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# Two sides of a coin: Assessing trade-offs between reliability and profit in mini grids and the policy implications for subsidies

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ABSTRACT

Universal access to electricity is an important milestone featured in countries development plans. It is well understood within the energy practitioner and research communities that to reach this milestone, distributed energy resources, especially mini grids, are to play a crucial role as they represent a least cost alternative to reach most rural communities. The success of mini grids though is highly reliant on favorable policies, particularly regulations pertaining to tariffs (i.e., electricity rates). In this research, we use Tanzania as a case study to investigate the likely consequences of grid and mini grid tariff equalization regulation which ignores the fact that the tariff charged on the grid is highly subsidized compared to mini grid tariffs that must be cost reflective for mini grid utilities to be financially sustainable. We recognize that a private mini grid operator has an obligation to make profits for the investors. Because of this, they have two critical yet divergent operating points from which to choose: (1) serving 100% of the demand at all times, potentially incurring operating losses during some periods and (2) partially serving the demand to maximize returns, potentially compromising customer satisfaction. Using an empirically-informed model of a mini grid sized to minimize net present cost that supplies power to 500 customers, we quantify the cost of reliability between these two key operating points and trace the curve relating profit and reliability, for two types of load scenarios: fixed loads and fixed plus flexible loads. We found that profit is optimized at a reliability of 92.3% and 86.0% for systems that meet fixed loads and fixed plus flexible loads respectively. This reduced reliability can have crucial implications on the viability of mini grids for providing electricity access, as customer dissatisfaction and profits may erode. We show that under the policy of tariff equalization between the centralized grid and mini grids, the latter is challenged to survive and therefore the communities which are being served through mini grids may experience de-electrification, which would represent a huge regression with regards to meeting the United Nations Sustainable Development Goal 7 (SDG7) of universal electricity access.

## 1. Introduction

### *1.1. Background*

Universal access to electricity is an important milestone featured in countries development plans. Fortunately, it is deservedly treated with the importance with which it requires, hence the widespread adoption of the United Nations Development Program (UNDP)'s Sustainable Development Goal number 7 (SDG7) by countries in their electrification plans. Over the past decade, huge progress has been made in electricity access expansion, with the number of people without access decreasing from 1.2 billion in 2010 to 733 million in 2020 globally [1], amid rising population. However, many countries are falling behind on the target of realizing a 100% electrification access by 2030 in line with SDG7. The World Bank estimates that under the current electrification policies, partially as a consequence of the COVID-19 pandemic's effect on the global economy, by 2030 about 660 million people will still be lacking access to electricity, the majority of whom shall be in rural Sub Saharan Africa (SSA) [1]. Thus, if the goal of universal access to electricity is to be achieved, special attention and huge investments have to be focused on rural SSA.

Rural electrification programs require the involvement of diverse stakeholders, including policy-makers, governments, utilities and researchers. These stakeholders collaborate on complex policy decisions centered around trade-offs between traditional grid expansion and off-grid technologies such as community scale mini grids and solar home systems (SHSs), assessing short and long term socio-economic benefits

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**Nomenclature**

| | |
|---|---|
| $\lambda$: | Electricity tariff [$/kWh] |
| $\epsilon$: | Small penalty on the rejected solar PV power [$/kWh] |
| $\theta$: | Battery cost [$/kWh] |
| $\gamma$: | Diesel fuel cost [$/L] |
| $\eta_b$: | Battery round trip efficiency [%] |
| $\eta_{inv}$: | Inverter/converter efficiency [%] |
| $c$: | Customer index |
| $x_c$: | Binary indicator of whether fixed demand for customer $c$ is met or not |
| $k$: | Time index |
| $g$: | Generator index |
| $m$: | Flexible demand index |
| $s_g$: | Binary indicator of whether a diesel generator is on or off |
| $C$: | Number of customers |
| $G$: | Number of diesel generators |
| $P_{fixed}$: | Aggregate power flow to meet fixed demand [kW] |
| $P_{flex}$: | Aggregate power flow to meet flexible demand [kW] |
| $P_s$: | Solar PV production [kW] |
| $P_R$: | Curtailed solar PV production [kW] |
| $P_{b,in}$: | Power flow into the battery [kW] |
| $P_{b,out}$: | Power flow out of the battery [kW] |
| $P_{ac,out}$: | AC power flow out of the inverter [kW] |
| $P_{ac,in}$: | AC power flow into the converter [kW] |
| $P_{dc,in}$: | DC power flow into the inverter [kW] |
| $P_{dc,out}$: | DC power flow out of the converter [kW] |
| $P_{dgen}$: | Power flow from a diesel generator [kW] |
| $P_{max,inv}$: | Inverter/converter maximum allowable power input [kW] |
| $F_{marg}$: | Diesel generator marginal fuel consumption per kW output [L/kW] |
| $F_{nl}$: | Diesel generator no load fuel consumption [L] |
| $DOD_{max}$: | Maximum battery depth of discharge |
| $SOC$: | Battery state of charge |
| $E_{b,max}$: | Battery maximum energy capacity [kWh] |
| $d_{fixed,c}$: | Fixed demand for customer $c$ [kW] |
| $d_{flex,m}$: | Partial demand met of flexible load m [kW] |
| $d_{max,m}$: | Maximum allowable demand that can be met of flexible demand $m$ [kW] |
| $d_{flex-bal,m}$: | Remaining demand of flexible demand $m$ yet to be met [kWh] |
| $D_{flex,m}$: | Flexible demand $m$ over $K$ timesteps [kWh] |
| $K$: | Lowest resolution of the flexible loads, in this case 24 h |
| $E_{PUMP}$: | Daily energy requirement for pumping water [kWh] |
| $\eta_{PUMP}$: | Water pumping efficiency |
| $\rho_w$: | Water density [kg/m$^3$] |
| $a_g$: | Gravitational acceleration [m/s$^2$] |
| $TDH$: | Total dynamic head [m] |
| $V_w$: | Volume of water to be pumped [m$^3$] |
| $HH_{av}$: | Average household size |
| $D_{w,av}$: | Daily average per capita demand [Liters] |
| $h_E$: | Elevation from water source to sink [m] |
| $v$: | Water flow velocity [m/s] |
| $h_F$: | Friction head [m] |
| $P_{PUMP}$: | Pump size [kW] |
| $S_{h,ave}$: | Average sun hours |
| $E_{MILL}$: | Daily milling energy requirement [kWh] |
| $Mass_{mz}$: | Mass of maize to be milled daily [kg] |
| $M_{power}$: | Miller motor power [kW] |
| $M_{cap}$: | Miller milling capacity [kg/h] |
| $S_{h,ave,min}$: | Average sun hours in worst month |

of each electrification pathway. The rapidly falling costs for renewable energy (RE) technologies, especially Solar Photovoltaics (solar PV) and energy storage technologies have made hybrid PV-Battery-Diesel mini grids a viable alternative pathway to electricity access alongside grid extension. There is a consensus in the current literature that large portions of the currently un-electrified rural populations in developing countries could be electrified at least cost through mini grids and SHSs [2–5]. To accelerate rural electrification through mini grids, some countries in SSA have been developing friendly policies on mini grids, allowing developers to charge cost reflective tariffs [6,7] to encourage private sector participation. These policies are complemented further by the commitment of donor funds on the order of billions of dollars to support deployment of mini grids [8] and subsidy programs such as the Kenya Offgrid Solar Access Project (KOSAP) in Kenya [9] and the Tanzania Rural Electrification Expansion Project (TREEP) [10].

However, despite the efforts made, deployment of mini grids as vehicles of rural electrification in SSA has been rather sluggish. This could be due to a myriad of reasons, including the fact that by the year 2020 only 13% of the $1.6 billion committed to the mini grid industry had been deployed [8]. Unlike grid electricity providing utilities, which in most cases in SSA are government-owned and run on public subsidies, mini grids are largely private sector led and are profit driven businesses. The main revenue generation streams for mini grid developers are from charging connection fees, electricity sales and sometimes grants. However, because of the low consumption nature of the rural customers and their limited ability to pay, the mini grid business models are challenging. For grid utilities, the shortfalls that arise from providing electricity to rural customers are absorbed through cross subsidization from the high consuming customers, mostly in large population centers and industries. Even in cases where utilities do not raise enough revenue to fund their operations, the governments often bail them out, as in the case of Eskom in South Africa [11]. Unfortunately the same cannot be said of the mini grids, whose subsidy programs that if they do exist, mostly end at the initial stages of the project with capital cost subsidization [12]. While up-front capital subsidies lessen the financial burden on mini grid developers during the project implementation phase, a lack of continued subsidy support when they are in operational phase further exacerbates the mini grid business model challenges, and can lead to failed mini grid systems. In a quest to improve financial sustainability of mini grid developers and reduce cost to mini grid customers, various mini grid energy generation and storage dispatch methods, whose objective is to meet the load demand at minimum cost, have been developed. These control strategies are broadly summarized by Barley and Winn [13]. Depending on the employed tariff structure, high system reliability is not necessarily positive for the economics of the mini-grid. For instance, for a solar PV-based mini grid with diesel generator back up running on a fixed tariff, it is most profitable to serve the system load in daylight hours leveraging the cheap-to-generate solar PV power but profit margins diminish during evening hours when the mini grid runs on diesel generators. Thus, the high reliability obligation has direct consequences on operating costs, and hence financial sustainability of a mini grid.

