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Local electricity market designs for interconnected nanogrids: Impact on rural electrification in Madagascar

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ABSTRACT

Sustainable, reliable, and affordable energy access is a major challenge in many parts of the world. The paper addresses this challenge by proposing a local electricity market (LEM) design for nanogrids deployed in Madagascar. Each nanogrid shares a solar PV and battery system, and it meets demand locally before trading surplus energy with other nanogrids on a microgrid bus, facilitated through the creation of a LEM. Two distinct market approaches are investigated and compared: central clearing and bilateral trading. Bilateral trading generates trading prices through direct interaction between consumers and producers, whereas central clearing sets a single trading price based on the cost-ordered supply curve. Our study shows that central clearing generates more consumer-friendly prices and facilitates the trading of all technically feasible energy, while bilateral trading may results in unmatched trading capacity. We find an average price for central trading of 0.49 €/kWh compared to 1.24 €/kWh with a bilateral trading mechanism. To promote the low market prices, a bottom-up retail tariff structure is proposed. The aim of this simplified tariff is to promote initial electrification by minimizing entry prices for end-users' first electricity access to 0.89 €/kWh compared to the current average of 2.11 €/kWh. The discussed results were evaluated in consultation with the local company in Madagascar to ensure practical suitability and to achieve maximum significance.

1. Introduction

Access to reliable, affordable, and sustainable energy is essential for human development, yet it remains a major challenge in many parts of the world. While urban areas in Europe are rapidly transitioning to renewable energy sources, rural areas in Africa are facing difficulties in accessing energy in the short term and establishing a sustainable energy supply in the long term. Still, one in ten people worldwide do not have access to electricity, and 75% of those live in sub-Saharan Africa according to the United Nations Developmenta Programme, UNDP (2023). The COVID-19 global pandemic aggravated this issue, leaving more people without access to energy and intensifying the urgency to find practical solutions to enable energy access, without either depending on the use of costly and unreliable fossil fuels (e.g. to power diesel generators) or waiting for the expansion of the national power grid.

Antonanzas-Torres et al. (2021) conducted an analysis on the environmental impact of solar home systems within Sub-Saharan Africa, focusing on their greenhouse gas emission factors. These systems are composed of photovoltaic (PV) panels, batteries for energy storage, and the required power electronics for system management. The study compared their emission factors to those from various electrification strategies, including national grids, fully PV systems, and hybrid PV-diesel off-grid mini-grids, in addition to standalone diesel generators. The findings revealed that, in many instances, the emissions from solar home systems were comparable to those of PV-based mini-grids and significantly less than emissions from both the national grids of Sub-Saharan Africa and diesel generators. Our paper aims to explore pathways towards achieving cleaner energy production, particularly for initial energy access. We delve into the potential of interconnected nanogrids, which combine the low-emission benefits of the solar home systems approach with those of PV-based mini-grids.

One approach is to develop a bottom-up, decentralized, and democratic energy system that uses peer-to-peer (P2P) electricity trading between households within a community. P2P trading enables the exchange of renewable energy between participants and eliminates the need for intermediaries or a national grid. Each actor (e.g. a prosumer,

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Nomenclature

E_{Ex}	Exported Energy in kWh
M_{rev}	Revenue Margin in €
p_{trade}	Price paid for Energy at the Market in €/kWh
tf_{grid}	Tariff for using the Grid in €/kWh
$C_B^{(i)}$	Cost of the Battery of each Nanogrid i in €
$C_{fix,B}$	Fixed Cost of each Battery in €
$C_{fix,PV}$	Fixed Cost of each Photovoltaic System in €
$C_{PV}^{(i)}$	Cost of the Photovoltaic System of each Nanogrid i in €
$CAPEX$	Capital Costs in €
E_D	Energy Demand in kWh
E_{PV}	Energy Production of PV in kWh
i	Index for each Nanogrid
$LCOE_{PV}^{(i)}$	Levelized Costs of Energy for each Nanogrids PV System in €/kWh
$LCOE_{total}^{(i)}$	Total Levelized Costs of Energy for each Nanogrid in €/kWh
m_B	Variable Costs of each Battery in €/Wh
m_{PV}	Variable Costs of each Photovoltaic System in €/W
$N_B^{(i)}$	Amount of Battery Capacity of each Nanogrid i in Wh
$N_{PV}^{(i)}$	Amount of Photovoltaic System of each Nanogrid i in W
t	Time-Index
C_E	Cost of Energy Supply in €
E_E	Imported Energy in kWh
p_E	Price paid for Energy in €/kWh
$tf(x)$	Specific Tariff at power demand x in €/kWh
tf_{max}	Maximum Tariff paid at Maximum Power Description in €/kWh
tf_{min}	Minimum Tariff paid at Minimum Power Description in €/kWh
x_{max}	Maximum possible Power Description in W
x_{min}	Minimum Power Description in W

