Energy Management System for Inter-Connected Self-Sufficient Microgrids with Blockchain-Based Peer-to-Peer Energy Market

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***Abstract*—Microgrids powered by renewable energy-based solar photo-voltaics (PV) and battery energy storage systems are a viable techno-economical solution in providing electricity to off-the-grid and rural areas in sub-Saharan Africa (SSA). Smart and productive use of available energy capacity of off-grid microgrids is the key element in the context of rural electrification, where customers' ability to pay and purchase power are limited. For cost-efficient utilization and distribution of renewable energy resources, this paper describes a methodology of an inter-microgrid energy management system (inter-MGEMS) applied in the concept of electrification with inter-connected self-sufficient microgrids. An an agent, that is, software, acts on behalf of microgrids' customers, to first enable, and also simplify their engagement to the energy trading. It utilizes a long short-term memory (LSTM) model to predict the consumer load profiles over the day and night periods, and based on that estimates the profiles for the energy available to be shared among the inter-connected microgrids. The available energy bids are placed at the inter-MGEMS. The energy trading in the inter-MGEMS is based on non-cooperative game theory approach, where each microgrid independently attempts to maximize its profit. The blockchain is used as a ground technology for the energy trading platform.**

***Index Terms*—Blockchain, off-grid, peer-to-peer, dynamic pricing, rural electrification.**

I. Introduction

Developing countries face significant challenges in energy access provisioning. This is mainly due to financial constraints and the high costs of extending centralized electricity distribution networks, according to traditional energy system design. Long transmission distances further increase energy losses, making grid expansion unfeasible in remote areas. The traditional electrification approach would also result in high costs of connection to the grid for the customer, as well as high operation and maintenance (O&M) costs for the transmission and distribution system operator (TSO/DSO). On the other hand, Sub-Saharan Africa (SSA) is among the most suitable regions for renewable energy sources, such as solar photovoltaic (PV) power systems due to the high levels of solar irradiation and energy generation potential [1], [2]. However, despite the recent increase in funding allocated and invested in different scale renewable-energy-based electrification projects, covering span from solar home systems (SHS), nano, and micro-grids to up to grid-scale mini-grid power plants, only 51.4% of the population in SSA has access to electricity [3]. The number decreases significantly in rural remote areas, where 57% of population in SSA is living [4], [5]. The electricity consumption of customers in these areas is small and spread out, which presents additional challenges to traditional high-cost access to electricity from the utility grid. Study in [6] proposes an alternative approach with off-grid microgrids powered by solar PV and battery energy storage (BES), in the first stage operated as a self-sufficient independent energy unit, but in the next step interconnected and formed a system unit with distributed PV generation and BES systems. This type of solution provides flexibility and allows the power system to be sized to the customer's specific needs, avoiding system over-dimensioning in introducing energy access to previously un-electrified, underserved communities. Energy demands evolve depending on the ability and willigness to pay for electricity. Therefore, solar PV systems are to be designed to be easily scalable if or when energy demands increase.

The approach used in utility grids, where energy is consumed without limitations and billed afterward, is not applicable due to the small size of the system and the limited amount of electricity available. Energy subscriptions, e.g. pre-paid or pay-as-you-go (PAYG) are alternative payment methods proposed for such a system. Energy surplus trading opportunities for end-users in the local peer-to-peer (P2P) energy market are introduced first within each individual microgrid system during the energy access provisioning stage, and later extended to interconnected microgrids.

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The inner microgrid energy management system (inner-MGEMS) is described in [7]. Due to the small size and limited energy capacity of a single microgrid system and the relatively low number of customers connected to one microgrid, the activity in the local microgrid P2P market is limited, causing restrictions to the surplus trading possibilities for the customer and efficient utilization of the available energy. However, energy trading among and between several microgrids connected together increases the scale of the overall system and the number of participants in the local energy market pool, thus improving electricity trading activity and utilization of the available energy capacity in local day-to-day market.