The challenge of providing reliable service through distributed mini grids at low cost catalyzed researchers into investigating trade-offs between reliability and cost in mini grids. Various researchers have proposed system planning and sizing methodologies to meet specific system reliability targets [14–16]. Cicilio et al. [14] incorporate cost–benefit reliability analysis in mini grid distribution network design. Lee et al. [15] proposed a generation equipment sizing strategy that considers energy use patterns and customers ability to pay to satisfy a set reliability. Arab et al. [16] determine the lowest cost PV-Battery combination for set system reliability. These studies serve as good guidelines for system planning, but offer little insight into systems that have already been deployed. There is nascend but growing literature documenting sustainability issues of mini grid projects, and lists a plethora of reasons that lead to project failures. These reasons include but are not limited to lack of community participation in project planning [17,18], policy around tariffs [19,20], low consumption levels [17,19,20] and mismatch between design demand and actual demand [17,21]. Focusing a lens on mini grids tariff policy, this paper contributes to this growing literature by investigating ways in which a mini grid operator may change behavior to insulate themselves from financial ruin when faced with changes in tariff regulations like the one experienced by JUMEME, where the Tanzanian government mandated a reduction of mini grids tariffs to match those of the public utility, TANESCO [19].

### 1.2. Research statement

In this paper, we assess potential effects of a tariff policy change on the operation of existing mini grid systems. Specifically, we quantify service reliability and financial impacts as mini grid developers have to respond to a tariff reduction policy. It is important to point out here that how a mini grid system is operated depends largely on how it has been sized. Mini grid systems can, in general, be classified into a quartet, these are: (i) large sized RE sources without diesel generation backup; (ii) large sized RE sources with diesel generation backup; (iii) moderately sized RE sources without diesel generation backup and (iv) moderately sized RE sources with diesel generation backup. These systems have differing consequences on capital cost, operational cost and reliability. A large sized RE system requires a high capital cost and has minimal operational cost but cannot guarantee 100% reliability without diesel backup. A moderately sized RE system requires less capital in comparison to a large sized RE system, but also provides the worst reliability without the diesel generation backup. In this paper we focus on the moderately sized RE with diesel backup system for two reasons: (1) it is the least cost design (it minimizes capital cost, hence upfront capital subsidy) and (2) it offers flexibility in operation, with trade-off between reliability and cost of operation.

We recognize that a mini grid operator has an obligation to make profits for their investors. Because of this, they have two critical yet divergent operating points from which to make a choice: (1) serving 100% of the demand at all times, potentially incurring operating losses during some periods and; (2) partially serving the demand to maximize returns, potentially compromising customer satisfaction. Thus, we investigate the interplay between reliability and profitability in mini grids. For a moderately sized RE with diesel backup mini grid system, there exists an optimal operating point at which profit is maximized, where reliability is typically less than 100%, depending on the load profile. The trade-off between reliability and profitability affects two things: (1) the marginal cost of reliability, which we define as the cost of meeting an additional unit of reliability beyond the optimal operating point and (2) the operational subsidy, which we define as a positive difference between the cost of delivered energy and revenue generated from what customers paid for it. We use Tanzania as a case study to answer the following research questions: (1) what is the cost of reliability in a mini grid?, (2) how does the cost of reliability affect operational subsidy? and (3) what implications on mini grid electrification policy does the cost of reliability have? We use a second generation version of Stochastic Techno-Economic Microgrid Model (STEMM), an open source quantitative model that incorporates uncertainty to evaluate and compare risk drivers in microgrid utilities developed by Williams et al. [22] to do the analysis. In this second generation version, we have implemented the STEMM tool in the Python programming language, moving it from Analytica in order to make it open-source, and we have extended STEMM's dispatch algorithms to include flexible loads support and smart metering capability. The core contributions of this paper can be summarized as follows: (1) we quantify the cost of reliability between two extreme points of 100% system reliability and point of global optimum maximum profit generation, (2) we trace out the curve relating reliability and profit between these two extreme points in (1) and (3) we recommend policy mechanisms that draw from these insights that ensure financial sustainability of mini-grids and reliable supply of power to mini-grid customers.

The rest of this paper is organized as follows: in Section 2 we present the modeling framework that allows us to do the analyses to answer the research questions, in Section 3 we present the case study and provide the justification for the case study chosen, in Section 4 we present and discuss key findings and provide some important policy considerations and lastly, in Section 5 we provide key conclusions aligning the research objectives and the findings.

## 2. Methods

In this section, we explain in detail the methods and metrics we use to assess the performance of minigrids. We start by giving an overview of STEMM as described in Williams et al. [22], discussing the capabilities and limitations. We then go on to describe the extensions that we have made to STEMM to answer our research questions.

### 2.1. STEMM overview

STEMM simulates the technical performance of the mini grid and financial outcomes using interlinked technical model and financial model. The key focus in this paper is the effect of mini grid control strategies on technical reliability and financial performance, therefore, we have modified STEMM's dispatch algorithm in order to simulation a larger range of scenarios. A dispatch algorithm determines how the mini grid's generators and storage assets are deployed to meet the load demand. In the legacy version of STEMM model, there are two dispatch algorithms based on cost based merit order, (1) load following and (2) cycle charging. The key difference between these two algorithms is that in the former, only excess PV generation is used to charge the battery bank, whereas in the latter, the battery bank is charged by running the diesel generator at higher load factor in excess of the actual load. Both these algorithms are implemented heuristically, that is the power generation components are dispatched in a sequential manner that attempts to minimize cost by prioritizing low cost technologies. As elegant as these algorithms are, they are limited to handling load profiles with the same temporal resolution. Because of this, when there is need to handle loads of different resolutions simultaneously, some crude assumptions have to be made around the lower temporal resolution loads to bring them to higher temporal resolution, with potential to result in sub-optimal operation. Thus, we extend STEMM's dispatch functionality to include ability to handle an arbitrary number of flexible loads at different temporal resolutions. To achieve this, we introduce a metaheuristic optimization dispatch algorithm aimed at profit maximization (revenue–expenses) from the sale of electricity. This new dispatch algorithm does two things: (1) it dispatches the generators optimally on an hourly basis ($k = 1$) and (2) it is forward looking on the flexible loads, meaning that at any time step $k$ it keeps track of the met and unmet flexible load demands.

### 2.2. Power system architecture

Fig. 1 shows a schematic diagram of the configuration of the power system, which consists of dispatchable generators, storage devices, inverter and loads, both fixed and flexible. The power system has two main nodes, the direct current (DC) and the Alternating Current (AC) buses, from which the rest of the power system components are connected. The inverter acts as a bridge between the DC bus and the AC bus. On the DC bus, we have the solar array and battery storage connected, while on the AC bus we have loads and diesel generator backup connected. We assume that the power system supports only AC loads. The direction of power flows is towards the arrow heads. The power flows $P_s$ and $P_R$ represent solar PV production and curtailed solar PV power respectively. Solar PV power is rejected when the PV

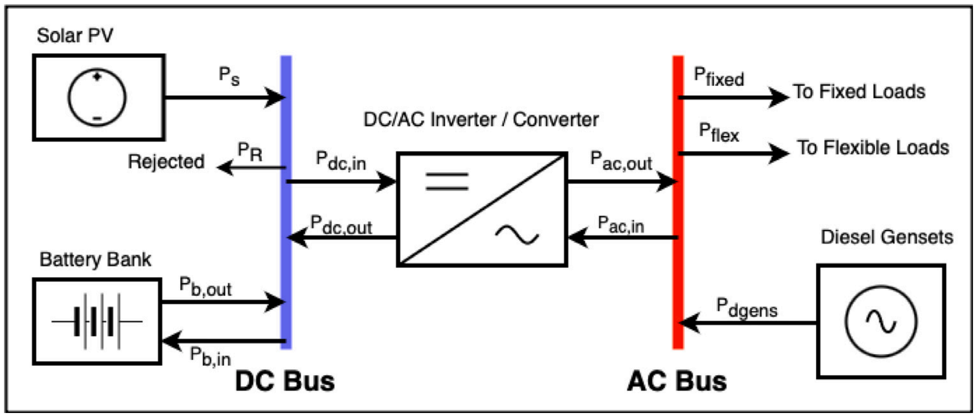



**Fig. 1.** Power system configuration, showing all relevant power flows. The blue line represents the DC bus, while the red represents the AC bus.

array produces more power than the battery bank and the load can absorb. Power flows $P_{b,in}$ and $P_{b,out}$ represent the battery charging and discharge powers respectively. The power flows $P_{fixed}$ and $P_{flex}$ are, respectively, the aggregated powers that go towards meeting the fixed and flexible loads.