consumer, or a nanogrid) is considered a peer enabling P2P electricity trading. Energy can be exchanged between individual households or between small groups of households. In the context of initial energy access in Africa, nanogrids encapsulate the idea of having four to six households interconnected to a local centralized battery and solar PV. In this regard, this paper presents a study of a real-world application of nanogrids located in the rural Diana Region of Madagascar, where currently there is no public grid connection. The nanogrids serve as the primary electricity access point for the region. By interconnecting the nanogrids, a microgrid can be established that allows the nanogrids to share electricity, thereby increasing the reliability of the supply. To establish efficient energy trading, a local electricity market design needs to be created as a framework that takes project specifics into account.

This paper explores two interrelated research questions regarding the market clearing and the tariff structure for a rural network of nanogrids in Madagascar:

1. How do the central clearing and bilateral trading market models impact the affordability, reliability, and sustainability of energy access in rural communities in Madagascar, and what factors should be considered when choosing the most suitable market model for these communities?
2. How does the proposed local electricity market design and new tariff structure benefit the Diana Region of Madagascar and other rural regions of sub-Saharan countries compared to the current energy access solutions?

The development and the evolution of the energy infrastructure of the nanogrid concept for Madagascar is illustrated in Fig. 1. In recent years, nanogrids have been established to meet the basic energy needs of households. Currently, these nanogrids are interconnected through a local energy market on a microgrid bus, with the aim of optimizing energy supply efficiency. In the ultimate phase, these microgrids combine to form a minigrid, and there are plans to integrate the microgrids into the main grid in the future. This in turn would ensure the provision of secure and cost-effective energy sources for rural areas.

The primary objective of this paper is to develop a solution for a local electricity market (LEM) that addresses the specific requirements of interconnected nanogrids in Madagascar. Different local electricity market designs can have significant impacts on price formation and market participant interactions. They also influence P2P trading. This paper evaluates two different market designs and their ability to achieve a reliable, affordable, and sustainable energy supply within the context of the nanogrids in Madagascar, where energy balancing occurs internally, and energy trading takes place externally within the microgrid.

2. Related literature

In the past decade, there has been an increasing focus on research into microgrid and nanogrid solutions, across both developing and developed nations, as highlighted by Kirchhoff et al. (2016). In their work, they identify key success factors for the integration of interconnected nanogrids, solar home systems, or distributed PV systems, a concept they refer to as swarm electrification. A key distinction between the deployment of these energy sharing concepts in developed and developing countries lies in the presence of a reliable grid. In developed countries, distributed PV systems share energy through an existing grid, facilitating energy exchange. Conversely, in developing countries, where interconnected nanogrids or swarm electrification projects are implemented, a similar reliable grid is often absent. Instead, connections are established directly through the setup of nanogrids or solar home systems, necessitating that these networks be entirely self-sufficient due to the lack of a backup grid. This independence significantly impacts the cost, pricing, and tariff structures for systems designed to provide initial energy access, as explored in our paper.

The research has focused on regions that exhibit distinct context and characteristics, e.g. shown by Rafique et al. (2019). Common characteristics include, for example, the imperative for off-grid solutions, abundant solar energy potential, limited economic resources, lack of experience with energy technologies, and deficient telecommunications infrastructure. These characteristics can be found in rural areas of Latin America, Asia, and Africa, and are even more pronounced in sub-Saharan Africa, where certain countries have low rates electrification in rural regions according to Maji et al. (2019). Therefore, developing microgrid solutions would constitute a bottom-up approach in the electrification of such regions, with the first phase being the installation of isolated solar panel systems (i.e. nanogrids). A microgrid is the aggregation of isolated installations into a larger network, aimed at enhancing performance, increasing reliability, and boosting peak power capacity. Some articles explore this concept with regard to sub-Saharan Africa. For example, Mekonnen et al. (2017) aim to provide an exhaustive examination of ongoing renewable energy-supported technologies for rural electrification in sub-Saharan Africa.