The study in this paper formulates an approach to create an inter-MGEMS as a decentralized energy trading platform, where each off-grid microgrid acts independently, to benefit the end-users of particular microgrid. The proposed inter-MGEMS approach is a continuation of the previous development of the concept. It follows the same principle of simplification of the user experience and applies similar technologies. The trading platform for the inter-MGEMS is based on game theory and utilizes block-chain technology to ensure fair and secure trading for each end customer.

The rest of the paper is constructed as follows. Section II reviews the related studies in the literature. Applied methodology is presented in Section III. Section IV illustrates the simulation results, and conclusions are made in Section V.

II. RELATED STUDIES

Renewables on small and micro-scale power systems are becoming widely used [8]. Customers' role is changing from consumers to prosumers, as they do not only take energy from the grid, but can also have their own solar PV system and generate power to cover their own needs, and feed the surplus energy to the grid.

A. *Role of microgrids in developing countries*

In developed countries, microgrids play a supportive role in the provision of consumer electricity needs, where users still rely mainly on the power grid.

In developing countries, small-scale solar PV system allows prosumer not only to lower electricity bills, by feeding surplus energy to the grid, but also to remain self-sufficient during outages and load shedding. The latter is rather common and applied in some SSA countries [9]. In off-the-grid locations like rural or remote areas that typically have low-density settlement and customers have relatively low loads, the installation of microgrids is techno-economically the most viable way of electrification [10].

Various small-scale electrification options exist, including solar home systems (SHSs) and solar charging systems (SCSs), or energy kiosks [11], [12]. However, in the context of off-grid microgrids, these systems offer only limited or part-time power—often restricted to phone charging—and thus cannot ensure reliable continuous electricity. Consequently, they are not sustainable electrification solutions. Combining renewable energy (RE) sources with battery energy storage (BES) at the microgrid level provides higher-quality, uninterrupted power access [13].

Affordability is a key factor in electrification for developing regions [14]. The relatively high costs of renewable energy technologies, maintenance requirements, and the limited financial capacity of rural populations continue to hinder widespread access. Affordability can be improved by aligning system capacity with actual energy needs through optimal sizing, which enhances both cost-effectiveness and efficiency [15], [16]. In parallel, innovative ownership models and flexible payment mechanisms have proven effective in easing financial barriers, as demonstrated in various mini-grid projects across Sub-Saharan Africa (SSA) [17].

Even with optimized microgrid sizing, individual user demand can vary daily, leading to energy surplus or shortage. In community-owned microgrids, one user may have excess energy while another faces a deficit. Additionally, a small number of users limits energy sharing potential. These challenges can be mitigated by interconnecting microgrids into a unified distribution system supported by an energy sharing platform.

B. *Energy trading at distribution system*

Decentralized microgrid energy management enables individual prosumers to independently manage their energy generation, consumption, and surplus sharing. Despite disadvantages, such as regulatory challenges and lack of centralized regulation, this approach engages the consumer in microgrid energy management and trading, provides flexibility, and aligns with the system concept proposed in the paper, where each microgrid is owned by different parties, each aiming to maximize its own profit. There are many studies on decentralized energy management, discussing different approaches and technologies such as P2P energy market, block chain, and machine learning [18]–[20]. The combination of these technologies enhances system sustainability, increases prosumer engagement, and improves the efficiency of energy sharing.

C. *Game theory application at energy trading*

Game theory is a mathematical framework that analyzes the decision-making process of different parties and stakeholders involved, where the decision of each participant depends on the actions of others. The aim of each participant is a maximization of its own welfare and benefits, typical motivation being minimization of own costs. The parties, each having its own interest are acting in conflict. There are two types of game theory rules: cooperative, when a group of participants can cooperate to reach the mutual benefits; and non-cooperative: where there are straight conflicts among participants, making them act independently in a game.

The game theory can be applied within different applications, in particular energy management and dynamic price regulation. For example, application of game theory in the scope of microgrids is studied in [21], where authors determine fair and optimal energy pricing in peer-to-peer (P2P) energy trading among consumers in a distributed energy system.