We model the fixed loads to have the same temporal resolution $k$. We assume that each load demand node (individual customer in this case) is connected to a dedicated smart-meter which is part of a larger smart-metering mesh network. Thus, at any time index $k$ these smart-meters communicate among themselves through a centralized controller to make intelligent decisions on which load demands to satisfy based on available energy resources. There can, however, be an arbitrary number of diesel generators and flexible loads at different temporal resolutions. Thus, the power flow $P_{dgens}$ represents a sum of all diesel generator contributions. The power flow $P_{flex}$ incrementally meets the flexible loads over $K$ time steps, such that $K$ represents the lowest resolution of the flexible loads.

### 2.3. The dispatch algorithm

We implement an economic dispatch algorithm that decides on how the generation and storage resources are dispatched at a time step of the resolution of the fixed load $k$. Given the state of the system at the end of the previous time step $k-1$ and current meteorologic conditions, the objective is to maximize profit at time step $k$ without regards to future system states. The flexible load demand has to be met over $K$ timesteps, where $K$ can take any number arbitrarily from 1 upwards. Therefore we run the optimization sequentially from $k=1$ to $k=K$. For every $k$th timestep, the objective $J$ is as shown in (1), where $\lambda$ [\$/kWh] represents the tariff, $\epsilon$ [\$/kWh] is an infinitesimally small penalty on curtailed solar PV, $\theta$ [\$/kWh] is the battery degradation cost, $\gamma$ [\$/L] is diesel cost, subscript $g$ is a diesel generator index, $G$ represents the number of diesel generators, $s_g$ is a binary indicator of the running mode (ON/OFF) of the diesel generator, $F_{marg}$ represents marginal fuel consumption of a diesel generator, $P_{dgen}$ is generator power output and $F_{nl}$ is no-load fuel consumption of a diesel generator.

$$J = \lambda[P_{fixed}(k) + P_{flex}(k)] - \epsilon P_R(k) - 2\theta P_{b,out}(k) - \gamma \sum_{g=1}^{G} s_g(F_{marg,g} P_{dgen,g}(k) + F_{nl,g}). \quad (1)$$

We prioritize meeting the flexible loads with the lowest cost energy, solar PV. To do this, we constrain the power supply towards flexible load demand to after sunrise when the solar PV starts generating power. In the event that there is not enough solar PV to meet all of the flexible demand during the day, the remainder is met by dispatching the battery and diesel generators after sunset. From a mini-grid operator's perspective, it is important to minimize the wasted solar PV production $P_R$ by storing excess energy into the battery storage. However, there is a battery degradation cost that is associated with power flows in and out of the battery. On the other hand, there is no real cost to rejected solar PV production, as the PV array's degradation is not a function of use, but of time since installation. Thus to discourage wasting solar PV production and encourage charging of the battery storage, we assign a small penalty $\epsilon$ on $P_R$, assign zero cost on charging the battery and assign a double rate degradation cost for discharging the battery. We evaluate the battery degradation cost as the battery capital cost divided by the amount of energy in and out of the battery until it reaches a specified capacity from origin, which we assume is 80%. We run the optimization subject to the system technical and physical constraints as defined in (2) through (14).

#### 2.3.1. Renewable energy generation & battery state of charge

The net power on the DC node or bus at any timestep $k$ is zero, as shown in (2). We keep track of the battery state of charge (SOC) at each timestep. The battery SOC ranges between the minimum SOC which is defined as the difference between maximum state of charge (which in this case we take as unity) and the maximum depth of discharge $DOD_{max}$, as shown in (3). Between the minimum SOC and maximum SOC, the battery SOC dynamically changes (ascends when there is a net energy flow into the battery and descends when there is a net negative energy flow into the battery), as shown in (4) where $\eta_b$ and $E_{b,max}$ represent the battery round trip efficiency and battery energy capacity respectively. In STEMM, the storage model that is supported is a kinetic battery model (KiBaM) based lead–acid battery as explained in Manwell and McGowan [23]. Therefore, the charging and discharging powers $P_{b,in}$ and $P_{b,out}$ are constrained by the physical properties of the battery.

$$P_s(k) + P_{dc,out}(k) + P_{b,out}(k) - P_R(k) - P_{b,in}(k) - P_{dc,in}(k) = 0. \quad (2)$$

$$1 - DOD_{max} \leq SOC(k) \leq 1. \quad (3)$$

$$SOC(k) = SOC(k-1) + \frac{\sqrt{\eta_b}}{E_{b,max}} P_{b,in}(k) - \frac{1}{\sqrt{\eta_b} \cdot E_{b,max}} P_{b,out}(k). \quad (4)$$

#### 2.3.2. DC-AC inversion & AC-DC conversion

Since only AC loads are supported by the power system we model, it follows therefore that the DC power supplied by solar PV and battery storage have to be transformed into AC power. This is achieved through the inverter, as shown in Fig. 1. Inevitably, the inverter introduces constraints on the magnitude of power that can be supplied towards meeting the load demand. These constraints are expressed in (5), where $\eta_{inv}$ is the inverter efficiency, and $P_{max,inv}$ is the DC power rating of the inverter. In the case that the power supply from the solar PV and battery storage is not sufficient to meet demand, the shortfall is made up through diesel generation. Depending on the volumetric cost of diesel and cost of charging the battery, the diesel generator may operate at a higher load factor such that the power output is higher than the load demand, with the excess charging the battery storage. In (6), we show the constraints on this excess diesel power.

$$P_{dc,in}(k) \cdot \eta_{inv} = P_{ac,out}(k); \quad P_{dc,in}(k) \leq P_{max,inv}. \tag{5}$$

$$P_{dc,out}(k) = P_{ac,in}(k) \cdot \eta_{inv}; \quad P_{ac,in}(k) \leq P_{max,inv}. \tag{6}$$

### 2.3.3. Load meeting & tracking

At any time step $k$, the net power on the AC bus is zero, as shown in constraint (7), where the power from the diesel generators and inverter meets the load demand, either fully or partially. As previously explained in Section 2.2, the powers $P_{fixed}$ and $P_{flex}$ are the aggregated powers that go towards meeting the fixed and flexible loads respectively. Constraints in (8) demonstrate this, where $c$ is an index of customers, $C$ the total number of customers, $d_{fixed,c}$ load demand for customer $c$, $x_c$ a binary indicator of whether customer $c$ is served or not, $m$ an index of flexible loads, $M$ is the total number of flexible load demands, and $d_{flex,m}$ is met partial flexible demand $m$.

$$P_{ac,out}(k) - P_{ac,in}(k) + \sum_{g=1}^{G} s_g P_{dgen,g}(k) - P_{fixed}(k) - P_{flex}(k) = 0. \tag{7}$$

$$P_{fixed}(k) = \sum_{c=1}^{C} d_{fixed,c}(k) \cdot x_c(k); \quad P_{flex}(k) = \sum_{m=1}^{M} d_{flex,m}(k). \tag{8}$$

$$x_c, s_g \in \{0, 1\}. \tag{9}$$

At the beginning of the $K$ timesteps there are $M$ flexible load demands $D_{flex,m}$ that must be served, either partially or fully. We keep track of the cumulative flexible load demand that has been met at every $k$th timestep over the $K$ timesteps. The unmet flexible load demand $d_{flex-bal}(k+1)$ going into the next timestep is the difference between unmet flexible load demand at the beginning of the current timestep $d_{flex-bal}(k)$ and the magnitude of the met partial flexible demand $d_{flex}(k)$, as shown in (11).

$$d_{flex-bal,m}(k=1) = D_{flex,m}. \tag{10}$$

$$d_{flex-bal,m}(k+1) = d_{flex-bal,m}(k) - d_{flex,m}(k). \tag{11}$$

$$\sum_{k=1}^{K} d_{flex,m} \leq D_{flex,m}. \tag{12}$$

As stated in Section 1, a mini-grid operator has two extreme operating points from which to choose to run the system; that of maximizing financial returns or commitment to meet the load in its entirety. The magnitude of flexible load demand that gets satisfied at each $k$th timestep is dependent on the dispatch strategy employed (whether we ensure 100% reliability or maximize profits). In a case where a 100% reliability is the goal, flexible load demand to be met ranges from the minimum of the unmet flexible load demand divided equally among remaining timesteps and the maximum allowable flexible load demand than can be satisfied, which is determined by the power capacity of the device/appliance $d_{flex-max}$, as shown in (13). When the mini-grid system is operated under the full load commitment, the variable $x_c$ is constrained to take the value of 1 (i.e. all fixed loads are met) and the variable $d_{flex-bal}(K)$ is constrained to take the value 0, which means that at the end of the $K$ timesteps, all of the flexible demand must be satisfied. However, if maximizing profits is the chosen dispatch strategy, then the range in magnitude of the flexible load demand to be met in the $k$th timestep starts from 0 to the maximum allowable flexible load demand that can be met, as expressed in (14). Running the system to maximize returns on the other hand allows for flexibility in the two variables, $x_c$ and $d_{flex-bal}(K)$. This flexibility results in the realization of the global optimum profit. The ability to reach global optimum profit is only achievable through use of smart-meters which communicate with a central control unit that can make intelligent decisions on which loads to shed.

$$\frac{d_{flex-bal,m}(k)}{K-k} \leq d_{flex,m}(k) \leq d_{flex-max,m} \tag{13}$$

$$0 \leq d_{flex,m}(k) \leq d_{flex-max,m} \tag{14}$$

## 3. Case study

For a case study, we use a hypothetical community in Tanzania of 500 mini grid customers to evaluate the cost of reliability for a business as usual scenario and to study the impact of adding flexible loads on the cost of reliability. The rest of this section is organized as follows: in Section 3.1 we present case study location justification by (i) providing a brief overview of the electrification status in Tanzania and (ii) highlighting a crucial policy decision put in place by the government of Tanzania concerning mini grids which has consequences on currently mini grid electrified communities and likely to affect future electrification efforts, in Section 3.2 we present key economic inputs that are necessary to carry out the analysis and state their sources, in Section 3.3 we explain how we model fixed load demand, in Section 3.4 we describe how we model the flexible load demand and in Section 3.5 we describe the system sizing algorithm.