In the research stream pertaining to microgrid and nanogrid solutions, akin to the one delineated in this paper, Giraneza et al. (2020)

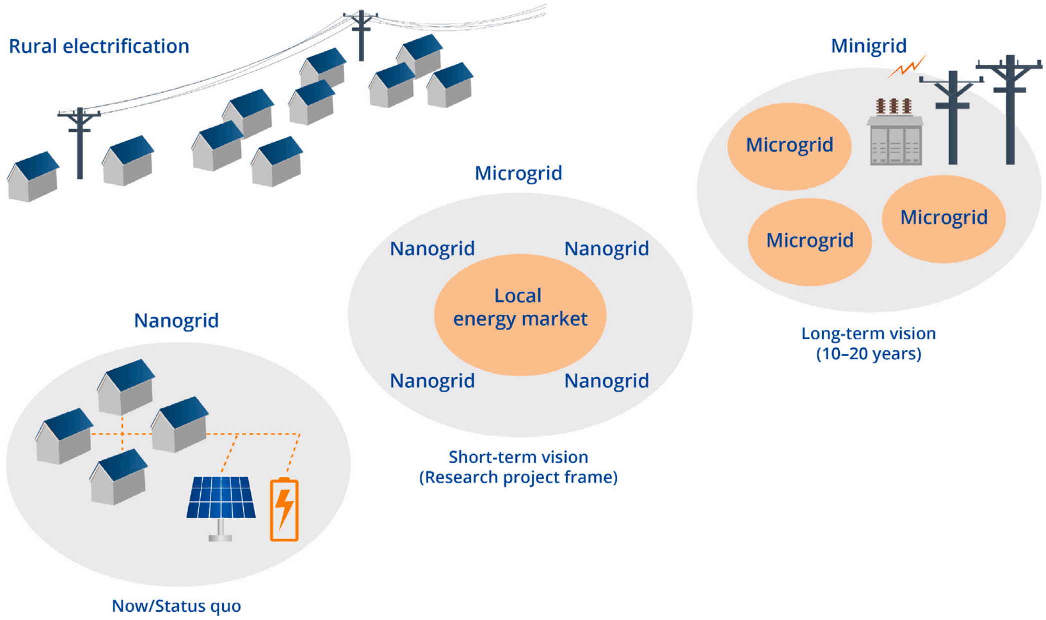


Fig. 1. Schematic diagram of the nanongrid concept for a physical and economic interconnected system in Madagascar.

studied microgrid solutions that encompass the integration of individual nanogrids alongside a shared energy storage infrastructure. In contrast, this paper introduces and explores the concept of P2P markets for nanogrids and the establishment of microgrids. Other papers take a more technically intricate approach, studies such as the one by Talapur et al. (2019) have proposed a modified control scheme tailored for a grid-connected microgrid, which is conceived as the amalgamation of multiple nanogrids.

A comprehensive review of the market framework to enable energy trading in a local electricity market is presented by Khorasany et al. (2018), who classify literature on potential market design and price clearing approaches. The same authors also provide a hybrid trading scheme for P2P energy trading that considers network constraints and price signals in their market design in Khorasany et al. (2019). A similar comprehensive review by Sousa et al. (2019) focuses on community-based models. It broadens the concept of bilateral contracts and microgrids. Additionally, it underscores the imperative for prosumers within P2P markets to employ strategic bidding approaches for enhancing their energy exchanges. It analysis further contrasts full and hybrid P2P, and community-based markets, delineating their primary distinctions, such as their respective pricing strategies.

