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Determining the impact of future load compositions on cost-reflective tariffs and monthly electricity bills in a rural solar PV mini-grid

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ABSTRACT

Renewables-based mini-grids can significantly increase electricity access in rural, non-electrified areas. Despite their potential, mini-grid deployment has been slower than expected due to low profitability in areas with initially low demand. Tariff settings that would improve profitability are challenging due to uncertainty of future demand. While previous studies have explored how tariff settings affect demand and how productive use increases profitability, the impact of load compositions on cost-reflective tariffs and users' bills remains unexplored. This study determines the impact of future load compositions on cost-reflective tariffs and monthly electricity bills in a rural solar PV mini-grid. By combining a case with an already installed solar PV-based mini-grid with spare capacity for future demand evolution and three future load composition scenarios, the study calculates cost-reflective tariffs under five different tariff structures (fixed energy, fixed and variable, time-of-use, power, and hybrid) and users monthly bills using the calculated cost-reflective tariffs. The results show that future load compositions significantly impact cost-reflective tariffs and monthly bills, with the effect depending on the tariff structure. Power-based tariffs show a higher reduction compared to energy-based tariffs for load compositions dominated by daily productive uses. The impact on bills for lower-usage households is significant.

1. Introduction

Renewable energy-based mini-grids play a crucial role in improving electricity access in rural areas of sub-Saharan Africa (SSA), where the majority of people without electricity access live. They are thus key to achieving the United Nations (UN) Sustainable Development Goal (SDG) 7. However, high upfront investment costs hinder their economic viability and pose a significant challenge in expanding electricity access in rural areas (Hartvigsson et al., 2021). As a result, most mini-grids in SSA depend on grants and subsidies to cover at least 30 % of their investment costs (Babayomi et al., 2023). To support SDG 7, the UN has allocated more than half of the estimated $45 billion annual budget to mini-grids and other off-grid solutions (Reber and Booth, 2018).

To ensure economic viability of mini-grids, it is essential that mini-grids are perceived as commercially viable, generating a reasonable return on investment, which is typically contingent on tariffs (Reber et al., 2018). In SSA countries, mini-grid tariffs are based on five different tariff structures: (*i*) uniform national tariff, matching with main grid tariff; (*ii*) efficient new entrant approach, which sets a benchmark tariff estimated as the cost of service for a new market entrant; (*iii*) bid tariff, set by the lowest price bid in a competitive process; (*iv*) individualized cost-based tariff, tailored to each mini-grids cost recovery limit by regulator; and (*v*) willing buyer/willing seller model, where tariffs are agreed upon between the developer and customers (Meister Consultants Group and Inc. a CC, 2020).

Many SSA countries implement highly subsidized uniform national tariffs, typically aligned with the main grid tariff and set below the actual costs incurred by mini-grids, to promote fairness and affordability for users with electricity access (Reber et al., 2018). Some countries, such as Ethiopia (for capacities greater than 200 kW), Kenya, and Rwanda, use individualized cost-based tariffs, which help to ensure cost recovery for developers and attract private investment by reflecting project-specific costs. However, this methodology faces challenges in regulating mini-grids due to the long payback period requirement and

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uncertainties, such as main grid arrival and future demand uncertainties (Meister Consultants Group and Inc. a CC, 2020).

Tariff settings based on different methodologies may have distinct structures, including energy-based, power-based, and hybrid tariffs. Energy-based tariffs are contingent on metered energy usage and encourage energy conservation. They can be fixed energy tariffs (FET) or vary over time, such as time-of-use (ToU) tariffs, which allow for demand-side management (DSM) (Mugisha et al., 2021). The fixed and variable tariff (FVT) is an energy-based tariff, where the fixed rate tariff has a predetermined cost per connection, whereas the variable tariff depends upon the energy consumption within a certain amount of time, typically one month. Block tariffs are another option, which charge different rates based on usage levels and additional fees for exceeding thresholds (Klug et al., 2022). Power tariffs (PT) are based on maximum power and thus could limit peak usage. Hybrid tariffs (HT) are a combination of energy- and power-based tariffs. Tariffs can be tailored to specific load categories, such as households (HH), community (CL), and productive use of electricity (PU),[1] reflecting their varied usage patterns. In this study, load compositions refer to the mix of electricity demand from different load categories, specifically from HHs and PUs, in a mini-grid.

To ensure the economic viability of mini-grids, various solutions and policies have been proposed. Especially in villages solely comprised of HHs, a significant challenge lies in providing affordable electricity to geographically remote communities in rural areas with dispersed populations, low demands, and living on $1.5 a day, at a reasonable electricity tariff (Mugisha et al., 2021) (Van Hove et al., 2022). Consequently, studies indicate that the integration of PUs can stimulate demand (Van Hove et al., 2022; Benson et al., 2019), enhance load factors, and thereby reduce the levelized cost of electricity (LCOE) (Booth et al., 2018). Additionally, capacity expansion is essential to meet the demand from PUs (Wassie and Ahlgren, 2023). However, the share of PUs to HHs should not be too high (Gelchu et al., 2021).

Recent studies emphasize a holistic approach addressing both supply- and demand-side factors to improve the economic viability of mini-grids (Ahlgren and Wassie, 2025). On the demand side, various management strategies have been proposed, including robotic process automation with the Grey Wolf Optimizer for dynamic balancing (Chen et al., 2025), demand response schemes with inclined block tariffs (Yang et al., 2025), and price-responsive models using linear and nonlinear functions (Dey et al., 2024). On the policy side, updating tariff policies to the evolving energy sector remains crucial (Feleafel and Leseure, 2025). Additionally, fuzzy logic combined with Monte Carlo simulations can be utilized to develop dynamic feed-in tariff models for better management of uncertainties (Habib et al., 2025).

The aforementioned studies (Van Hove et al., 2022) (Benson et al., 2019) (Booth et al., 2018) (Wassie and Ahlgren, 2023) and (Gelchu et al., 2021) highlight the pivotal role of PUs in enhancing the economic sustainability of mini-grids. However, it remains uncertain which loads will grow and dominate future demand, indicating the uncertainty of future load compositions. How this evolve depends on economic development and activities of the community following electrification. Studies utilize multiple scenarios in order to represent this future demand uncertainty (Gelchu et al., 2025) and assess the impact of various tariff types on the electricity consumption of different users (Yunusov and Torriti, 2021). Furthermore, studies focus on examining factors influencing electricity usage patterns (Wassie and Ahlgren, 2024) and long-term forecasting methods (Riva et al., 2018). Yet, to the best of the authors' knowledge, no study has determined the impact of load composition on cost-reflective tariffs, defined as the minimum tariff required to recover the cost-optimal investment costs for mini-grids, and the monthly bills. Thus, the study aims to determine the impact of future load compositions on cost-reflective tariffs and monthly electricity bills of users under different tariff structures in a rural solar PV mini-grid.

The mix of user loads and load characteristics influences the composition of the system load, which in turn impacts cost-reflective tariff settings. The cost-reflective tariff affects users' monthly bills, potentially altering users' load characteristics. The study problem formulation focuses on quantifying how load compositions impact cost-reflective tariffs and how these tariffs impact monthly bills. Policy implications thereof are discussed. This formulation, acknowledging that there are other internal and external factors not fully captured by this feedback loop, forms the applied conceptual framework, illustrated in Fig. 1.

2. Method

To determine the impact of future load compositions on cost-reflective tariffs and monthly electricity bills, the study employs a quantitative research approach. The impacts are determined by calculating the cost-reflective tariffs required to recover the investment cost of mini-grids through monthly revenues for alternative load composition evolutions (scenarios), as presented in Fig. 2.