### 3.1. Study location justification

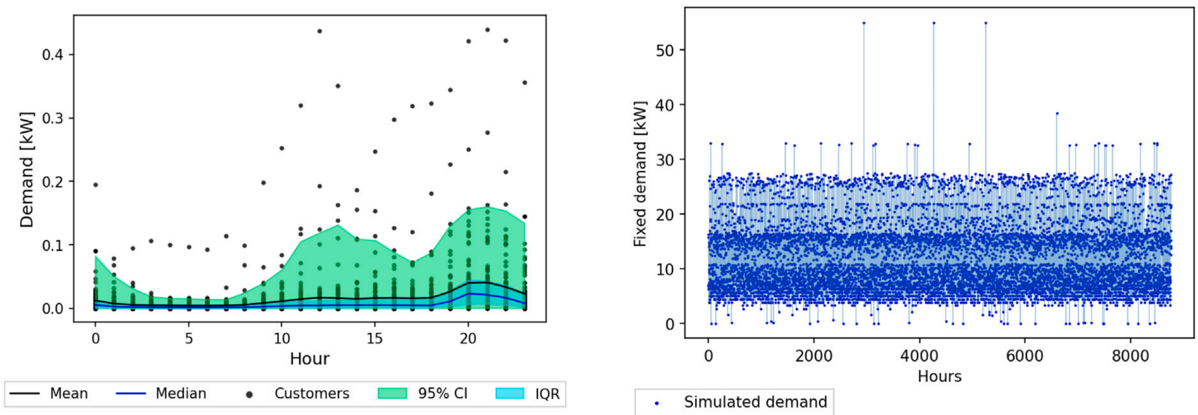
Tanzania is a country situated in East Africa. In 2021, Tanzania was estimated to have a population size of 61.5 million [24], of which according to the World Bank 63% stayed in rural places. In the same year, the World Bank reports that the national electricity access for Tanzania stood at 42.7%, with urban to rural divide of 77.3% and 22.7% respectively. The Tanzanian mini-grid market is the most mature in SSA, having been developed much earlier compared to others due to conducive regulatory framework [25]. In fact, there were 209 mini-grids installed on official records in Tanzania, accounting for about 15% of the Tanzanian generation capacity [25] in 2020. The Tanzanian government mandated the reduction of the mini-grids tariff to match that of the Tanzania Electric Supply Company (TANESCO) in 2020 [26], a move with huge consequences on the financial sustainability of the mini-grids. An example of a mini-grid utility that was affected is JUMEME whose revenues were reduced by over 90%, with decreasing reliability and putting a stop to making new connections [26].

### 3.2. Economic inputs

To simulate and assess the technical and financial performance of the mini grid power system, we need data on technology cost, fuel cost and tariff. For these, we use available data from open sources which include peer reviewed publications, utility publications and the World Bank. We use the technology costs to size the mini grid energy generation and storage devices, while the tariff and diesel costs are used to simulate the performance of the mini grid. Table 1 shows key economic data inputs and their sources.

### 3.3. Fixed demand modeling

We use historical demand data from an existing mini grid serving 91 customers in rural Tanzania, comprising of 51 residential consumers and 40 medium and small enterprises to construct a demand forecast model. The Fig. 2 shows the historical electricity demand data observed from an actual mini grid and the synthetic 8760 load profile. In Fig. 2(a), we show the scatter plot of the historical electricity demand of the individual 91 customers over a typical day. On the same figure, we have also shown the mean and median over the 24 h. To simulate electricity demand, we employ methods developed by Orosz et al. [29] in which they modeled demand by means of cumulative distribution




(a) Distribution of demand across customers for different hours of the day. Data sourced from a mini-grid owned and operated by Powergen Renewable Energy in Tanzania.

(b) Aggregated synthetic 8760 load demand profile for hypothetical 500 minigrid customers.

**Fig. 2.** Historical electricity consumption data and synthetic demand data.

**Table 1**
Key inputs used.

| Parameter name | Value | Units | Source |
|---|---|---|---|
| Exchange rate | 1/2297.76 | $/TZS | World Bank data |
| Tariff | 250.62 | TZS/kWh | [27] |
| Diesel cost | 0.85 | $/L | [28] |
| Solar PV cost | 1,200 | $/kWp | [28] |
| Solar PV life | 20 | year | [28] |
| Charge Controller cost | 400 | $/kW | [28] |
| Charge Controller life | 20 | years | [28] |
| Inverter cost | 800 | $/kW | [28] |
| Inverter life | 10 | years | [28] |
| Diesel Generator cost | 400 | $/kW | [28] |
| Diesel Generator life | 10 | years | [28] |
| Battery Storage cost | 500 | $/kWh | [28] |
| Battery Storage life | 7 | Years | [28] |
| Modeling horizon | 1 | Years | Authors' discretion |

functions (CDFs) generated from empirical probability density functions (PDFs) of measured load data (which in this case is the load data shown in Fig. 2(a)). Fig. 2(b) shows an aggregated 8760 synthetic load simulated for the 500 customers. It is important to point out here that the historical demand data used to built demand prediction model are for a mature mini grid where consumption is steady. Historical rural consumers consumption data from Kenya showed that in general, the steady demand is reached in the second year after customers first get electricity connections, as shown in [30]. Because of this, the revenues for the first two years are underestimated, while costs are underestimated. This however does not significantly affect conclusions drawn from the study as the steady state consumption period is much longer compared to growth phase consumption, and decision making is based on long term demand.

### 3.4. Flexible demand modeling

For this case study, we consider two types of flexible loads: (1) groundwater pumping for domestic consumption and (2) grain (maize) milling, the two most common energy intensive daily activities in typical rural villages in SSA. Here, we present the modeling methodology of these loads.

#### 3.4.1. Groundwater pumping

To evaluate the daily energy requirement $E_{PUMP}$ [kWh] for groundwater pumping, we use Eq. (15), where $\rho_w$ is water density, $a_g$ is the acceleration due to gravity, $TDH$ is the total dynamic head, $V_w$ is the daily water requirement and $\eta_{PUMP}$ is the pump efficiency.

$$E_{PUMP} = \frac{1}{3.6 \times 10^6 \cdot \eta_{PUMP}} \cdot \rho_w \cdot a_g \cdot TDH \cdot V_w. \tag{15}$$

While $\rho_w$ and $a_g$ are known constants, $TDH$ and $V_w$ are location specific, hence vary widely. We evaluate $V_w$ and $TDH$ as in (16) and (17), where $HH_{av}$ is the average household size, $D_{w,av}$ is the average per capita daily water requirement, $C$ the number of min grid customers, $h_E$ is the elevation from suction basin to discharge basin, $v$ is fluid (water) velocity and $h_F$ is friction loss. At this juncture, it is important to point out that we account only for the elevation head. This is because the velocity and friction loss are dependent on pipe properties (diameter and surface roughness), and also because for most applications their contribution to the $TDH$ are small and negligible. Further, we do not need to be accurate in terms of how much the pumping energy requirement is, as it does not affect the objectives of the study we are undertaking.

$$V_w = HH_{av} \cdot D_{w,av} \cdot C. \tag{16}$$

$$TDH = h_E + \frac{v^2}{2a_g} + h_F. \tag{17}$$

Ideally, the energy demand for pumping water should be satisfied with the cheap to generate solar PV power during the day. Thus we size the water pump to meet the daily water pumping energy requirement in a period of average sun hours $S_{h,ave}$, as expressed by Eq. (18).

$$P_{PUMP} = \frac{E_{PUMP}}{S_{h,ave}}. \tag{18}$$

To determine $h_E$ in Eq. (17), we use groundwater depth data from Macdonald et al. [31], in which they used borehole yields to estimate aquifer productivity at a spatial resolution of 5 km × 5 km across the continent of Africa. For our case, we assume a mid range aquifer depth of 50 m. The Fig. 3 shows the distribution of 30 611 sampled points in mainland Tanzania.