In terms of comparing different market clearing strategies in local electricity markets and the implications for market prices, Mengelkamp et al. (2017) present an analysis of two different market clearing methods with two different bidding strategies, and they compare the financial outcome. However, their study does not compare the methods' ability to trade the maximum of available energy within the local energy market. Wirasanti et al. (2022) compare two different market clearing approaches (auction-based method and game theory) in a prosumer case study considering national grid and market operations. They take the market price of energy, as well as the allocated quantity, into account. However, their case setting is not significantly different from other non-cooperative day-ahead market studies. Adding to this discussion, a recent study by Guan et al. (2021) and Heilmann et al. (2022) explores power market transaction modes, specifically bilateral negotiation and centralized bidding, through the lens of evolutionary game theory. This investigation models and analyzes equilibrium behaviours, revealing outcomes that are heavily dependent on the conditions of supply and demand.

In taking the design of local electricity markets one step further, Qiu et al. (2023) claim that setting up an end-user tariff is done through strategic retail pricing. Maldet et al. (2022) and Sütő et al. (2023) focus on the role of grid and network usage tariffs in local markets, but they overlook the benefits and costs of trading energy in a local electricity market. Regarding relevant studies in other geographical contexts, it is worth highlighting the contributions of Kirchhoff et al. (2019) and the work of Kamal et al. (2022) carried out in South Asian regions.

This paper contributes to the existing literature on electricity markets and P2P trading, through its focus on trading between nanogrids for off-grid rural areas. The study addresses the challenge of balancing nanogrids within a microgrid and provides insights into the implementation of a local electricity market for P2P trading. We investigate trading between nanogrids beyond the level reported in previous studies of individual household trading, and we offer valuable insights for off-grid areas in developing countries. We recognize the unique context of initial energy access in rural areas, considering low power and energy demand patterns, and we explore the use of a communication-free control algorithm for regions with either limited or no telecommunication signals. Overall, this paper expands the knowledge of electricity markets and P2P trading for rural nanogrids as reviewed by Xia et al. (2023) and provides valuable contributions for future sustainable energy solutions in off-grid areas. The main research contributions are as follows:

- A P2P electricity trading model for application between nanogrids in the context of initial energy access. To date, P2P and LEM approaches have been researched and applied extensively to households (prosumers and consumers) in developed countries as (Bjarghov et al., 2021) show. By contrast, our study is the first to applying this concept to a nanogrid setting and for developing countries.
- Comparison of bilateral trading and central clearing, and the implications for market prices and traded energy volumes. The study presents a new approach to calculating and comparing these market clearing methods.
- Improved tariff design for the end-user of the nanogrids, including benefits from local electricity market but also costs from energy trading. The paper demonstrates the incentives and the tariff design to promote an affordable nanogrid network based on potential market designs (bilateral versus pooling).
- Local electricity market design for a rural off-grid area in Madagascar. This paper reports a hands-on case study where active nanogrids were in the process of being interconnected.

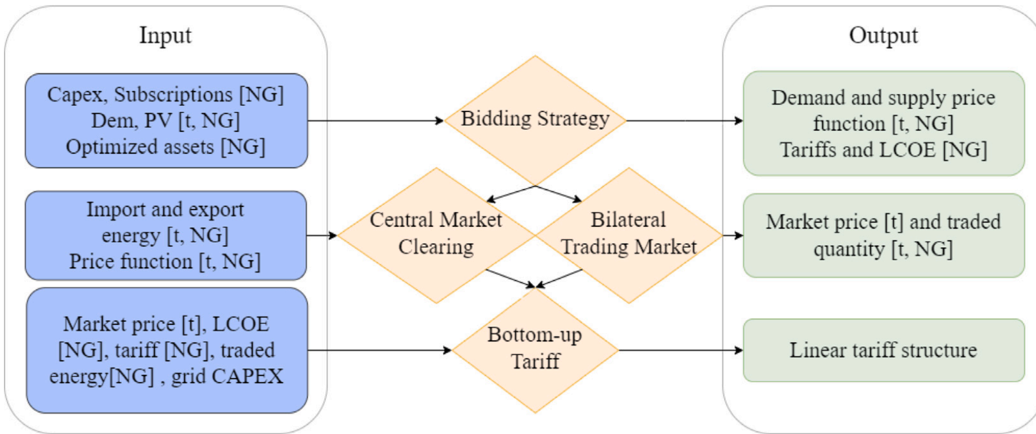


Fig. 2. Modelling working steps.