The calculation of the cost-reflective tariffs utilizes the FET, FVT, ToU, PT, and HT tariff structures (pricing mechanisms employed for various purposes). These tariff structures can be used for different purposes based on the business model and incentives associated with the mini-grid (Reber and Booth, 2018), including recovering costs, promoting the use of renewable energy sources, managing peak demand, and encouraging energy efficiency. The utilization and benefits of each tariff structure are influenced by several factors, such as user behavior, regulatory requirements, and the specific objectives of power suppliers and decision-makers (Reber et al., 2018).

System revenue depends on the load efficiency of the system's capacity. To represent possible load developments, a method is employed to identify a combination that leads to a high load factor, which serves as a measure of the system's capacity efficiency. The study determines the mix of HHs and PUs by normalizing and combining their respective demands, a method adapted from (Gelchu et al., 2021).

To determine the impact of future load compositions on cost-reflective tariffs and monthly electricity bills, the study calculates and compares the tariffs and users' bills under the different tariff structures and for load composition evolutions. Based on the findings, the study explores potential policy implications.

The calculation uses demand data based on measured load data from a specific case. The measured demands of the connected load, based on three categories of HHs (HH-1 representing low usage, HH-2 representing medium usage, and HH-3 representing high usage), PU, and CLs, are used. Household load categorization follows a multi-tier framework that classifies electricity consumption into distinct tiers: Tier 1 (low usage) is for consumption of $\geq$0.012 kWh and 0.003 kW; Tier 2 (moderate low usage) is for consumption of $\geq$0.2 kWh and 0.05 kW; Tier 3 (medium usage) is for consumption of $\geq$ 1 kWh and 0.2 kW; Tier 4 (high usage) is for consumption of $\geq$3.4 kWh and 0.8 kW; Tier 5 (very high usage) is for consumption of $\geq$8.2 kWh and 2 kW (Niki, 2015).

Therefore, this study evaluates the impact of load composition using a scenario-based quantitative approach that goes beyond simple scenario construction. Each scenario is quantitatively analyzed by calculating cost-reflective tariffs, the corresponding user bills, and revenues under different tariff structures. This enables a systematic assessment of how variations in load composition can influence revenue generation, cost recovery, user affordability, and the overall economic viability of mini-grids. The method provides a transparent and data-compatible basis for evaluating mini-grid performance, making it well-suited for policy-relevant analysis of future load compositions. While other analytical techniques, such as probabilistic modeling or optimization-based methods, could also be used, the scenario-based quantitative

[1] Productive use of electricity is any application of electricity energy services in activities that increase income or enhance economic value (Aarakit et al., 2024).

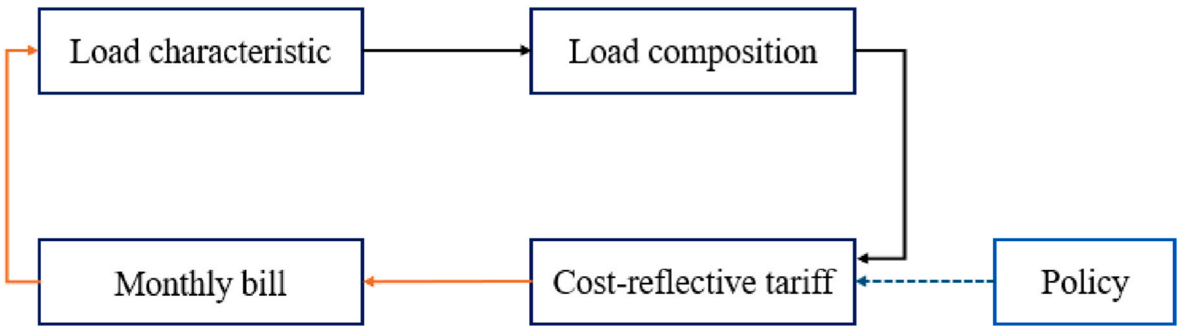

Fig. 1. Conceptual feedback loop of load characteristics, load composition, cost-reflective tariffs, and users' monthly bills. Orange arrows represent the influence of the monthly bill on load characteristics and load characteristics on load composition. Black arrows indicate the impact of load composition on cost-reflective tariffs and of cost-reflective tariffs on user bills; the blue broken arrow illustrates the role of policy on adjusting tariffs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

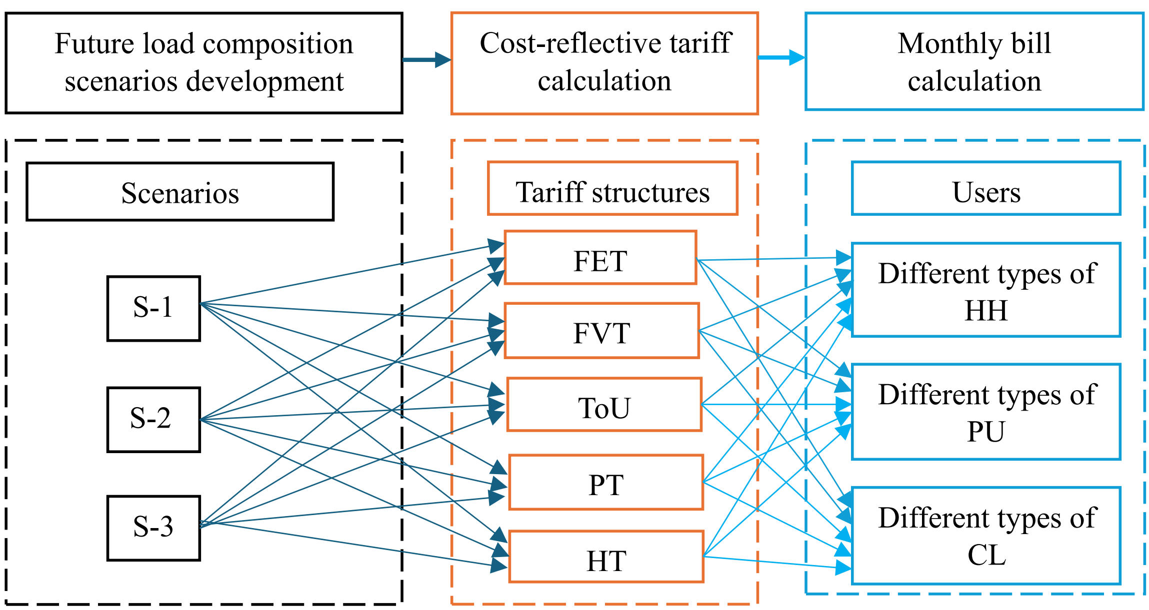

Fig. 2. The calculation steps of the research approach.

approach was chosen for its transparency, policy relevance, and compatibility with available data for mini-grid systems.

2.1. System description

Due to the expected future load growth and the uncertainty about the future demand evolution, the initial generation capacity must be well above the initial demand, or else demand would soon reach its limit, and further growth would be constrained. Thus, in the early life of a mini-grid, there is considerable uncertainty about how demand will evolve, whether it will be mainly household demand or productive use demand, and whether it will develop rapidly or more slowly. This is the point of departure of the system considered in this study, which assumes a fixed-capacity supply with considerable spare capacity for future demand development. Supply is assumed to be covered by solar PV, as this is now the most common option for new systems and accounted for 50 % of operational mini-grids in 2020 (Bloomberg New Energy Finance SE for A, 2020).

2.2. Load composition scenarios

The growth of electricity demand is due both to increased consumption by already connected users and connections by new users, HHs, and PUs. PUs can be classified based on their usage patterns and frequency into daily and non-daily PUs, each with distinct energy needs and consumption behaviors.