#### 3.4.2. Maize milling

We estimate the daily milling energy requirement $E_{MILL}$ as a product of the mass of maize that needs to be milled daily, the miller motor power $M_{power}$ and the inverse of the milling capacity $M_{cap}$. Typically, $M_{power}$ and $M_{cap}$ are size parameters of an existing mill that can be taken off the shelf and are used as the basis for custom sizing. This is expressed formally in (19). Similarly, as in the case of pumping water, we would like to meet the milling energy requirement using the

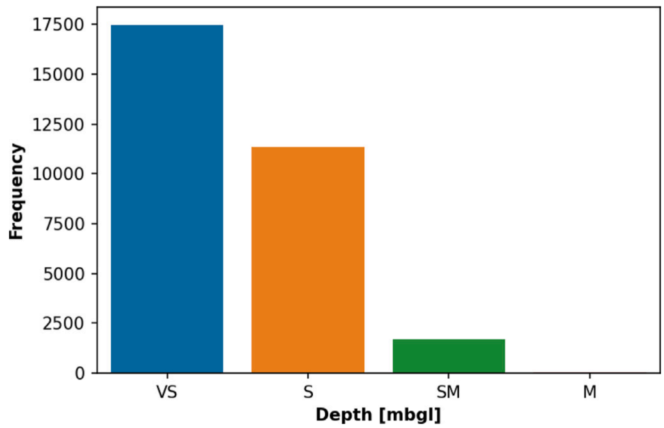



**Fig. 3.** Aquifer depths in Tanzania across 30 611 sampled points countrywide. These points are sampled at 5 km × 5 km arrays. VS means *very small*, and represents an mbgl in the range of 0–7. S means *small*, and represents mbgl in the range of 7–25. SM means *small medium*, and represents mbgl in the range of 25–50. M means *medium*, representing mbgl in the range of 75–100.

**Table 2**
Technical inputs for evaluating flexible demand.

| Parameter name | Value | Units | Source |
|---|---|---|---|
| Daily water consumption | 27–200 | L/person/day | [32] |
| Depth to groundwater | 50 | m | Midpoint value from range in [31] |
| Pump efficiency | 70 | % | Author's discretion (worst case) |
| Annual corn consumption | 135 | kg/person/yr | [33] |
| Milling capacity (base) | 300 | kg/h | [34] |
| Motor power (base) | 3 | kW | [34] |
| Average household size | 5.1 | Persons | [35] |

cheap to generate solar PV power. Thus, we size the motor such that the energy requirement could be realized over the period of average sun hours $S_{h,ave,min}$ in a month with the lowest insolation, as expressed in (20), where $M_{power,des}$ represents the desired motor power. The capacity $M_{cap,des}$ of the custom sized mill is estimated by dividing the mass of maize to be milled in a day by the average sun hours, as expressed in (21).

$$E_{MILL} = Mass_{mz} \cdot M_{power} \cdot M_{cap}^{-1}. \tag{19}$$

$$M_{power,des} = E_{MILL} \cdot S_{h,ave,min}^{-1}. \tag{20}$$

$$M_{cap,des} = Mass_{mz} \cdot S_{h,ave,min}^{-1}. \tag{21}$$

We assume the miller operates once a week on the market day, typically on Fridays. We acknowledge that in reality, the millers offer milling as a service and thus can operate intermittently on different days based on customers' needs. Thus the assumption that a mill is operated once a week overestimates the daily energy requirement on that particular day hence revenue, while underestimating the daily energy requirement for all other days and consequently, the revenue.

#### 3.4.3. Technical inputs & flexible load

To estimate the flexible loads, we rely on inputs from peer reviewed publications and government statistics as sources of reliable data. Table 2 shows these inputs, their values and sources. It is crucial to state here that because the daily water consumption is given as a range, we take the number in the middle of that range, assuming that a typical person would use the average. Using the values in Table 2, for the 500 customer hypothetical community, we found that the annual energy requirement for water pumping and maize milling would be 20.33 MWh and 3.22 MWh respectively.

### 3.5. System sizing

Getting the power system size *right* is a crucial component of designing off the grid electricity systems. By the *right* system size, we mean a system that is able to satisfy 100% of the demand at minimal net present cost (NPC) and hence the levelized cost of energy (LCOE). The NPC and LCOE are evaluated as in (22) and (23), where $t$ represents a time period, $T$ the total number of time periods, $E_t$ is generated energy in period $t$ and $r$ is the discount rate.

$$NPC = Cost_0 + \sum_{t=1}^{T} \frac{Cost_t}{(1+r)^t}. \tag{22}$$

$$LCOE = \frac{NPC}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}. \tag{23}$$

The mini grid is sized to fully meet the residential electricity demand using typical meteorological year insolation and ambient temperature data from the European Union (EU)'s photovoltaic geographical information system (PVGIS) database as described in Huld et al. [36]. A two step, near optimal sizing strategy is employed. This strategy utilizes a heuristic dispatch algorithm that, over a typical meteorological year prioritizes solar and battery over diesel generator to search for a viable PV Battery Diesel combination with the least LCOE. In evaluating the LCOE, we make assumptions that the load profile and meteorological conditions remain unchanged every year throughout the system lifetime. The system size is evaluated as follows. In step 1, the initial components sizes are evaluated as thus: the battery bank has to be equal to daily average demand, the initial solar PV array size is equivalent to the daily average demand (kWh) divided by the average sun hours and the initial diesel generator size is equivalent to maximum of the average daily demand profile (kW). In step 2, combinations of different solar PV, battery and diesel generator sizes, varied from 70% to 130% of the initial sizes, in steps of 5% are created (this results in 2197 different system sizes). Then the LCOE is computed for each of the combinations. A system size that satisfies 100% of the load with the least LCOE is chosen. In anticipation of unaccounted for inefficiencies and demand uncertainties, the general rule of thumb in industry is to oversize the solar PV and battery storage by up to 40% [37]. However, because the goal here is to minimize the capital cost, for the final system size we adjust the solar PV and battery are adjusted by a modest 15% margin

**Table 3**
System components sizes and costs.

| Component | Size | Unit | Unit cost ($) | Life (yr) | Annual capital cost ($ yr$^{-1}$) |
|---|---|---|---|---|---|
| Solar PV Array | 54 | kWp | 1200 | 20 | 3240 |
| Charge controller | 47 | kW | 400 | 20 | 940 |
| Battery | 259 | kWh | 500 | 7 | 18,500 |
| Inverter | 55 | kW | 800 | 10 | 4400 |
| Diesel Gen 1 | 20 | kW | 400 | 10 | 800 |
| Diesel Gen 2 | 41 | kW | 400 | 10 | 1640 |
| | | | | Total | 29,520 |

(i.e. they are sized to be 115% of evaluated sizes). In the case that for the chosen system size, the generator size is less than the maximum demand of the average load profile, the generator size is adjusted to be 110% of the maximum demand. To avoid disruptions and because the diesel generator runs with higher efficiencies at higher load factors, two diesel generators at power rating ratios of 2:1 whose sizes add up to the evaluated generator size are used in the simulations (see Table 3).

## 4. Results and discussions

We perform comparative analyses of the mini-grid technical and financial performances under the two scenarios of full load commitment and profit maximization on two cases: (i) the baseline case (*case I*), which only considers the fixed demand and (ii) the secondary case (*case II*) which considers both the fixed demand and the flexible demand. For each scenario, we analyze the system technical and financial performance at the extreme operating points of full load commitment (100% system reliability) and profit maximization. To do the analysis, we use the 2015 radiation and temperature data from the European Union (EU)'s photovoltaic geographical information system (PVGIS) database as described in Huld et al. [36]. We make an assumption that these 2015 data represent ground truth data and that for all other years the differences with the 2015 data are negligible.

### 4.1. System performance

Fig. 4 shows typical annual system technical and financial performance measured as percentages of the fixed load and operational profit (hereinafter referred to as just profit) under the full load commitment strategy for the base case respectively. We define operational profit as a positive difference between revenue generated selling units of electrical energy and expenses incurred generating that energy. In A, respective energy flows towards meeting the load under the baseline and secondary cases are shown. The total demand breakdown in Fig. 4 1 shows that adding the defined flexible loads to the fixed loads increases the total demand by 23%. This additional flexible demand reduces the rejected solar PV by about 58% (from 24% to 10%), increases solar PV that is directly supplied to the load by 36.5% (from 33% to 52%), and reduces solar PV that charges the battery storage by 7% (from 60% to 56%) as shown in Fig. 4 2. Under both cases, the profit maximization scenarios result in only the solar PV and battery storage being used to meet the demand. A full load commitment in both cases requires that the diesel generators be dispatched to satisfy demand when the stored energy is depleted. In 4B, the respective cash flows revenue, cost and profit are shown. We evaluate profit as the difference between the revenue generated and cost incurred while meeting the load. The actual cashflows that are realized are, on the revenue stream side, the energy sales while on the expenditure site the cost is from running the diesel generator. The cost of dispatching the battery storage (battery degradation cost) does not constitute an actual cashflow, hence we do not include it in the calculation of profit. For both cases, running the system at full load commitment scenario increases the revenue generation, however the profit is minimized. This is because the marginal cost of meeting the demand beyond the maximum profit point is higher than the revenue generated. We observe that introducing flexible demand while running the system under profit maximization strategy increases the profit by 14.5%. This is because the flexible nature of the flexible demand allows the dispatch algorithm to take advantage of the solar PV generation during the day. On the other hand, running the system at full load commitment with flexible loads decreases the profit by 10%. This is because of the elevated need to deploy diesel generator, hence diesel consumption which increases by about 106%. These results are suggestive of that to improve the financial sustainability of mini-grids, they should be operated in such a manner that 100% reliability is not a target.