D. *Blockchain application at energy industry*

Blockchain is a technology originally developed for cryptocurrency applications that uses cryptographic hashing, decentralized consensus mechanisms, and encryption techniques to protect the security and authenticity of data in a decentralized system. A core technology of blockchain is a smart contract, which acts as self-executing programs that automatically enforce agreements when predefined conditions are met, eliminating the need for intermediaries [22].

The application of blockchain goes beyond crypto-currency. Thus, for example, it can be used in P2P energy trading, serving as a secure ground for the trading platform [23].

III. METHODOLOGY

The methodology presented in the paper is a continuation of the concept development presented in [6]. It describes a way of electrification of rural areas in SSA with a PV-BES-based microgrid system, which includes provision of electricity, connectivity and digital services. Study in [24] describes the extension of the concept with the formation of a scalable distribution system consisting of self-sufficient PV-based microgrids. Research carried out in [7] describes the methodology of inner-MGEMS of microgrid where a user is a participant in the P2P energy market. Due to small amount of users, there is still energy excess or energy needs that can't be covered with a single microgrid system capability and capacity. The interconnection of microgrids to the union distribution system allows energy to be shared between microgrids, involving more consumers to share energy, which increases the capability and efficiency of the available energy utilization as well as sustainability of the distribution system. Moreover, the presence of battery energy storage in each of microgrid allows us to provide more flexible energy sharing, which can be done in a predictive way, before actual consumption.

A. *Microgrid energy agent*

Following the approach of minimal involvement of an end-user in energy trading, decribed in [7], each system is presented as a software agent application.

Figure1 illustrates the structure of a microgrid energy agent. It consists of parts defining the available or required shared energy and its pricing.

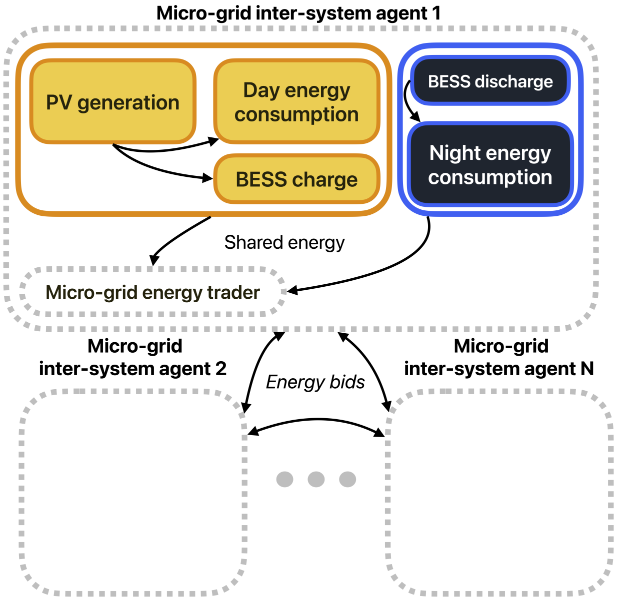

Fig. 1: Microgrid energy agent configuration.

1) Energy management: Based on the load profiles of consumers, an agent estimates the energy available to the energy sharing across microgrids. Due to a RE-based microgrid main power and energy source varies depending on the period of operation, the estimation is applied separately for the day and night time period.

The day-time period is considered between 6:00-18:00, when the system is supplied by PV-panel array and BES. The total generated energy, E_{gen} by the PV array, over the period is given by:

$$E_{\mathrm{gen}} = \sum_{t=6}^{18} P_{\mathrm{PV}}(t) \cdot \Delta t, \tag{1}$$

where $P_{\mathrm{PV}}(t)$ is the solar PV output power at time t, which is defined according to [25], as:

$$P_{\mathrm{PV}}(T) = P_{\mathrm{nom}} \cdot (Irr/Irr_{\mathrm{ASTM}} \cdot (1 - \gamma(T - T_{\mathrm{ASTM}}))\,, \tag{2}$$

where

- P_{nom} - Nominal power of the PV panel (W);
- $I(t)$ - Irradiance at time t (W/m^2);
- $T(t)$ - Ambient temperature at time t (°C);
- $T_{\mathrm{ASTM}} = 25°C$ - ASTM temperature;
- $Irr_{\mathrm{ASTM}} = 1000W/m^2$ - ASTM temperature;
- Δt - Time step (h);
- $\gamma = \alpha_{Imp} + \beta_{Imp}$
- α_{Imp} - Temperature current coefficient (%/°C);
- β_{Imp} - Temperature voltage coefficient (%/°C).