The most common types of daily PUs are shops, small bars, and workshops. However, their electricity usage characteristics differ. Shops and small bars have evening peak loads, similar to HHs, while workshops (WSs) are typically used during the daytime and have a higher demand than shops and small bars (Hartvigsson and Ahlgren, 2018; Gelchu et al., 2023a).

Non-daily PUs, on the other hand, are load types that are not used daily. Examples include millers (Ms), which operate three or four days per week, mostly during market days when more grains are collected, and water pumps (WPs) for irrigation. Further, in rural areas, certain families often use Ms monthly, typically once or twice per month (Emmanouil et al., 2021). WPs can be used for irrigation, operating in cycles rather than daily. Additionally, Ms are more likely to be used in rural areas compared to WPs for irrigation (Emmanouil et al., 2021; Uwitije et al., 2023).

To represent possible load developments, three alternative future load composition scenarios are formulated based on the assumed demand growth of HHs and the two types of PUs.

- Scenario 1 (S-1): demand growth is entirely from HHs.

- Scenario 2 (S-2): demand growth from HHs and daily PUs.
- Scenario 3 (S-3): demand growth from HHs and non-daily PUs.

In determining the load profile for each scenario, the base case (BC) load profile of existing connected loads in the specific case study area is used. For each scenario, the number of load types contributing to demand growth is determined based on the system's capacity. This involves incrementally adding one user at a time to the base case demand while evaluating the system's energy and power limits as constraints. Once these limits are reached, the maximum number of new connections is identified and used to develop load profiles for the three alternative future load compositions. This demand growth is assumed to occur at any point during the lifetime of the mini-grid. Furthermore, for S-2 and S-3, to account for potential alternative load compositions within mini-grids, the study considers a mix of respective HHs and PUs based on the method described in Section 2.

Prior literature has highlighted the importance of PUs for mini-grid economic viability. This study extends that work by developing load composition scenarios that distinguish between daily and non-daily PUs, a differentiation not previously explored. Incorporating these two PU types alongside households allows the analysis to capture variations not only in the number of new users but also in their operational characteristics, such as peak coincidence, daily variability, and load factors. Linking each prospective user addition to its hourly load profile ensures that differences in the calculated electricity bills reflect structurally distinct load compositions rather than mere changes in overall demand, providing a realistic and nuanced representation of potential mini-grid futures and their economic impacts.

A sensitivity analysis is conducted to evaluate how varying household demand shares of the projected future demand affect cost-reflective tariffs under the different tariff structures. Household shares range from 0 % to 100 %, with the maximum feasible share corresponding to the load composition that achieves the highest load factor, is used. The analysis focuses on S-2 and S-3, while S-1 is excluded, as its demand growth is assumed to originate entirely from households. This sensitivity analysis further extends the scenario framework by exploring intermediate load compositions not fully captured in the three core scenarios. By varying the HH share within the system's feasible limits, the analysis provides a robustness check on how different compositions influence cost-reflective tariffs, addressing potential future uncertainties beyond the three main scenarios.

2.3. Calculation of cost-reflective tariffs

A cost-reflective tariffs should at least recover the total investment cost, including replacement cost and operation and maintenance cost of the mini-grid. Thus, the term monthly revenue requirement (RR) is introduced. To determine the cost-reflective tariff, the total present cost (TPC) is used to calculate RR over the mini-grid lifetime in months (T), as shown in Eq. (1). The TPC is calculated using the initial investment cost, replacement cost, and operation and maintenance cost (Reber et al., 2018; Ethiopian Energy Authority, 2020).

$$RR = \frac{TPC}{T} \quad (\$) \tag{1}$$

The calculation of the different cost-reflective tariffs, under the considered tariff structures, is detailed here for each of the structures.

2.3.1. Fixed energy tariff

The cost-reflective tariff using the FET structure is calculated by dividing the required RR of the system by the monthly energy usage for each user (i) as (Anwar, 2020):

$$FET = \frac{(RR)_m}{\sum_t^m D_{t,i}} \left(\frac{\$}{kW}\right) \tag{2}$$

where $(RR)_m$ is the total required revenue of the system for month (m) (in \$), and $D_{t,i}$ is the demand of user i (in kW) at time interval t in seconds in a month.

2.3.2. Fixed and variable tariff

The FVT structure includes both a fixed tariff (FT) component and a variable tariff (VT) component. The FT is calculated based on the RR to return the TPC of the distribution system only ($(DC)_m$) and then divided it by the total number of users (n) as shown in Eq. (3). On the other hand, the VT, is calculated using in Eq. (2), but the RR utilized in this equation does not account for the $(DC)_m$, as shown in Eq. (4) (Anwar, 2020).

$$FT = \frac{(DC)_m}{n} \, (\$) \tag{3}$$

$$VT = \frac{(RR)_m - (DC)_m}{\sum_t^m D_{t,i}} \, (\$ / kW) \tag{4}$$

where $(DC)_m$ is the total present cost of the distribution system in a month (in \$).

2.3.3. Time of use

The ToU tariff structure involves setting tariff rates (price for peak and off-peak hours) and determination of tariff shape (duration of peak and off-peak hours), with peak hours being periods of highest demand and off-peak hours occurring outside these times. To calculate the peak tariff (T_P), the peak factor (f_p) is multiplied by the RR and divided by the expected total energy usage (D) during peak hours (N) (Eq. (5)). Similarly, to determine the off-peak tariff (T_{OP}), the off-peak factor (f_{op}) is multiplied by RR and divided by the expected total energy usage during off-peak hours (M) (as shown in Eq. (6)). The f_p is obtained by dividing the average peak power during peak hours (AVR_n) by the total average peak hour (AVR_T) (as shown in Eq. (7)), while the f_{op} is determined by dividing the average peak power during off-peak hours (AVR_m), by the AVR_T (as shown in Eq. (8)), where AVR_T is calculated using Eq. (9). The AVR_n and AVR_m is calculated using Eqs. (10) and (11), respectively (Anwar, 2020).

$$T_P = \frac{RR_T \times f_p}{\sum_n^N D_n} \left(\frac{\$}{kW}\right) \tag{5}$$

$$T_{OP} = \frac{RR_T \times f_{op}}{\sum_m^M D_m} \left(\frac{\$}{kW}\right) \tag{6}$$

$$f_p = \frac{AVR_n}{AVR_T} \tag{7}$$

$$f_{op} = \frac{AVR_m}{AVR_T} \tag{8}$$

$$AVR_T = AVR_n + AVR_m \quad \left(\frac{kW}{hr}\right) \tag{9}$$

$$AVR_n = \frac{\sum_n^N D_n}{N} \left(\frac{kW}{hr}\right) \tag{10}$$

$$AVR_m = \frac{\sum_m^M D_m}{M} \left(\frac{kW}{hr}\right) \tag{11}$$

where D_n is the expected total energy usage during peak hours from n to N hours and D_m is the expected total energy usage during off-peak hours from m to M hours.

Table 1
Measured daily energy use and peak power of each load type in the Koftu mini-grid (Gelchu et al., 2023b).

Load types	Daily energy use (kWh)	Peak power (kW)
HH-1	0.08	0.02
HH-2	2	0.7
HH-3	6	2
CH	0.6	0.05
SCH	14	3
WP	9	7

2.3.4. Power tariff

The cost-reflective tariff using PT is calculated by dividing the RR by the sum of the peak demand for each load ($D_{p,i}$), as shown in Eq. (12).

$$PT = \frac{(RR)_m}{\sum_i^I D_{p,i}} \left(\frac{\frac{\$}{kW}}{month} \right) \tag{12}$$

2.3.5. Hybrid tariff

The cost-reflective tariff using HT is calculated by combining the energy and power tariff types. The energy tariff component (HET) is calculated by using 50 % of the RR calculated using Eq. (2), while the power tariff (HPT) is calculated based on the rest 50 % of the RR, using Eq. (12).