The Table 4 shows a summary of the technical and financial performance of the mini-grid for both cases I and II over a period of a year at the two extreme ends of the operating spectrum, the 100% load meeting commitment and the profit maximization points. The difference in profit between these two operating points under case I is $2319, and comes at the expense of 7.67% of the load not being met, resulting in an average of 841.37 h (9.6%) of system unavailability per customer annually. For case II, the gross income difference between these two extreme operating points is $4615 and the maximum profit is realized at a cost of 14.04% of unmet load and system unavailability of 1631.9 h (18.6%) of average system unavailability per customer. What these results suggest is that by choosing to operate the mini grid in such a way that 100% of the load is satisfied, the operator would miss out on a potential 22.4% and 39% of profit for cases I and II respectively. At a customer level, the mini grid operator would miss out on close to 5 $ yr$^{-1}$ and close to 9 $ yr$^{-1}$ for cases I and II respectively. These results further cement a remark made earlier that while at liberty to serve partial loads, addition of flexible loads to the mini-grid enhances its financial returns.

### 4.2. Cost of reliability

The Figs. 5(a) and 5(b) show the curve of the relationship between profit and reliability in a mini-grid for cases I and II respectively. There are three critical points shown on these figures, $A$, $B$ and $C$, which have direct relationships to points $A'$, $B'$ and $C'$. Each point is expressed as a proportion of the profit at full load commitment scenario. The points $A$ and $A'$ are profit and cost at full load commitment respectively. The points $B$ and $B'$ are profit and cost at no load commitment scenario. Intermediate points for reliability targets in the range ($R^*$, 100%) are evaluated as follows. We know that the portion of demand that makes up the remaining 100% - $R^*$ is through diesel generation, which means therefore that for a reliability target $R_{target}$ such that $R^* < R_{target} < 100\%$, the portion $R_{target} - R^*$ is met through diesel generation. We formulate a simple optimization based generator(s) dispatch algorithm whose target objective is to meet the load $(R_{target} - R^*)/(100\% - R^*) \times D_T$ at lowest cost, such that $D_T$ is the total demand met through diesel generation at 100% reliability. To evaluate values for intermediate points in the range $(0, R^*)$, we formulate an optimization based dispatch strategy which dispatches solar PV and battery storage with an objective to minimize battery usage to meet demand $R_{target}/R^* \times D(R^*)$, where $D(R^*)$ is demand met at reliability $R^*$. It is important to note here that these curves are theoretical and idealistic in that they assume a perfect foresight. A practical way to enforce reliability values is to constrain the supply

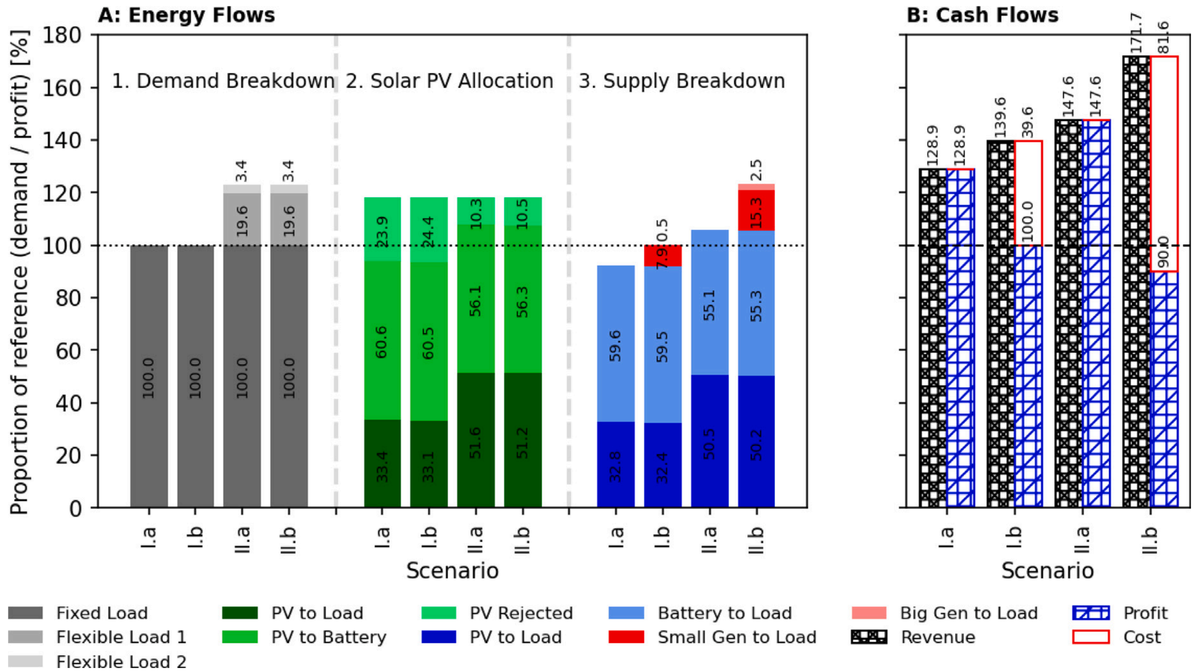



**Fig. 4.** Typical system annual technical and financial performance for the four scenarios of fixed demand profit maximization (I.a), fixed demand full commitment (I.b), fixed demand and flexible demand profit maximization (II.a) and fixed and flexible demand full commitment (II.b). In A, the respective energy flows are shown as proportions of the reference fixed demand. In 1, contributions of different load categories are shown. In 2, solar PV production components are shown. In 3, contributions towards meeting the demand are shown. In B, respective direct cash flows are shown as proportions of the profit at fixed demand full commitment scenario.

**Table 4**
Financial and technical performance under full load commitment and no load obligation scenarios.

| Case | Scenario | Profit [\$/yr] | Reliability [%] | Customer hours | Lost profit [\$/yr] |
|---|---|---|---|---|---|
| I | Full load | 8018 | 100 | 4,380,000 | 2319 |
| I | Max profit | 10,337 | 92.33 | 3,959,314 | 0 |
| II | Full load | 7218 | 100 | 4,380,000 | 4615 |
| II | Max profit | 11,833 | 85.96 | 3,564,037 | 0 |

to meet specific reliability target at the highest resolution timestep $k$, which in this case is an hour. From a mini-grid operator's perspective, it is better to operate the system such that there is no obligation to meet all of the load to maximize the profit at some reliability $R^*$. On the other hand, what customers want is 100% reliability. Unfortunately from a mini grid operator's perspective serving 100% of the demand in an environment where an option of raising the tariff is nonexistent due to regulation would result in some lost potential profit which is the difference of $B$ and $A$. Because in this case the cash flow that constitutes an actual cost is that of diesel consumption from running the diesel generator, the curve between point $B'$ and $A'$ characterizes the trend of cost of reliability. The marginal cost of reliability $Cost_{R,marg}$ is evaluated as a slope of the curve between the points of optimal profit (point $B$) and 100% reliability (point $A$). This is formally shown in Eq. (25), where $F_{tot}$ and $E_{tot}$ refer to total fuel and demand met at 100% reliability. We found that the marginal cost of reliability is 302 \$/% and 329 \$/% for an additional unit of reliability beyond the maximum profit point for cases I and II respectively. These values have to be treated with caution, they are highly dependent on system size, meteorological conditions, tariff and fuel cost. Further, it is impossible to know $E_{tot}$, $F_{tot}$ and $R^*$ ahead to plan the operations. We would like to point out that this however does not render these equations impractical. Using historical data from previous years of running the mini grid, predictive modeling techniques could be employed to make estimates for these values.

$$Cost_{R,marg} = -\frac{Profit_B - Profit_A}{R^* - 1}. \tag{24}$$

$$Cost_{R,marg} = -\frac{\lambda R^* E_{tot} - (\lambda E_{tot} - \gamma F_{tot})}{R^* - 1}. \tag{25}$$

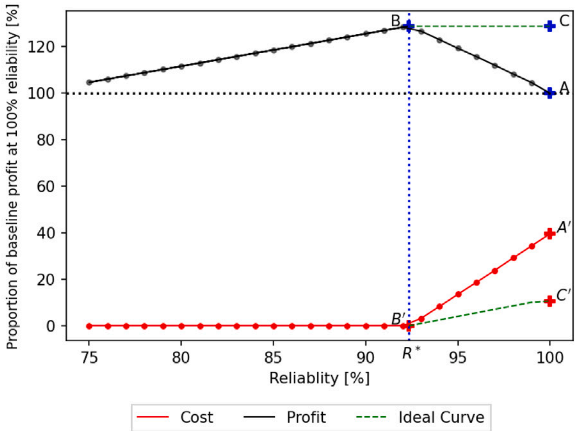
The points $C$ and $C'$ represent an ideal operating point from both the mini-grid operator and customers perspective because it represents maximum realizable profit at 100% reliability. In fact, the mini-grid operator would be perfectly happy to operate at any arbitrary point anywhere along straight lines connecting $B$ to $C$ and $B'$ to $C'$ as this would yield the same profit realized at $R^*$. Achieving this ideal operating point would need the regulator to make one of three policy decisions: (1) allow the mini-grid operator to charge a higher tariff and subsidize the tariff, (2) offer fuel subsidies to the mini-grid operator and (3) concurrently offer fuel subsidy and tariff subsidy.

