electricity demand (left) and number of customers (right) in the mini-grid. The cost-minimized strategy is shown in blue and the diesel-only strategy is shown in dotted orange lines.

Figure 4 shows total electricity demand (left graph) and number of customers (right graph) for the two runs. Total electricity demand depends on individual electricity demand and the number of users. Therefore, a change in number of customers directly affects total electricity demand. After half of the simulation period, both number of customers and total electricity demand starts decreasing using the cost-minimized strategy. However, as the operator manages to reduce mismatch between demand and supply for a longer period using the diesel-only strategy, total electricity demand does not decrease until the end of the simulation.

Figure 5 shows at what time capacity is installed using the two capacity expansion strategies. The left graph shows capacity installment over time using the cost-minimized expansion strategy and the right graph shows capacity installment over time using the diesel only expansion strategy. The color represents the energy source, brown represents diesel, blue represents hydropower, grey battery and yellow solar PV. Filled bars show installed generation capacity and striped bars show generation capacity waiting to be installed (e.g. capacity expansion from DER-CAM and not yet implemented by the operator).

Figure 5 shows installed capacities for the two strategies. Filled bars show installed capacity and striped bars show capacity waiting to be installed (e.g. capacity expansion from DER-CAM and not yet implemented by the operator). In terms of capacity, both strategies show similar sizes for the first investments and an increase in the second investment. As the smallest generation capacity available for hydropower is 100 kW, the cost-minimized strategy shows a larger generation capacity expansion than the forced diesel. Regardless of the differences in the second investment, electricity demands are similar for the two strategies, which is seen in the left graph in Figure 4. As can be seen in Figure 5, the cost-minimized strategy only manages to implement one capacity expansion investment while The diesel-only strategy manages to implement three capacity expansions.

Figure 6 shows a simple system layout for the capacity expansion strategies. The left figure shows the system layout for the cost-minimized expansion strategy and the right figure shows the system layout for the diesel only expansion strategy.

Figure 6 shows simple system layouts for the two expansion strategies. The systems includes the initial 100 kW hydropower, which in both cases represent a considerable share. In terms of system layout, the difference between the two systems are the addition of a solar PV/battery system in the cost-minimized capacity expansion strategy.

Table 7 shows the levelized costs of electricity (LCOE) for the two expansion strategies. LCOEs are calculated using the definition in [67]. The discount rate used is 6% [35] and the system's lifetime is considered to be 20 years (including any possible re-investments). As seen in Table 7, the LCOE for the diesel only expansion strategy is roughly 30% times higher than the cost-minimized expansion strategy. The higher LCOE for the diesel only expansion strategy is expected due to the high operation costs associated with diesel.

Table 7 shows levelized cost of electricity (LCOE) for the two expansion strategies.

	Cost-minimized expansion strategy	Diesel only expansion strategy
Levelized cost of electricity (USD/kWh)	0.11	0.14

5.2 Sensitivity Analysis

The main short-term feedback between the operator's economy and electricity usage is based on the customer's sensitivity to power availability, which is expressed in Equation 3. In order to build confidence in the modeling approach, sensitivities to changes in Equation 3 are investigated by changing the values for k and PA_0 . Reducing either k or PA_0 values increase customer's sensitivity to power availability and should therefore have a negative impact on electricity usage and the operator's accumulated profit. Furthermore, increasing k or PA_0 values reduce customer's sensitivity to power availability and should therefore have a positive impact on electricity usage and the operator's accumulated profit. 15 runs have been performed by changing the parameter values according to the intervals in Table 7. The parameter values were chosen as they represent a wide range of outcomes.

Table 8 Parameter intervals used during sensitivity simulations for Equation 3.

Customer group	k	PA_0
SME	10 to 30	0.22 to 0.30
Households	20 to 40	0.32 to 0.40

Overall the outputs (the operator's accumulated profit, electricity usage and power availability) showed small changes from the adjustments in k and PA_0 . The results were almost exclusively consistent. Meaning increased sensitivity (reduced k or PA_0 values) led to a limited reduced electricity usage and accumulated profit, while a decreased sensitivity (increased k or PA_0 values) led to an increased electricity usage and higher accumulated profit. Nevertheless, very high sensitivities (very low k values and/or low PA_0 values) in the forced diesel strategy resulted in reduced power availability and electricity usage to the extent that the third investment could not be implemented.