2.4. Monthly electricity bill

The monthly electricity bill (MEB) for each user category is calculated using the cost-reflective tariffs under the FET, FVT, ToU, PT, and HT structures, using Eqs (13)–(17), respectively (Anwar, 2020).

$$MEB_{FET} = FET^* \sum_i^I D_i \ (\$) \tag{13}$$

$$MEB_{FVT} = FT + VT^* \sum_i^I D_i \ (\$) \tag{14}$$

$$MEB_{TOU} = T_{P,N}{}^* \sum_n^N D_n + T_{OP,M}{}^* \sum_m^M D_m \ \ (\$) \tag{15}$$

$$MEB_{PT} = PT^* D_{p,i} \ \ (\$) \tag{16}$$

$$MEB_{HT} = HET^* \sum_i^I D_i + HPT^* D_{p,i} \ \ (\$) \tag{17}$$

where $MEB_{ET}, MEB_{FVT}, MEB_{TOU}, MEB_{PT}, and\ MEB_{HT}$ are the monthly electricity bills of users, calculated under the FET, FVT, ToU, PT, and HT structures, respectively.

3. Case, data, and assumptions

A case with characteristics of recently installed mini-grids, with a considerably larger supply capacity than demand, was selected. Below, the selected case is presented together with actual case-based data inputs and other assumptions used for the calculations.

3.1. Case

The selected case is a solar PV-based mini-grid located in Koftu (8.83°, 39.05°), Ethiopia, 40 km southwest of Addis Ababa, established in 2018. The mini-grid consists of 250 kW of solar PV, a 50 kW diesel generator, and a 1000kWh battery energy storage system (BESS). Excluding the diesel generator, the mini-grid is capable of generating 1553 kWh per day. A survey conducted in 2021 showed that 146 HHs, 1 church (CH), 1 school (SCH), and 1 WP are connected to the mini-grid. The demand of the connected load, measured over one week, from December 6 to 13, 2021, indicated that only 27 % of the generated energy was consumed, indicating a considerably larger supply capacity than demand (Gelchu et al., 2023b).

The survey was conducted using a mixed sampling approach. Households were stratified into low-, medium-, and high-usage categories based on energy meter readings and socio-economic conditions. From the connected households, 26 households were selected: 13 low, 8 medium, and 5 high-usage users, ensuring representative coverage across user categories. This sample size represents less than 20 % of all households within the community. Despite this, the stratified design of the sample ensures proportional representation of users, providing sufficient detail to develop household load profiles with minimal bias in the case area. Preliminary field observations and energy meter data confirm that the connected household groups show similar appliance ownership and consumption patterns. In addition, measured data were collected using three households, one from each usage category (low, medium, and high), selected from the interview samples.

During data collection, community loads, including one school and one church, as well as productive uses, specifically one water pump, were present in the case study area. These users were not sampled individually; instead, they were integrated comprehensively to ensure accurate representation of their load characteristics. Thus, for non-household loads, including productive uses and community loads, all existing users were included using census sampling due to their small number. The measured demand was measured per minute. The measured daily energy use and peak power of each load type in the Koftu mini-grid are presented in Table 1.

3.2. Data and assumptions used

The TPC of the selected mini-grid is $2.56M, calculated with a 7 % discount rate and based on the economic and technical parameters of the mini-grid components shown in Table 2, excluding the diesel generators and the distribution system. In SSA, the initial cost of distribution networks, metering elements, and end-user devices typically accounts for 21 % of the TPC (Moner-Girona et al., 2018). This study considers the distribution cost, with an additional 4 % for operational and maintenance costs (Moner-Girona et al., 2018), to be 25 % of the overall TPC, totaling $0.85M.

Table 2
Economic and technical parameters of the mini-grid components.

Component, unit	Cost ($)	OMC[a] ($/year)	RC [b] ($)	T (year)	Nrep[c]	SV[d] (%)	Reference
Solar PV, kW	1500	50	300	25	0	10	Khezri et al. (2022)
Civil Work, solar PV, kW	40 %	1 %	40 %	25	0	20	Abdelaziz and Eltamaly (2018)
Inverter, kW	711	0	650	10	2	10	Abdelaziz and Eltamaly (2018)
BESS, kWh	330	0	330	10	2	20	Kiptoo et al. (2020)

[a] OMC is operation maintenance cost.
[b] RC is replacement cost.
[c] Nrep is the number of replacements over the project lifetime, T.
[d] SV is the value of a scrap of the mini-grid components.

Table 3
Assumed daily energy use and peak power of the WS and M load types based upon measured data from a mini-grid in southwestern Tanzania (Hartvigsson and Ahlgren, 2018).

Load types	Daily energy use (kWh)	Peak power (kW)
WS	18	16
M	26	14

Table 4
The number of load types and daily energy use used in the scenario formulation.

Scenarios	Load type	Number of load types	Total daily energy use (kWh/day)
S-1	HH-2	225	887
S-2	WS	10	1065
	HH-2	224	
S-3	M	2	936
	HH-2	224	

To represent household demand in the formulation of load profiles for all scenarios, the measured medium usage household (HH-2) load profile from the Koftu mini-grid is used. For S-2, WS represents a daily PU, while M represents a non-daily PU for S-3. However, WSs and Ms demand assumptions are from a mini-grid in southwestern Tanzania (Hartvigsson and Ahlgren, 2018) since there is no connected WS and M in the Koftu mini-grid. The daily energy use and peak power for WS and M used in the scenarios are presented in Table 3.

The daily energy ratio of HH to WS and M is 9:1 and 13:1, respectively. The mix of HHs and PUs for S-2 and S-3, determined using the method outlined in (Gelchu et al., 2021), shows that WS accounts for 71 % of the daily energy for S-2, while M accounts for about 89 % for S-3, with the rest coming from HHs. Based on this mix, the daily energy ratio between HH and WS shifts to 22:1, and the ratio between HH and M shifts to 104:1. The calculated mix of respective HHs and PUs is considered to represent future demand growth for S-2 and S-3.

The load types and total daily energy for each scenario, determined based on the method described in section 2.2, are shown in Table 4. The number of new HHs in S-1 is similar to those for S-2 and S-3. However, in addition to HHs, S-2 includes WSs, and S-3 includes Ms, with a larger number of WSs than Ms. This difference is due to the non-coincident peak times of the HHs and the BC; HH demand peaks in the morning and evening, while the WSs and Ms peak at midday. The total daily energy in the BC is 430 kWh/day. The daily energy differences between the scenarios result in varying excess energy compared to the installed capacity, with S-2 showing 12 % and 10 % lower excess energy than S-1 and S-3, respectively.

To determine the peak and off-peak hours for calculating cost-reflective tariffs using a ToU tariff structure, the BC load profile is considered (shown in Fig. 3). The BC peak load occurs in the early morning (06:00–10:00) and in the evening (18:00–21:00). Since a two-block ToU tariff (peak and off-peak) is applied, the peak period is conservatively assumed to extend from 1:00 to 10:00 and from 18:00 to 24:00 to account for potential early-morning consumption and to simplify tariff application. The off-peak hours is from 10:00 to 18:00.

4. Result and analysis

The cost-reflective tariffs and monthly bills of users calculated under the different tariff structures for each load composition scenario are presented in this section.