The temperature coefficients are defined according to [26]. The total consumed and accumulated energy over the day period is defined as:

$$E_{\mathrm{cons}} = \sum_{t=6}^{18} P_{\mathrm{load}}(t) \cdot \Delta t + C_{\mathrm{nom}} * (1 - SoC_{\mathrm{init}}), \tag{3}$$

where:

- E_{load} – Total consumed energy during the daytime;
- $P_{\mathrm{load}}(t)$ – Power consumption of the load at time t;
- Δt – Time step duration;
- C_{nom} – Nominal battery capacity;
- SoC_{init} – Initial state of charge (SoC) of the battery at the start of the period.

Fully charging the battery for nighttime use is as important as meeting the consumer load priorities, given its critical role in maintaining microgrid operation and enabling energy sharing during hours without solar generation.

Using the historical day load profiles, the agent utilizes an LSTM model to predict consumer load profiles over a defined day period. These predictions are then used to estimate the available energy profile for sharing, while accounting for system power constraints such as:

$$E_{\text{share}}(t) = \min \begin{pmatrix} E_{\text{gen}}(t) - E_{\text{cons}}(t), \\ (P_{\text{max\_syst}} - P_{\text{load}}(t)) \cdot \Delta t \end{pmatrix}. \tag{4}$$

During a night period, all the energy available in a microgrid is conditioned by the size of the BES. Since nighttime load profiles differ significantly from daytime ones, a separate LSTM model is trained specifically on night consumption data to improve prediction accuracy. The available energy for sharing during night hours in the inter-MGEMS is determined as:

$$E_{\text{share}}(t) = \min \begin{pmatrix} C_{\text{nom}} \cdot SoC(t) - E_{\text{load}}(t), \\ (P_{\text{max\_syst}} - P_{\text{load}}(t)) \cdot \Delta t \end{pmatrix}. \tag{5}$$

For both the day and night periods, the electricity consumption is re-estimated every 10 minutes based on the current state of the microgrid. The frequent re-estimation is conditioned by the small amount of energy in the system, which generates the need of the fast response of a microgrid agent on rapid or uncommon customers' energy.

The vector of shared energy over the day/night period is used for the mapping of energy flows over the system and preliminary price formation, which can be affected by the end customers during a trading period.

The actual available energy for inter-MGEMS is defined as an unbalanced energy of the inner P2P market.

2) Price formation: The price formation and market actions on the inter-microgrids energy market is based on Game Theory, where each agent aims to maximize its profit, as a result a profit of the customers of the microgird. The prices defined in NAD (Namibian dollar) for the inner energy market are used as a basis for the inter-trading bids, as [7]:

$$p_{0,\text{day}} = \frac{22 \text{ NAD}}{2 \cdot 4 \text{ kWh}} = 2.75 \text{ NAD/kWh}, \tag{6}$$

$$p_{0,\text{night}} = \frac{22 \text{ NAD}}{2 \cdot 1 \text{ kWh}} = 11 \text{ NAD/kWh}. \tag{7}$$

The upper and lower level for bidding is defined as the maximum price of willingness to pay and the minimal price of willingness to sell, set by the microgrid customers. The bidding price for the inter energy trading (p_{d}) is defined by

$$p_{\text{d}} = \min \left(p_0 e^{k\left(E_0 - \sum_{i=1}^{n} E_i\right)} + p_{\text{inter\_fee}},\ p_{\text{up}} \right), \tag{8}$$

where p_0 is initial energy price, E_0 initial amount of shared energy, p_{up} maximal possible energy price, k price-energy relation coefficient, and $p_{\text{inter\_fee}}$ is an additional fee for the inter-MGEMS.