6. Discussion

In rural electrification, where access to electricity is limited and when increasing capacity often improves reliability, it is important to consider demand as endogenous [51]. This paper has presented an integrated modeling approach consisting of a mixed integer linear optimization model (DER-CAM), a bottom-up load model and a System Dynamics model of a mini-grid operator. The presented modeling approach combines the techno-economic challenges of investing in generation capacity with the issues of feedback, delays and non-linear behavior in the operation of mini-grids in rural electrification.

Using data from two mini-grid projects in Tanzania and data on local energy resources two different capacity expansion strategies were investigated: a cost-minimized strategy and a strategy relying only on diesel. None of the capacity expansion strategies allowed for the operator to cover long-term operational and managerial costs as well as expansion costs. Failure of the two strategies can be explained by differences in capital and operation costs associated with each mix of energy sources. The cost-minimized capacity expansion strategy has high capital costs and low operational costs while the diesel-only solution has low capital costs and high operational costs.

The higher capital costs for the cost-minimized strategy are explained by higher investment costs per kW of capacity. The cost-minimized capacity expansion strategy relies on a mix of energy sources (PV, battery, diesel and hydropower), which is similar to what others have identified, e.g. Kenfack et al. [40] in Cameroon and Sen et al. [68] in India. Even though the total costs for the cost-minimized capacity expansion strategy is lower, initial investment costs are higher and act as a barrier for the operator. Capital costs used in the simulation were taken from a range of international sources and can vary largely depending on local availability. Furthermore, our research uses fixed costs during the simulation period.

However, based on previous observation for solar PV, wind power and battery storage, costs will likely decrease significantly in the future while diesel prices can fluctuate considerably. According to IRENA [69], solar PV investment costs could fall to well below 1000 USD/kW by 2025. Furthermore, an assessment by Fraunhofer Institute [70] predicts that PV module prices alone are likely to fall more than 50% until 2050. Similar assessments on battery technologies suggests cost reductions on the scale of 50% in the coming decade [71]. These assessments of future prices are however done on large scale, and it is likely that prices for applications in rural electrification will differ and be closely linked with regional contexts. Nevertheless, taking into account possible reductions in solar PV, batteries, wind power and fluctuations in fuel prices, the cost-minimized strategy would likely perform better when compared to the diesel-only strategy. However, the impact that reduced costs would have on the outcome is uncertain and should be subject of future research.

Another factor impacting investment cost and financial performance is the capacity. A larger capacity results in larger investment costs and larger differences between demand and generation. Smaller capacities have lower investment costs (but often a higher cost per kW) and could therefore allow for a better fit between demand and supply, which would improve power availability. The smallest size of diesel generators and solar PV panels used in the simulations are 10 kW and 1 kW respectively. The smallest size of hydropower and wind

power used in the simulations are 50 kW and 25 kW respectively. Having smaller sizes available for hydropower might yield better result for the cost-minimized investment strategy. The main process by which high investment costs impact the operator's economy is through increasing the time delay between matching demand and generation. Higher investment costs increase the time the operator needs to collect resources for the investment. With a gap between demand and generation capacity, power availability is reduced affecting customer's electricity usage. In interviews in community A, several customers responded that they considered disconnecting from the mini-grid due to a dissatisfaction with the electricity supply (some had already opted to acquire their own diesel generator). Similarly, Steel [23] identified a relationship between electricity reliability and operator performance on a national level in Kenya. However, to accurately describe the relationship between power availability and customer satisfaction is difficult. As found by Aklin et al. [72] there are multiple factors affecting customer satisfaction, with the most prominent being the hours of service, voltage stability and reliability of supply.

Another issue found by Ahlborg et al. [20] in Tanzania and Kirubi et al. [10] in Kenya is that mini-grid operators managed to cover their operating and maintenance costs but failed to generate enough income for investing in new generation capacities. Most demand-generation matching tools minimize total costs (in DER-CAM's case these include investment costs, operation and management costs, and reinvestment costs over a 20-year period) and consider all costs equally. In rural electrification, access to financial tools and banking services for investments are not readily available. Without access to these services, acquiring resources for large investments can be difficult. If operators lack resources or access to financial services, resources for capacity investments will be more challenging for the operator to obtain. Therefore, in terms of long-term economic stability, a balanced approach should be taken between capacity investments and operational costs.