4.1. Cost-reflective tariffs

The cost-reflective tariffs calculated for each scenario (S-1, S-2, and S-3), using Eqs. (2)–(12), are presented in Fig. 4. The tariff structures based on energy usage, FET, VT of FVT (Fig. 4a), and HET of HT (Fig. 4d), exhibit distinct cost-reflective tariffs while showing the same relative differences across scenarios. Specifically, for S-2, the cost-reflective tariff is 17 % and 15 % lower than S-1 and S-3, respectively. In each scenario, the cost-reflective tariff calculated using VT of FVT and HET of HT results in reductions of 25 % and 50 %, respectively, compared to that calculated using FET. This disparity arises because the FT in FVT distributes 25 % of the TPC among users, averaging $7.5/month per user, while the HET in HT is based on 50 % of the total RR. Notably, S-2 shows a 2 % lower FT compared to S-1 and S-3 due to a 2 % higher number of users.

As shown for all scenarios, the cost-reflective ToU-based tariff (Fig. 4b) reveals that higher energy usage during peak hours, compared to off-peak hours, results in peak-hour tariffs that are 50 % lower than off-peak tariffs. Due to differences in energy usage during peak and off-peak hours across scenarios, S-2 exhibits the lowest peak and off-peak tariffs compared to S-1 and S-3. Specifically, the peak and off-peak rates for S-2 are 22.3 % lower than those for S-1, and 17 % and 21.6 % lower than those for S-3, respectively.

The sum of each user's peak load will vary based on the future load composition, even with a fixed mini-grid capacity. The cost-reflective

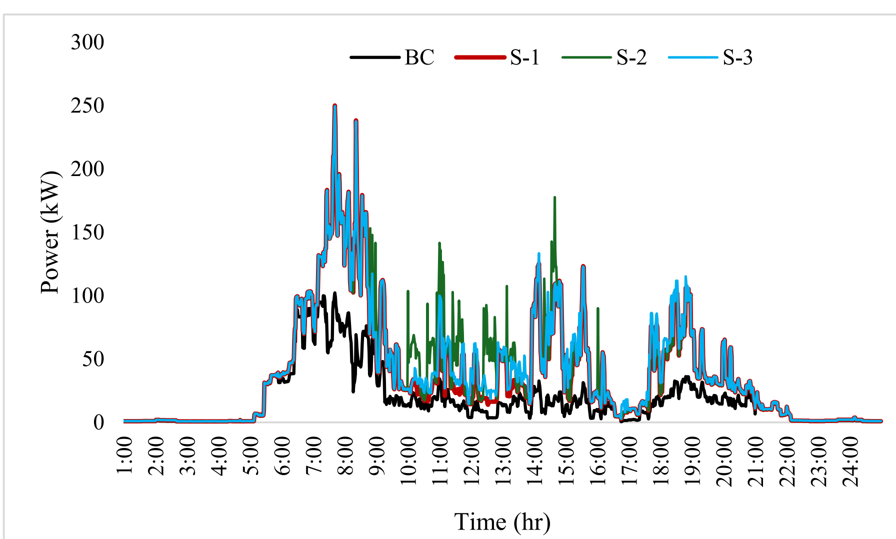

Fig. 3. Load profiles for the base case and the three scenarios.

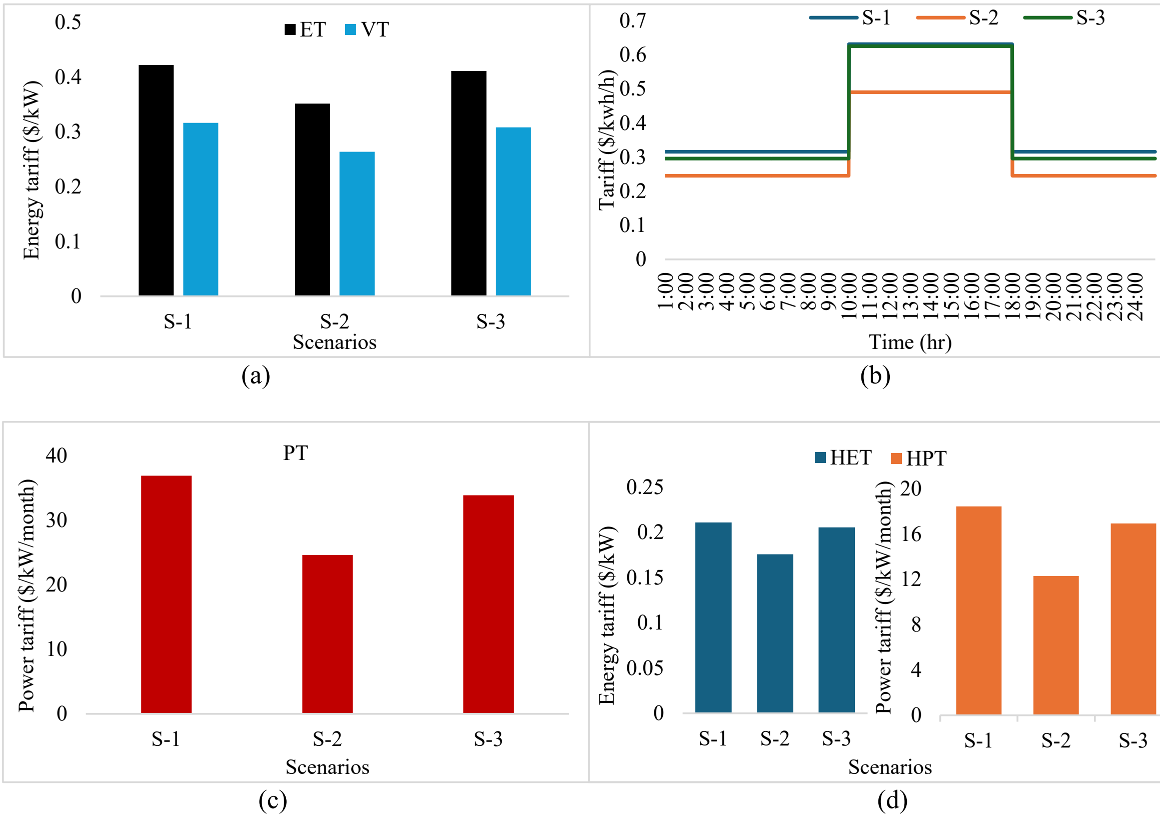

Fig. 4. Cost-reflective tariff for each scenario based on the different tariff structures: (a) FET and VT of FVT, (b) ToU, (c) PT, (d) HT.

tariff based on the PT structure, which depends on the total peak load, is shown in Fig. 4c. As shown in Fig. 4c, S-2, which has the highest peak load sum, results in power tariffs that are 33 % and 27 % lower than those for S-1 and S-3, respectively. In contrast, the cost-reflective tariff based on the HT structure that distributes the required revenue evenly between energy and power tariff components is shown in Fig. 4d. Both

Table 5
Monthly bills for each user, calculated based on the cost-reflective tariff under different tariff structures for each scenario. Color coding indicates the cost level: the highest costs are shown in red, and the lowest costs are in green for each user and scenario.

Scenarios	Types of users	Monthly bill ($)				
		Tariff structures				
		FET	FVT	ToU	PT	HB
S-1	HH-1	0.98	8.34	0.73	0.81	0.90
	HH-2	25.68	26.87	27.47	27.71	26.70
	HH-3	79.18	66.99	68.70	69.57	74.37
	CH	7.85	13.49	6.19	1.97	4.91
	SCH	171.99	136.60	178.72	103.30	137.65
	WP	113.34	92.61	142.05	265.04	189.19
S-2	HH-1	0.82	8.04	0.57	0.54	0.68
	HH-2	21.39	23.47	21.34	18.49	19.94
	HH-3	65.94	56.88	53.37	46.41	56.17
	CH	6.54	12.33	4.81	1.31	3.93
	SCH	143.23	114.85	138.83	68.92	106.07
	WP	94.39	78.22	110.35	176.82	135.60
	WS	189.82	149.79	252.59	380.59	285.21
S-3	HH-1	0.95	8.30	0.69	0.75	0.85
	HH-2	25.02	26.35	26.62	25.44	25.23
	HH-3	77.14	65.44	65.35	63.86	70.50
	CH	7.65	13.32	5.83	1.81	4.73
	SCH	167.55	133.25	172.77	94.83	131.19
	WP	110.42	90.40	139.22	243.30	176.86
	M	157.23	125.51	217.08	479.27	318.25

High

Low

HET and HPT tariffs are 50 % lower than the FET and PT, while maintaining the same relative differences across scenarios as observed in the FET and PT structures.