In the case that the regulator decides to subsidize tariff, the adjusted tariff $\lambda'$ would be as expressed in Eq. (26). Otherwise if the regulator decided to subsidize the fuel price, the adjusted fuel price $\gamma'$ would be as expressed in Eq. (27). The Table 5 shows the evaluated tariff and diesel cost adjustment to serve all the load while keeping the profit level at the optimal reliability level. Under case I, the tariff would need to be increased by 18.2% or the diesel cost be lowered by 72.9%, while under case II the tariff would need to be increased by 36.4% or diesel price lowered by 70.5% to maintain the maximum profit at 100% reliability (achieve point C).

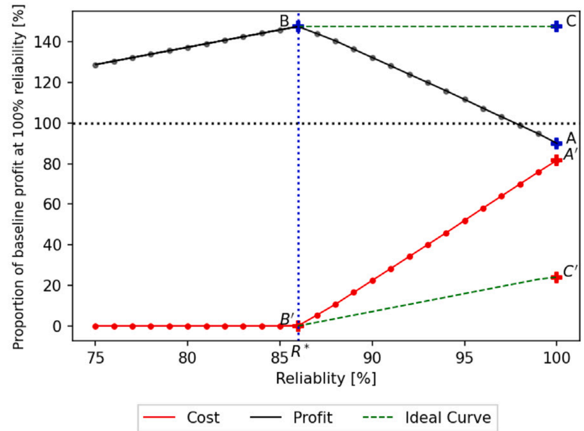
$$\lambda' = R^* \lambda + \frac{\gamma F_{tot}}{E_{tot}}. \tag{26}$$

$$\gamma' = \frac{\lambda E_{tot}(1 - R^*)}{F_{tot}}. \tag{27}$$

The regulator may decide to adjust or subsidize both the tariff and diesel price such that the mini grid operator is not worse off




(a) Case I




(b) Case II

**Fig. 5.** Trade-off between reliability and profit in a mini-grid. The vertical axes represent the fraction of revenue, cost and profit expressed as a percentage of profit at 100% system reliability. The horizontal axes represent reliability. The blue scatter points represent the revenue, the black scatter points show profit and the red scatter points show the cost at a fixed annual reliability respectively. Points A and B represent profit at 100% reliability and profit at no load obligation scenario respectively.

**Table 5**
Tariff and diesel price adjustment and per unit subsidy.

| | | Tariff [\$/kWh] | | | Fuel Price [\$/L] | | |
|---|---|---|---|---|---|---|---|
| | | Actual $\lambda$ | Adjusted $\lambda'$ | Subsidy $(\lambda' - \lambda)$ | Actual $\gamma$ | Adjusted $\gamma'$ | Subsidy $(\gamma - \gamma')$ |
| Case | I | 0.11 | 0.13 | 0.02 | 0.85 | 0.23 | 0.62 |
| | II | 0.11 | 0.15 | 0.04 | 0.85 | 0.25 | 0.60 |

running the system to meet 100% of the demand. The Eq. (28) shows the relationship between the optimal operating point profit and the simultaneously adjusted tariff and diesel price.

$$R^{*}\lambda = \lambda' - \gamma' \frac{F_{tot}}{E_{tot}}. \tag{28}$$

The Fig. 6 shows the trade-off of adjusted tariff and adjusted diesel price at which the system would meet 100% of the demand and maintain a profit that is equivalent to the profit realized at optimal reliability $R^*$. On the same plot, we show the levels of tariff and fuel subsidization that would be required to maintain the optimal reliability profit level. A point along the line plot consists of a pairs $(\lambda', \gamma')$ and $(\lambda' - \lambda, \gamma - \gamma')$ such that 100% demand can be met and the operator would realize the same profit level as when they operate the system at the optimal reliability point $R^*$. There is a difference in maximum adjusted tariffs of 15.4% between cases II and I. This is because under case II, there is an increased need for diesel generation due to the added flexible load, which absorbs some of the solar PV generated energy that would under case I be stored into the battery for consumption after sunset.

### 4.3. Effects of profit oriented dispatch

We evaluated how the system generation equipment dispatch under the profit maximization scenario affects system availability. For the two cases we are analyzing, we evaluated the number of hours the system is unavailable and when during the day the power is unavailable. Fig. 7 shows the number of hours the system is available in a year and when the system is unavailable. An average customer has power for 7919 h (90% of the time) under case I and has power for 7128 h (81.34% of the time) under case II. For both cases, power is mostly unavailable during the night and early morning hours (when it is mostly needed). Under case II, the unavailability is higher compared to under case I because the cheaper-to-generate solar PV energy produced during the day is absorbed by the flexible loads, thus reduced battery charging. These results show that while the addition of flexible loads may improve revenue generation when operating under a profit maximization strategy, it can also yield a net negative impact on the customers, with substantial increase in frequency of power outages. We acknowledge that power outages may trigger behavioral changes in customers. As an example, some customers may decide to find alternative means of electrification like small gasoline generators and small solar lighting systems. These in turn could lead to an increase in revenues decline, which could further deteriorate the financial sustainability of the mini grid operator.

### 4.4. Sensitivity analysis

We have tested the sensitivity of profit to changes in tariff, fuel price and flexible demand. For each scenario, each of these variables was independently decreased and increased by 10% and 20% while all others were held constant and the change in profit noted. Fig. 8 shows a summary of the sensitivity analyses. Under both cases I and II, under the scenario of profit maximization there is no change in flexible load and no change in fuel usage as both these variables are zero. Therefore, because the profit is equivalent to the revenue under profit maximization scenario, the change in profit scales linearly with change in tariff. Thus, in both cases I and II, when tariff is changed by 10% or 20%, the corresponding amount of change in profit is observed. For the maximum reliability scenario, under both cases profit is most sensitive to change in tariff. A 10% and 20% changes in tariff result in corresponding 13.96% and 27.92% under case I, which is a change of a factor of 1.4 under the maximum reliability scenario. Under the case II, a 10% and 20% changes in tariff result in 19.07% and 38.14% corresponding changes in profit, or a factor of 1.9. Profit is second most sensitive to changes in fuel price, and least sensitive to changes in flexible load. What these results tell is that what can either boost or knock profits in the conceptual mini-grid under study is a change in tariff, followed by a change in diesel price and then flexible load.

### 4.5. Policy implications

Analysis results we have presented show that regulations pertaining mini grids may yield adverse consequences on either or both the mini grid utilities and mini grid customers. The mini grid sector in SSA is predominantly private sector led, and thus to not only continue growing but also be financially sustainable, the mini grid projects must be economically viable. A regulation that lowers mini grids tariff to the level