Apart from acquiring physical assets (e.g. transformers, power lines and poles) by purchase, another method for mini-grid operators to acquire physical assets is in the form of donations. In cases when operators rely on donations (such as churches, NGOs or companies via good will work) to support their activities, it is difficult for operators to fully control when and what physical assets will be available. One example is that the operator connects customers when distribution lines, poles, or transformers are donated without taking the maintenance and capacity requirements into account. Such a behavior could reduce power availability and show a negative impact on the operator's profit similar to the behavior identified using the cost-minimized strategy.

Tendencies towards this behavior were identified in community A and B. The mini-grid in community A has been served by a 100 kW hydropower plant since its construction (more than 15 years ago). Initially, the plant was constructed to supply the local hospital and a few surrounding houses. As time passed, the mini-grid expanded and has now around 450 customers. Even though this system has been operating on or even above its limit for some time, the operator has continued to connect new customers. Most recently the operator connected almost 100 customers after receiving governmental support aimed at specifically increase number of connections. Reduced power availability resulted in customers acquiring diesel generators and expressing dissatisfaction in the service and some considered to disconnect from the mini-grid. In community B, connections have been granted using external support, e.g. donated cables and power lines or financial support aimed at expanding the distribution system. This led the operator to base their rate of connections on resource availability rather than the capacity of the mini-grid.

The LCOE presented for the two capacity expansion strategies (0.11 USD/kWh for the cost-minimized strategy and 0.14 USD/kWh for the diesel only strategy) are slightly lower than reported from other studies. Blum et al. [67] found the LCOE for micro hydro power based systems to be 0.14€/kWh and between 0.22 and 0.48 €/kWh for diesel based systems. The costs for hydropower was taken from [62], which reports LCOE ranges from 0.02 to 0.27 USD/kWh. Since the initial generation capacity in the presented case is 100 kW hydropower, the two strategies represent hybrid systems, but with a varying fraction of diesel. R. Kimera et al. [73] calculated LCOE for various fractions of hydropower in micro-grids in rural Uganda. They found that the LCOE ranged from 0.03 to 0.3 USD/kWh.

An alternative to expanding the generation capacity in the mini-grid is to connect the mini-grid to the national grid, if available. The grid connection can then supply large amounts of power which can reduce power availability issues. However, the reliability of electricity is generally low in developing countries [74] and the interconnection could therefore cause issues, especially if the mini-grid's operator is relying on the national grid for stability. The benefits are therefore dependent on the reliability and availability of the national grid. Furthermore, in order for mini-grids to become connected to and benefit from the national grid, appropriate and well-designed policies are needed [7].

7. Conclusions

This paper has presented an integrated modeling approach consisting of a System Dynamics model, a mixed integer linear optimization model and a bottom-up load model. Unlike previous studies using tools to minimize capital costs in rural electrification, the proposed approach captures the feedback between available generation capacity, overall electricity demand and an operator's economic performance. When applied to a case using data from two mini-grid projects in Tanzania, the results show that minimizing total cost for capacity expansion is not the most beneficial for the mini-grid operator's long term financial performance due to high investment costs for PV and hydropower. Initial investment costs and capacity sizes play an important role. Rather than promoting a specific energy source, the results show that in contexts where customers are sensitive to reductions in power availability and when operators suffer from weak financial performance, choosing energy sources that have a short implementation time is important. Investors and mini-grid operators should therefore be aware of potential causes that reduce power availability and try to minimize these, e.g. reduce overloading probability by controlling customer connection rates and make assessments of future growth in electricity usage. The expansion strategies used in this study were evaluated based on their economic impact. Including environmental impacts (such as CO₂ emissions) in the cost-minimization process (which DER-CAM is equipped for) would yield different results.

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Appendix

Wind data from the World Bank's Renewable Energy mapping project in Tanzania [60].