4.2. Calculated monthly electricity bills of different users

The monthly electricity bills of different users, presented in Table 5, exhibit significant variations influenced by the type of tariff structure utilized for calculating cost-reflective tariffs and load compositions. This variability is particularly noticeable when compared to the commonly employed tariff structure, FET. For S-2, a low cost-reflective tariff results in a lower monthly bills for users (HH-1, HH-2, HH-3, CH, SCH, and WP) compared to S-1 and S-3. The average reductions for all users shown for S-2 are between 12 % and 33 % when compared to those for S-1 and between 10 % and 27 % when compared to those for S-3, with the lowest and highest reductions in FV and PT structures, respectively. Yet, CLs and PUs show monthly bill reductions from similar tariff structures in different load composition scenarios, but not for the HHs, as shown in Table 3. CLs and PUs show significant reductions of monthly bills under PT and FVT, respectively. PT shows a bill reduction of over 75 % for CH and over 40 % for SCH compared to FET. The FVT reduces the monthly bill of users having higher consumption in a system, reducing PUs' bills by over 17 % compared to the FET. However, PUs' bills under PT are more than 100 % higher compared to those under FVT.

The extent of reduction and the tariff structure that leads to reduced bills vary across HH usage levels and load compositions. Table 5 shows that PT tariff structures lead to lower monthly bills than other tariff structures for HH users for S-2, showing reductions of 14 % or more compared to FET. Whereas for S-1 and S-3, the ToU tariff shows a reduced bill for HH-1 (at least 25 % lower than for FET), while FET shows a reduced bill for HH-2 (5 % bill reduction compared to FVT and ToU). The monthly bill for HH-1 under ToU tariffs indicates a reduction, although it is slightly higher than PT. However, FVT significantly increases monthly bills for low-usage users like HH-1 and CH by more than 8 times and 2 times, respectively, compared to FET in all scenarios. HH-3 exhibits a reduction in monthly bills under different tariff structures for S-1 (under FVT) and S-3 (under PT), resulting in reductions of 15 % or more when compared to FET.

The sensitivity analysis was conducted to assess the impact of varying household demand shares on projected future demand and on the resulting cost-reflective tariffs under different tariff structures (Appendix D). The results show that the cost-reflective tariff is higher when household shares are reduced to 0 %, compared to a load composition of 100 % households, achieving a higher load factor. Furthermore, the cost-reflective tariff for S-2 is higher than for S-3. This is because, although S-2 can connect a larger number of daily productive users than S-3 can connect non-daily productive users, the non-coincidence of their peak hours among the non-daily productive users and households allows additional households to be added, resulting in a lower cost-reflective tariff for S-3.

For all scenarios, the calculated monthly electricity bill using FET is lower than the tariff in Ethiopia. The monthly bill for HH-1 in S-2 is 69 times higher than the amount calculated under the old tariff in Ethiopia and 28 times higher compared to the amount under the new tariff (see Appendix A for the old and new electricity tariffs in Ethiopia and Appendix B for the monthly bills of users based on these tariffs). This difference is more pronounced for S-1 and S-3, with increases of 6 % and 5 %, respectively. While CH follows the same pattern as HH-1, other HHs, as well as CL and PUs, show monthly bills 5 to 11 times higher compared to those calculated using the new tariff in Ethiopia.

The variations of load compositions significantly affect total revenue collection, even when using old and new tariffs in Ethiopia, with S-2 generating the highest revenue compared to S-1 and S-3. The total monthly revenue of the mini-grid calculated using the cost-reflective tariff is higher compared to when it is calculated with the electricity tariff in Ethiopia (see Appendix C). Specifically, the total monthly revenue under the cost-reflective tariff is significantly higher, 21, 16, and 20 times greater, for S-1, S-2, and S-3, respectively, compared to the old tariff. However, this increase is reduced to 12, 9, and 11 times under the new tariff.

The monthly distribution of RR among HH, CL, and PU is presented in Fig. 5. The tariff structures impact the total RR collected from these load types differently. In S-2 and S-3, where there are more PUs, the ToU and PT tariffs reduce HH bills and shift RR collection to PUs. This results in a reduction of the HH share by 5 % and 17 % in S-2, and by 2 % and 7 % in S-3, compared to FET. The HB tariff structure also shifts more RR to PUs, reducing the HH share by 8 % in S-2 and 3 % in S-3. Conversely, the FV relatively reduces the RR share from productive uses.

5. Discussion

The results of the study show how future mini-grid load compositions significantly impact the cost-reflective tariffs, which are lower for load compositions with a high share of daily productive use rather than household and non-daily productive use. The magnitude of this difference depends on the tariff structure. It is more significant with power-based tariffs than with energy-based tariffs, indicating the impact of the sum of users' peak loads compared to the users' aggregate energy usage on cost-reflective tariffs. For time-of-use and hybrid tariff structures, the impact of mini-grid load compositions on the cost-reflective tariffs across the scenarios shows differences that fall between energy- and power-based tariffs. In contrast, the fixed component of the fixed and variable tariff structure shows a modest (2 %) difference across the future mini-grid load compositions.

The calculated cost-reflective tariffs, determined using the fixed energy tariff structure, compare well with previous studies reporting values for solar PV-based mini-grids ranging from $0.25 to 0.61/kWh (Come et al., 2021). However, they are much lower than the tariff ($1.75/kWh) that unconnected customers in SSA would pay for energy generation through alternative means like kerosene or batteries (Reber and Booth, 2018; Reber et al., 2018). However, the calculated monthly electricity bill under the fixed energy tariff is lower than the implied tariff for all future load composition scenarios.

The calculated cost-reflective tariff, using the fixed energy tariff structure for the future load composition with more daily productive use, is $0.351/kWh. This is more than eleven times higher than the old (until 2024) average tariff of $0.03/kWh paid by household users in Ethiopia. In Ethiopia, a new tariff was implemented September 11, 2024, which raises the average price to $0.07/kWh through quarterly price adjustments, marking the largest increase in four years (Ethiopian Electric Utility, 2024). This new tariff is also more than four times higher than the calculated lower cost-reflective tariff, using the fixed energy tariff structure. This shows that the new tariffs in Ethiopia are insufficient to cover mini-grid investment costs, highlighting the need for additional measures to ensure economic viability.

Future mini-grid load compositions also affect mini-grid revenues, showing the importance of considering the impact of the future load composition as a key factor during tariff revisions, which occur every four years in the case of Ethiopia (Niki, 2015). However, connecting to a system with changing tariffs may pose risks, including price volatility, long-term investment challenges, reluctance to adopt demand-side management strategies, and ensuring profitability (Dutta and Mitra, 2017).