An additional fee for inter-system trading is introduced to encourage energy sharing primarily within the own microgrid. It prioritizes the needs of the microgrid own customers and helps avoid purchasing energy from inter-connected neighbor microgirds, while it is possible to do with microgrid's own power and energy capacity.

B. Inter-microgrids energy trading

The energy trading among microgrids' agents is implemented in the blockchain energy trading platform. According to the concept presented in [27], each system has a connectivity source. Each microgrid energy agent links a local and cloud digital service of the P2P market and places its bids on the latter. Considering that microgrid energy management is a critical system vulnerable to cyber attacks and cheating threads, the application of blockchain establishes a secure foundation for the trading platform.

An agent places a bit for each period. The period of bidding is 10 minutes and equals the period of shared energy re-estimation. In conditions of the strick constrains of the available shared energy, a short period for an energy bid is defined to provide enough inertia for the agent to find a selling-purchasing equilibrium price.

The initial price for the bidding is defined in Eq. 8. If an energy bid is fully sold, an agent starts to increase the price to define the equilibrium point between selling and purchasing prices. An agent which buys energy follows an opposite approach. If the whole energy bit is purchased, an agent starts to decrease purchase bidding price to minimize energy costs and reach the selling-purchasing equilibrium price.

IV. SIMULATION RESULTS

The proposed methodology is evaluated using an inner-MGEMS model developed in Python. Real load profiles collected from a pilot system in Namibia serve as input for the model [27]. Additionally, historical irradiance and temperature data are used to simulate solar PV power generation.

Two separate LSTM models are trained on preprocessed day and night load profiles, respectively. During the simulation, the

TABLE I: Microgrid system parameters.

Idx.	P_{PV} (kWp)	C_{BESS} (kWh)	P_{inv} (kW)	Customers (N)	$Price_{\text{limits}}$ (NAD/kWh)
1	5.4	8	5	4	2-20
2	5.4	16	10	4	2-15
3	5.4	4	3	4	2-30
4	5.4	8	5	4	2-20
5	5.4	16	10	4	2-15
6	5.4	4	3	4	2-30
7	5.4	8	5	4	2-20
8	5.4	4	3	4	2-30
9	5.4	16	10	4	2-15
10	5.4	4	3	4	2-30