Units are kW and based on a 25 kW wind power plant.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1	5.84	9.86	19.72	14.27	12.3	11.73	13.19	8.75	6.97	9.04	7.35	7.26

2	6.3	10.24	20.33	12.49	12.73	10.83	11.47	7.54	6.3	6.87	8.04	6.54
3	7.23	10.93	18.97	9.87	10.8	9.51	11.73	6.6	6.58	7.33	6.73	5.73
4	8.2	7.43	17.22	10.21	8.21	9.09	13.47	6.69	5.03	5.97	7.07	7.69
5	10.22	6.37	14.31	8.93	7.14	9.09	13.05	5.63	4.17	5.23	5.88	6.82
6	7.88	5.17	12.09	9.55	7.38	9.14	11.77	4.32	4.09	5.21	4.3	7.26
7	5.29	6.02	12.16	8.87	7.12	8.97	11.2	4.35	4.03	3.76	4.3	5.96
8	5.72	6.7	13.64	7.05	5.96	7.51	9.49	3.69	3.02	2.89	2.99	6.53
9	7	4.96	14.99	7.29	4.69	7.72	7.74	3.03	2.18	2	3.2	6.29
10	6.65	5.46	14.28	7.62	3.5	7.33	6.2	2.1	1.33	2.01	2.63	6.16
11	7.43	7.01	13.77	7.11	3.02	5.04	4.72	1.98	0.93	1.95	1.97	5.21
12	9.03	7.97	14.46	6.55	2.5	4.21	2.89	1.66	0.48	2.05	1.98	5.33
13	9.24	7.91	13.77	5.99	2.07	3.43	2.19	1.54	1.02	2.29	1.03	5.46
14	8.28	9	13.07	5.38	2.5	2.97	1.62	1.41	1.31	1.97	0.94	4.69
15	7.87	8.23	11.83	7.82	3.05	1.92	1.33	1.06	1.63	1.85	0.82	5.11
16	6.65	7.82	11.59	6.82	2.81	1.29	0.63	0.78	1.85	1.95	0.99	6.51
17	4.62	7.32	10.25	4.8	2.92	1.3	1.23	0.67	1.96	1.83	1.35	6.91
18	4.52	6.88	9.51	5.88	4.27	1.48	2.15	0.69	3.36	1.23	2.32	7.96
19	3.76	6.51	10.14	7.32	4.67	2.23	3.01	0.92	4.13	1.73	2.82	7.65
20	4.47	5.81	10.27	8.38	5.21	2.33	3.82	1.34	4.73	2.3	3.45	7.95
21	4.72	5.23	13.27	9.41	5.7	2.86	4.55	1.82	4.68	2.64	3.47	8.96
22	4.92	6.52	14.5	13.05	6.91	4.13	5.51	2.31	4.15	2.35	3.47	9.37
23	5.23	8.35	17.48	15.14	9	6.61	7.62	4.02	4.95	3.32	4.38	8.94
00	7.65	10.17	20.01	18.01	12.45	13.1	11.68	6.77	7.76	6.01	7.21	9.13

Solar insolation data from the World Bank's Renewable Energy mapping project in Tanzania [60].

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0.04	0.03	0.04	0.07	0.06	0.04	0.02	0.03	0.06	0.10	0.09	0.05
8	0.18	0.19	0.20	0.24	0.21	0.16	0.14	0.15	0.23	0.29	0.26	0.19
9	0.36	0.39	0.42	0.44	0.40	0.33	0.31	0.34	0.42	0.50	0.45	0.36
10	0.49	0.59	0.59	0.60	0.55	0.47	0.47	0.50	0.61	0.64	0.58	0.50
11	0.56	0.70	0.68	0.64	0.65	0.59	0.58	0.62	0.69	0.73	0.63	0.58
12	0.58	0.73	0.67	0.56	0.68	0.62	0.62	0.65	0.68	0.70	0.60	0.54
13	0.56	0.67	0.59	0.43	0.57	0.55	0.56	0.57	0.59	0.61	0.45	0.43

14	0.45	0.54	0.40	0.34	0.42	0.43	0.43	0.41	0.42	0.47	0.31	0.31
15	0.32	0.39	0.24	0.23	0.26	0.25	0.27	0.25	0.25	0.32	0.21	0.22
16	0.16	0.22	0.13	0.13	0.14	0.10	0.12	0.12	0.13	0.16	0.12	0.11
17	0.05	0.08	0.05	0.04	0.04	0.02	0.03	0.03	0.04	0.04	0.03	0.03
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
00	0	0	0	0	0	0	0	0	0	0	0	0