Households are typically the primary users in rural areas of SSA. This study highlights that a system with a higher proportion of household connections, especially during the initial lifespan, limits the connection of new users and constrains demand growth. The limitation of demand growth results in high cost-reflective tariffs. Therefore, implementing tariffs that encourage demand growth, especially in a system with a fixed capacity, is crucial. Increased demand can lead to reduced tariffs, addressing challenges posed by high rates, such as the limited ability of rural populations to afford electricity (Hartvigsson et al., 2021; Wassie

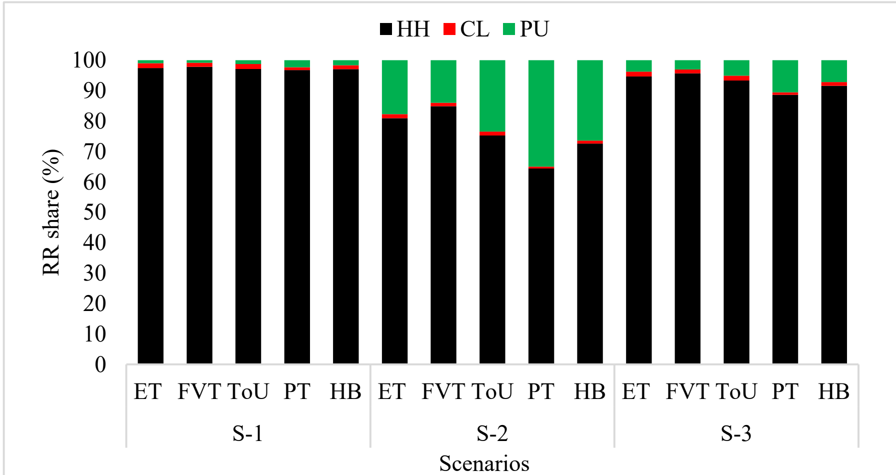

Fig. 5. Percentage shares of revenue from household, community, and productive use, under the different tariff structures for each scenario.

and Ahlgren, 2023). This would be important for lower-usage households, governments, and for the profitability of investors. The sensitivity results also show that achieving a reasonable distribution between household and productive use shares of the load composition can help to lower cost-reflective tariffs. This is in line with previous studies and highlights the importance of using the load factor as a tool for load management to enhance the economic viability of rural mini-grids (Gelchu et al., 2021; Gelchu and Ehnberg, 2024).

Demand growth can be achieved through time-of-use tariffs. For instance, incentivizing electric mills to operate during peak solar hours rather than in the morning. This timing benefits users, as they often use sunlight to dry their products, resulting in higher-quality, drier flour (Booth et al., 2018). Additionally, using water pumps for irrigation and millers during harvesting can further increase annual demand growth. However, implementing time-of-use tariffs may require advanced metering technology, which could raise costs and necessitate demand flexibility of users (Yunusov and Torriti, 2021).

The impact of future mini-grid load compositions on cost-reflective tariffs shows a significant impact on users' monthly bills and profitability, depending on the tariff structure. Evaluating the sensitivity of different tariff structures reveals significant impacts on monthly bills and revenue collection from load categories. Power tariffs can reduce monthly bills for community loads by more than 40 %, but they can increase bills for productive use by over 100 % compared to fixed energy tariffs. In the load composition with only households, high-usage households will have similar monthly bill behavior as productive users, indicating that power tariffs may be less advantageous for productive uses and high-usage households. However, power tariffs can provide more stable revenue and better cost recovery, even if users reduce energy consumption, particularly in systems with more non-daily productive uses (Yunusov and Torriti, 2021).

On the other hand, in load compositions with more household and non-daily productive use, low- and medium-usage households experience reduced bills under time-of-use and fixed energy tariff structures, respectively. Notably, the relative reduction in monthly bills is more pronounced for low-usage households (more than eight times under fixed and variable compared to the fixed energy tariff structure), highlighting the importance of selecting appropriate tariff structures based on usage levels. These reductions in monthly bills for low-usage households and the ability to connect additional productive uses under the time-of-use tariff indicate that, for villages like Koftu, implementing a time-of-use tariff is the most advantageous option. The larger reductions of the monthly bills under time-of-use tariffs for households also highlight the significance of implementing demand-side management for low- and medium-usage households.

Most SSA countries recognize that cross-subsidies can be integrated into the tariffs (Ethiopian Energy Authority, 2020). The differences in monthly electricity bills and the percentage shares of collected required revenue per month indicate that certain tariff structures can incentivize specific users while penalizing others. Consequently, this may create a need for additional subsidies or incentives for the penalized users, highlighting the importance of also considering cross-subsidy impacts. The differences in the required revenue collected between the three load categories show that load compositions with more household and non-daily productive use can lead to increased revenue collection from households, in turn affecting both household affordability and subsidy needs.

To support private mini-grid operators facing challenges due to low tariffs, some countries use feed-in tariffs, where operators receive fixed prices for every unit of energy generated. However, the energy is sold to users at a different, often lower, price compared to the feed-in tariff (Herbert and Phimister, 2019). In this regard, this study shows that mini-grids with future load compositions with more daily productive uses may have financial advantages compared to those primarily serving households and non-daily productive loads. This indicates the need for mini-grid developers to select rural communities with existing economic activity and, thus, productive use loads rather than targeting household-dominated communities. Such priorities are, however, likely not aligned with donor support for mini-grids targeting low-income households.

To enhance revenue, some developers have adapted their business models by adjusting tariff structures and encouraging productive use loads, for instance, through appliance financing. However, the result of this study stresses the importance of adopting comprehensive business model approaches, taking the future load composition impacts into account. It would also be useful to evaluate how applied business models have stimulated demand by considering future load composition uncertainties.

The observed nearly zero nighttime consumption indicates that continuous-use appliances, such as household or community refrigerators, were not present in the case study area, since no such appliances were identified during data collection. However, rural urbanization could substantially increase energy demand from such appliances. Their inclusion would raise base and peak loads, potentially reduce the number of newly added productive users, affect system economic viability, and require demand-side management. Additionally, continuously operating appliances can lower cost-reflective tariffs under energy-based structures. Therefore, incorporating continuous appliances would likely alter both load composition and corresponding tariff estimates.

An installed solar PV-based mini-grid designed with spare capacity to allow for future demand growth was used in this analysis. Future load composition scenarios were developed based on load categories rather than specific appliances, offering more generalizable insights. Using a fixed-capacity mini-grid helps to determine the impact of load compositions while maintaining a constant total present cost. The selected case study area is characterized by a high morning peak of a kind that is less common. This study also acknowledges limitations related to the survey sample. Although the household sample represents less than 20 % of all connected households, stratified sampling ensured proportional representation of major consumption groups. Larger samples in future work could further enhance statistical robustness. Community institutions found in the case area, specifically one school and one church, were fully included through census sampling. However, their limited number reflects the specific context of the case study area and may vary across other mini-grid settings. Thus, while the sampling strategy provides reliable load patterns for modeling, broader surveys in future research could enhance generalizability. Additionally, this study acknowledges limitations in scenario development. While other scenarios could be developed, the scenario analysis in this study is focused on households, daily PUs, and non-daily PUs, providing a framework for evaluating PU impacts. Despite these, the findings would generally be applicable to most SSA rural contexts. The main contributions of the study are to indicate: (*i*) how future mini-grid load composition impacts cost-reflective tariffs under different tariff structures; and (*ii*) how the future mini-grid load composition impacts monthly bills of mini-grid users under different tariff structures.

Methodologically, the approach is novel in estimating cost-reflective tariffs from the demand side, considering the load composition rather than the supply side. Future studies could expand the analysis by considering additional cases with different load characteristics and a broader set of possible load composition scenarios, including additional PU types, probabilistic load growth, or more complex adoption patterns.

6. Conclusion and policy implications

This study determines impacts of mini-grid load compositions under various tariff structures on cost-reflective tariffs and users' monthly electricity bills of a rural solar PV mini-grid. The findings indicate that future mini-grid load compositions can significantly impact cost-reflective tariffs and users' monthly bills, depending on the tariff structure. Load compositions with more daily productive uses result in a lower cost-reflective tariff compared to load compositions with more household and non-daily productive uses, with reductions of 33 % and 27 % under power-based tariff structures and 17 % and 15 % under energy-based tariffs.