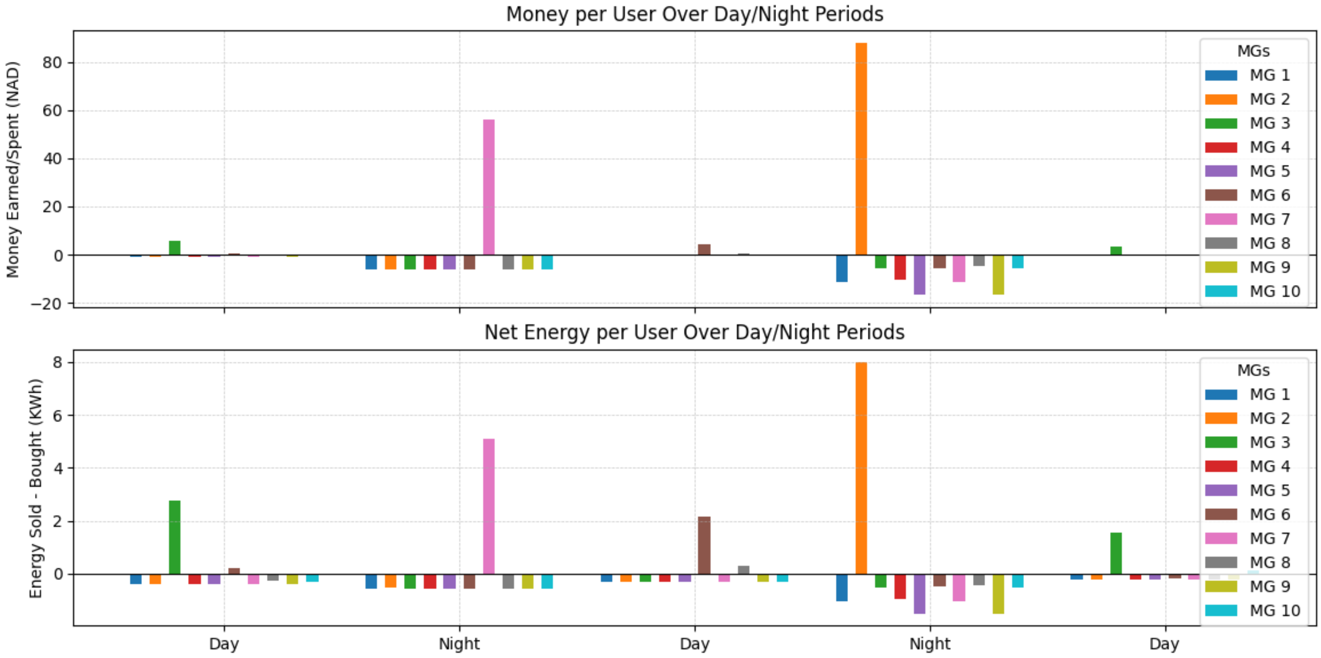

Fig. 2: Simulation of the energy sharing among ten inter-connected microgrids.

predicted states are continuously re-estimated using live load data as ground truth to reflect actual system conditions.

The simulated distribution system consists of 10 microgrids. Each microgrid has different BES capacity and four end users. The inverter nominal power rating as well as electricity price range are chosen according to the BES capacity. The technical details of the systems are presented in Table I. The choice of microgrid components is reasoned with consideration of interconnection of not only optimal-sized microgrids but a varying infrastructure, which can have over-/undersized of BES capacity. The blockchain is realized with ”hashlib”, ”uuid”, ”json” and ”requests” libraries. All agents run on the same hardware but are represented by different ports on the local host. Figure 2 illustrates the trading operation of the 5 operating periods. The plots show that trading activity is higher during night time periods. This is driven by the high rate of solar irradiance during the day, which allows enough power generation to cover consumer needs and to charge the BES full. Purchase peaks are associated with systems that have oversized BES. In such cases, the PV array is unable to charge the BES full during the day, leading to the purchase of additional energy from other microgrids.

The night time energy purchase peaks are associated with microgrids that have small BES, which is insufficient to meet customer demands. In contrast, microgrids with larger BES sell more energy and generate higher profits for their customers.

The operation of inter-MGEMS over a month generates a profit of $130–200 NAD per microgrid and exchanges up to 44 kWh per system. In the absence of inter-MGEMS, supply shortages could lead to electricity outages in single microgrid.

V. CONCLUSION

This paper aimed to develop and evaluate a decentralized energy management system—inter-MGEMS—for interconnected, self-sufficient microgrids in off-grid regions, utilizing predictive load modeling, dynamic pricing, and blockchain-based peer-to-peer energy trading.

The simulation of inter-MGEMS operation shows significant improvements in energy supply quality while generating an additional revenue stream for microgrid customers. Engaging a larger number of customers in energy trading increases the share of sold and purchased energy on the local energy peer-to-peer market place, enhancing power supply quality even for both over- and under-dimensioned microgrid system configurations. Predictive energy flows forecast, combined with battery energy storage within a microgrid, enables exchange of required amount of energy in advance matched to actual electricity consumption between the interconnected microgrids. This approach allows for the use of inverters with lower nominal power, and power lines with smaller cross-sections between the microgrids, reducing system costs, and significantly postponing grid upgrades, which are periodically required to meet growing consumers’ energy demand. The control of energy flows over the distribution grid is not considered in the model and is subject to further investigation. The development of a control system that interacts with the inter-MGEMS and optimizes the energy flow routes represents the next step in advancing this decentralized energy system approach. Such a system would minimize power losses and improve energy distribution across and between the interconnected microgrids.

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