List of variables in the System Dynamics model

Variable name	Variable name	Variable name
Administration costs	Effect of Electricity Demand on Total Factory Productivity	Local Demand
Agriculture Land Price	Effect of Power Availability on Total Factory Productivity	Operation and Maintenance Costs
Agriculture Labor	Electricity Demand SME	Perceived Connection Risk HH
Agriculture Land	Electricity Demand HH	Perceived Connection Risk SME
Agricultural Land Productivity	Equipment Cost for Operator	Perceived Power Availability HH
Agricultural Land per HH	External Demand	Perceived Power Availability SME
Agricultural Land Utilization	Goods to Capital Conversion	Power Availability
Agriculture Production	Goods to Natural Resource Conversion	Reforestation
Average Distance to Grid	HH Desired Connection Rate	SME Desired Connection Rate
Average Connection Cost SME	HH Connection Rate	SME Connection Rate
Average Connection Cost HH	Immigration	SME Production
Community Attractiveness	Income effect on Agriculture Goods Demand	SME Production Capacity
Connection Price SME	Income Generating Crop	SME Sales

Connection Price HH	Industrial Capital Demand	Total Factory Productivity
Cost of Capacity Construction	Industrial Labor	Customer Density
Crop price	Initial Fertility Rate	Operator Desired SME Connection Rate
Death Rate for Working Age Population	Installed Battery Capacity	Operator Desired HH Connection Rate
Death Rate for School Age Population	Installed Diesel Capacity	Operator Income from HH Customers
Deforestation	Installed Hydropower Capacity	Operator Income from SME Customers
Demand for Forest Restoration	Installed PV Capacity	
Effect of Education on Total Factory Productivity	Installed Wind Capacity	

List of stocks in the System Dynamics model

Stock name	Stock name	Stock name
Agricultural Demand	HH Non-Customers	Population
Agricultural Land	HH Customers	School Age Population
Available Financial Capital	HH Average Income	SME Non- Customers
Estimated External Demand	Operator Economic Balance	SME Customers
Estimated Local Demand	Land For Industrial Production	SME Average Income
Forest	Loan	Technical Personnel
	Number of People with School Education	Working Age Population

List of constants for the System Dynamics model

Constant	Value	Constant	Value
Average amount of industrial resources per ha of land	50 USD/ha	Initial land productivity	11 goods/ha

Battery construction time	4 weeks
Capital Elasticity	0.5 dmnI
Community area	25 km ²
Connection cost per km	10 000 USD/km
Connections per technician	2/week
Density to distance conversion factor	3 km
Diesel construction time	8 weeks
Education elasticity on TFP for Agriculture	0.4 dmnI
Elasticity of fertility rate to average income	-0.25 dmnI
Electricity elasticity on TFP for SME	0.3 dmnI
Electricity Price HH	0.1286 USD/kWh
Electricity Price SME	0.2 USD/kWh
Fertile period	1 300 weeks
Fraction to restore Ag	0.3 dmnI
Fraction of children going to school	0.68 dmnI
Fraction of income HH spend on connection	0.05 dmnI
Fraction of income spent on non-agricultural goods	0.2 dmnI
Fraction of IS save	0.2 dmnI
Fraction of labor in agriculture	0.75 dmnI
Fraction of SME income spent on connection	0.1 dmnI
Fraction of loan to pay back per week	0.13 %
Fraction of sales generated	0.4 dmnI

Initial forest coverage	15 000 ha
Initial TFP SME	1 dmnI
Fixed Installation cost HH	50 USD/connection
Fixed Installation cost SME	60 USD/connection
Loan fraction	0.6 dmnI
Monetization of capital	0.005 USD/week
Normalized cost HH	50 USD/connection
Normalized cost SME	150 USD/connection
Normalized Customers HH	400 customers
Normalized Customers SME	80 customers
PV construction time	13 weeks
Reforestation time	300 weeks
Resource elasticity	0.3
Technician salary	40 USD/week
Time delay for capital formation	52 weeks
Time to change Agricultural demand	10 weeks
Time to change external demand	10 weeks
Time to change local demand	5 weeks
Time to change personnel	30 weeks
Wind power construction time	26 weeks
Time to finish school	520 weeks
Time to change average	2 weeks

as income	
Fraction of land for industrial production to be restored	0.3 dmnl
Hydropower construction time	52 weeks

income	
Time to deforest	10 weeks

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