The impact of future mini-grid load compositions on users' monthly bills varies across load categories. Households are more impacted than community and productive users, depending on the tariff structure. Community and productive users experience reduced monthly bills under power, fixed and variable tariff structures, respectively. While low- and medium-usage households can see reduced bills under time-of-use and fixed energy tariffs, respectively, low-usage households may face significantly higher bills, up to eight times more, under fixed and variable tariffs compared to fixed energy tariffs. These findings emphasize the importance of considering the impact of future mini-grid load compositions for ensuring economic viability and sustainability of mini-grids.

The study clearly shows that certain combinations of load and tariff structure can strongly affect the monthly bills of low-income households and thus constitute an important barrier to expanded electricity access for the less favored. Thus, it is essential that tariff settings and revisions pay particular attention to the impact on low-usage households. The uncertainty about the mini-grid future load composition post electrification ought to be considered in tariff decisions and revisions to both protect low-usage households through fair pricing and ensure profitability for investors.

The importance of productive use in mini-grids for financial viability is now well established, but in contrast to previous studies, this study clearly distinguished between daily and non-daily productive use and could conclude that this distinction is essential since their impact on the mini-grid economy differs sharply.

CRediT authorship contribution statement

Milky Ali Gelchu: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Jimmy Ehnberg:** Supervision, Methodology, Conceptualization. **Dereje Shiferaw:** Supervision. **Erik O. Ahlgren:** Supervision, Methodology, Conceptualization.

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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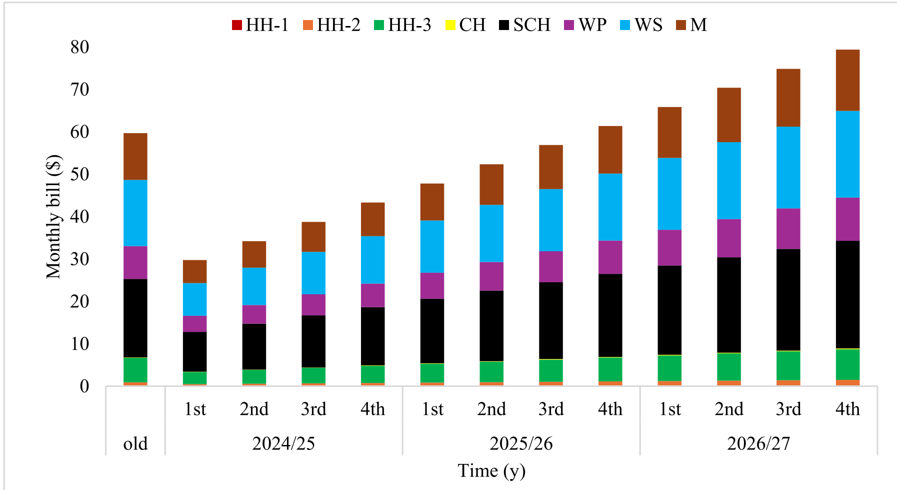
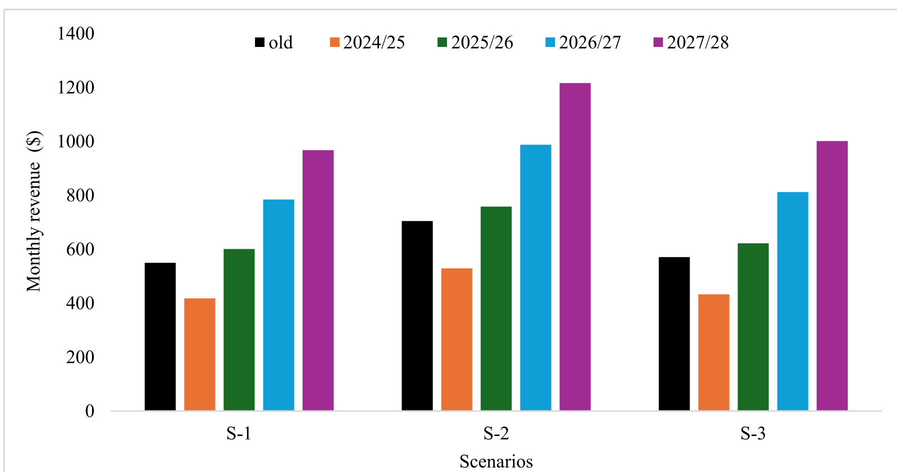
Appendix A. Old and new electricity tariff in Ethiopia

Monthly electricity consumption (kWh)	Old tariff (ETB)	New tariff (ETB)															
		2024/25				2025/26				2026/27				2027/28			
		1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Up to 50 kWh	0.27	0.35	0.43	0.52	0.6	0.68	0.76	0.84	0.92	1	1.08	1.16	1.24	1.32	1.4	1.48	1.56
Up to100 kWh	0.77	0.95	1.13	1.31	1.49	1.67	1.85	2.03	2.21	2.39	2.57	2.76	2.94	3.12	3.3	3.48	3.66
Up to 200 kWh	1.63	1.89	2.15	2.41	2.67	2.93	3.19	3.45	3.72	3.98	4.24	4.5	4.76	5.02	5.28	5.55	5.81
Up to 300 kWh	2	2.46	2.92	3.38	3.84	4.3	4.76	5.22	5.68	6.14	6.6	7.06	7.52	7.98	8.44	8.89	9.35
Up to 400 kWh	2.2	2.66	3.12	3.57	4.03	4.49	4.95	5.41	5.86	6.32	6.78	7.24	7.7	8.15	8.61	9.07	9.53
Up to 500 kW	2.41	2.85	3.29	3.73	4.17	4.62	5.06	5.5	5.94	6.39	6.83	7.27	7.71	8.16	8.6	9.04	9.48
Above 500 kWh	2.48	2.92	3.35	3.79	4.23	4.66	5.1	5.54	5.97	6.41	6.84	7.28	7.72	8.15	8.59	9.03	9.46
Small industry	1.53	1.76	2.02	2.29	2.56	2.82	3.09	3.36	3.62	3.88	4.15	4.41	4.68	4.93	5.2	5.46	5.73

Appendix B. Monthly bill of users based on the electricity tariff in Ethiopia



Appendix C. Total monthly revenue based on the electricity tariff in Ethiopia



Appendix D. Sensitivity analysis of cost-reflective tariffs considering varying household demand shares and tariff structures

Share of HH (%)	Scenarios	Tariff structures							
		ET	PT	TOU		HT		FVT	
				TP	TOP	HET	HPT	FT	VT
0 %	S-2	0.79	16.57	0.46	0.92	0.39	8.28	4.87	0.59
	S-3	0.35	6.13	0.22	0.45	0.18	3.06	1.32	0.26
25 %	S-2	0.55	18.29	0.35	0.70	0.27	9.14	5.30	0.41
	S-3	0.41	11.96	0.27	0.55	0.20	5.98	2.62	0.30
50 %	S-2	0.46	20.23	0.30	0.61	0.23	10.12	5.96	0.34
	S-3	0.43	20.12	0.29	0.61	0.21	10.06	4.41	0.32
75 %	S-2	0.40	22.27	0.27	0.54	0.20	11.14	6.65	0.30
	S-3	0.41	25.98	0.29	0.60	0.20	12.99	5.77	0.31
100 %	S-1	0.42	36.89	0.32	0.63	0.21	18.45	7.60	0.32
	S-2	0.35	24.61	0.25	0.49	0.18	12.31	7.40	0.26
	S-3	0.41	33.87	0.30	0.63	0.21	16.93	7.60	0.31

Data availability

Data will be made available on request.

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