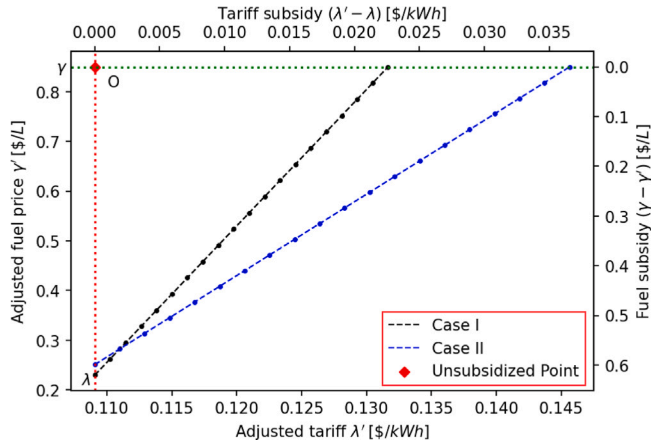



**Fig. 6.** Trade-off between adjusted tariff and adjusted diesel price to run the system at ideal point C.

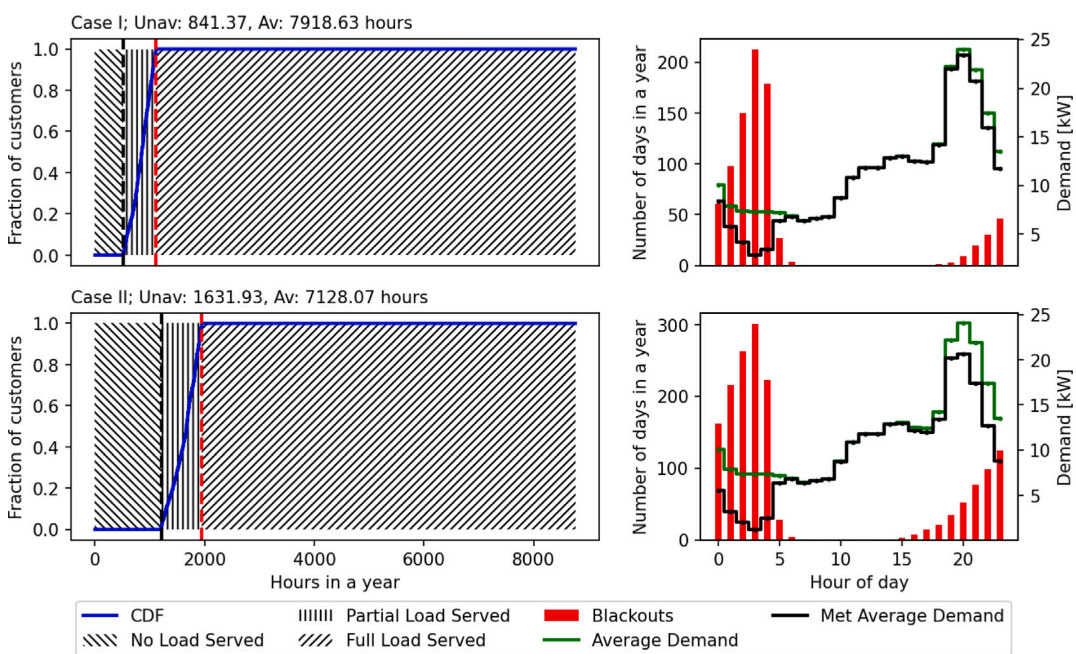



**Fig. 7.** Annual system availability. These are what the colors represent: backward slanting hatch lines are for hours when power is not available to any customers, vertical hatch lines indicate transition hours in which partial load is served, forward slanting hatch line shows hours 100% demand is met, and red bars indicate the number of days in a year for which the power is unavailable for an average customer by hour of day.

of the heavily subsidized grid electricity tariff may not only force mini grid operators into taking drastic measures like running the systems in a manner which maximizes profits while trying to keep the project afloat – which could come at an expense of reliability and hence customer dissatisfaction – but endangers the very existence of private sector participation in rural electrification efforts, a result which runs counter to the goal of universal electricity access. From an energy justice lens, tariff equalization is a sensible and imperative objective to achieve, thus we do not argue against implementing such a policy. Instead, we argue that tariff equalization policies by governments must be comprehensive and include mechanisms to prevent disincentivization of private sector participation in providing connections to the often remote, far to reach communities whose only realistic hopes of getting electricity services are through off the grid systems.

We have demonstrated that lack of flexibility with regards to tariff setting may force operators compromise on reliability, especially during the night when there is no cheap to generate solar PV power. Further, we have quantified in monetary terms how far worse the operators would be if they insisted on meeting all the load, and quantified the marginal loss (cost of reliability) operators would incur. To increase revenue, additional demand is a potential solution. However, as we have demonstrated, addition of flexible demand provides an additional incentive for the operators to run systems such that reliability is compromised in the night hours, arguably the time for which electricity is most needed based on typical load profiles. This deterioration of reliability could have dire consequences in these communities and put into disrepute provision of basic services like primary healthcare and cold storage of fresh agricultural products in businesses. Therefore, it is of utmost importance that before implementing strict, non-negotiable policies around mini grid based electricity provision, governments need to have a clear, thorough understanding of the domino effect likely to be triggered by policy design and implementation, hence plan mitigation strategies.

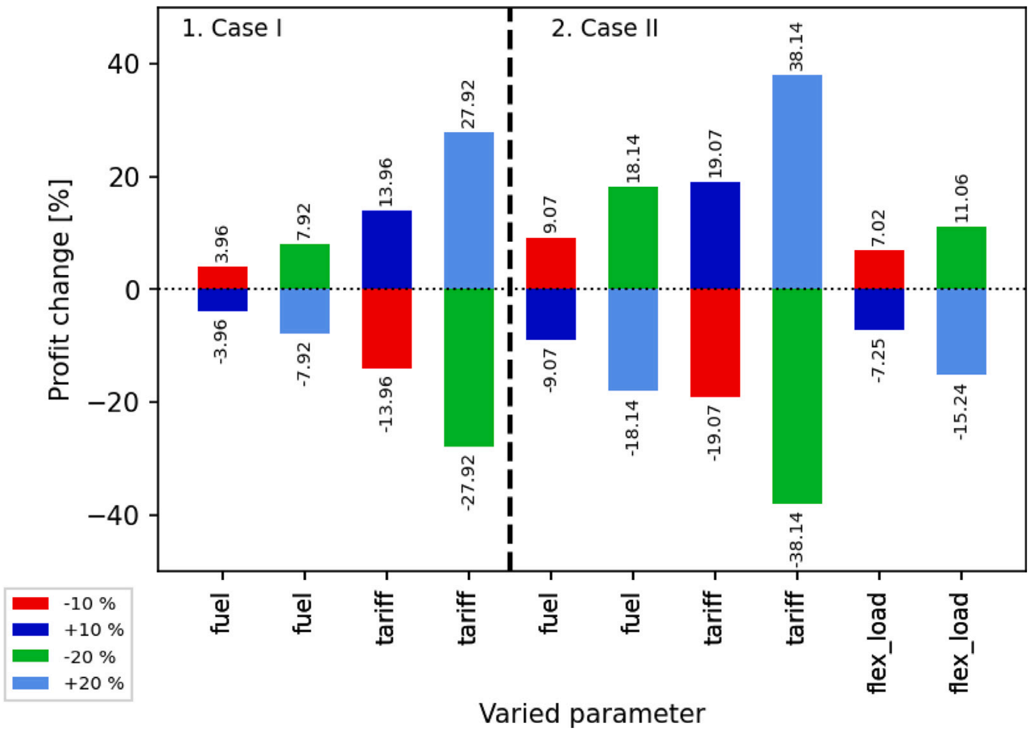



**Fig. 8.** Sensitivity of profit to changes in flexible load, fuel price and tariff.

## 5. Conclusions

This paper has these objectives: (1) quantify the cost of reliability between two extreme operating points of 100% system reliability and point of global optimum profit generation in a mini-grid, (2) trace out the curve relating reliability and profit in a mini-grid and (3) recommend policy mechanisms that draw from the findings in (1) and (2). Here, we state conclusions derived from the results in addressing these objectives.

The results we have presented show that electricity tariff equalization regulation between grid and mini grids in an environment where grid is publicly owned and heavily subsidized, while the mini grids solutions are implemented by the profit driven private sector participants can have adverse impacts on the financial sustainability of mini grid utilities. When faced with such regulations, mini-grid operators in turn have to think carefully about how to run systems to maximize returns and stay afloat. Unfortunately, running systems such that returns are maximized does not always guarantee 100% reliability, with it being compromised at times of high demand - the night hours. We have shown that to improve the financial sustainability of the mini-grids, the operators may run the systems with profit oriented dispatch of generation equipment which compromises reliability. Further, the results show that for a hybrid solar PV - battery storage - diesel generator backup mini grid there exists a peak profit point which corresponds with a specific reliability point $R^*$, determined by the load profile and solar PV to battery ratio, called the optimal reliability. We describe this reliability point as a highest achievable reliability after which supplying more demand results in diminishing returns due to increased marginal cost of running the system. With the assumptions we made in this analysis, we have shown that the marginal cost of reliability is 302 \$/% and 329 \$/% for cases I and II respectively.

The relationship between profit and reliability is described by two piece-wise functions, one linear and one affine with intervals $[0, R^*]$ and $[R^*, 100]$ respectively, where $R^*$ is the optimal reliability. Ideally, the optimal reliability should be 100%, but this can only be achieved if the marginal gain of supplying a kWh of electricity exceeds the marginal cost of generating a kWh of electricity. Thus, to incentivize the mini-grid operators to meet 100% demand, there are two policy mechanisms to consider, (1) direct subsidies or (2) allowing operators to charge cost reflective tariffs. We have shown that to encourage the operators to meet 100% demand, a tariff subsidy level of 18.2% and 36.4% or a diesel price subsidy level of 72.9% and 70.5% have to be provided under cases of fixed demand and fixed demand plus flexible demand respectively.

The conclusions presented in this paper are context specific. However, they provide an important blue print pertaining the likely consequences of a policy like the one made by the Tanzanian regulator to lower mini-grid tariff to equal that of TANESCO. It is therefore important for regulators to ensure that in efforts to lower tariffs to improve affordability for rural customers who are served through mini-grids, they do not make similar policy decisions which may result in de-electrification due to unsustainable returns for mini-grid operators which would mark a huge regression in steps towards meeting the goal of universal electricity access.

## CRediT authorship contribution statement

**Lefu Maqelepo:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fhazhil Wamalwa:** Writing – review & editing, Methodology, Investigation. **Nathan Williams:** Writing – review & editing, Supervision, Funding acquisition. **Jay Taneja:** Writing – review & editing, Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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