3. Modelling local electricity markets

Within LEMs, P2P trading has gained prominence as a method to enable all participants to engage in the buying and selling of energy within a localized electricity market as several studies show, e.g. Lezama et al. (2019), Horta et al. (2017), Bjarghov et al. (2021).

Energy trading can occur through various mechanisms, such as central clearing or bilateral trading. Bilateral trading is a market approach that enables direct interaction between buyers and sellers, eliminating the need for a central auctioneer. The approach is commonly employed in P2P energy trading systems, allowing individuals and small businesses to sell their excess renewable energy directly to others within their local community. The central market clearing process remains widely used to determine equilibrium prices for each time step in an electricity market. The process is typically employed in electricity markets such as the day-ahead market, where energy suppliers offer their energy at marginal costs and are ranked based on their prices. The clearing price is then found at the intersection of the supply and demand curve. Both central clearing and bilateral trading can be utilized to enable P2P trading within a LEM, each offering distinct advantages and facing specific implementation challenges.

Designing a LEM for interconnected nanogrids involves three main steps, as shown in Fig. 2. The first step is setting up the bidding strategy, including selling and buying bids with the nanogrid-specific prices and time-variable quantities. These bids are submitted to two different market mechanisms with the aim of finding a trading price for each time step. Building upon the market clearing, a bottom-up retail tariff is designed to pass on the benefits of the LEM to the end users.

3.1. Bidding strategy

The bidding strategy plays a crucial role in determining the outcomes of a local electricity market by establishing the price function for supply and demand. In traditional electricity markets, the supply price is typically based on the marginal cost of production units. However, in the context of nanogrids acting as prosumers and relying on renewable energy sources, the marginal cost is close to zero. Therefore, a different approach is needed to determine the bidding strategy and to establish fair market prices that can cover all costs associated with energy trading. The bidding strategy involves the formation of buying bids (hereafter referred to as 'bids' in this paper) and selling bids (hereafter referred to as 'offers' in this paper).

The offering price for each nanogrid in the bidding strategy is determined on the basis of its levelized cost of energy (LCOE). The LCOE represents the average cost incurred by each nanogrid to produce one kilowatt-hour (kWh) of energy over the asset's expected lifetime. It takes into account various factors such as the initial costs of PV systems and batteries, operational and maintenance expenses, and the projected lifespan of the assets. The LCOE serves as the minimum price that each nanogrid should demand from the market when participating in energy trading. By setting the offering price based on the LCOE, those responsible for the nanogrids ensure that they cover their production costs and the nanogrids' energy generation economically viable.

By contrast, the bidding price is determined by the energy price that each nanogrid consumer pays, as it is the maximum that would be paid for the nanogrid franchisee to purchase energy in the market. The nanogrid franchisee, acting as an intermediary, then trades energy in the local electricity market. Thus, the aim of the bidding strategy is to establish a fair market price that considers both the production costs (represented by the LCOE) as the lower limit and the consumption prices (represented by the end-user tariffs) as the upper limit. The strategy is not individually optimized to trade the maximum amount of energy in the market but is rather focused on setting a fair price that covers the costs and ensures the economic viability of the nanogrids.

The LCOEs for nanogrids can vary slightly, depending on whether energy is traded directly from the PV system or from the battery. Consequently, offering prices are set at two levels: during the daytime, when the specific LCOE of each PV system is used, and during the nighttime, when the combined LCOE of both PV and battery is considered. This approach optimizes the use of the battery, enabling efficient trading during periods of low PV generation. To determine the LCOEs in the studied case, we calculated the total investment costs for each nanogrid based on data from existing field installations (see Eqs. (1) and (2)). These costs included fixed expenses per installation, such as transportation and labour, as well as variable costs based on the size of the PV system and battery. The cost function, denoted by C for each nanogrid indexed as i, encompasses the expenses for both photovoltaic systems (PV) and batteries (B). This function is composed of fixed costs, labelled 'fix', and variable costs, denoted by 'c' and are multiplied by the quantity of units deployed.

$$C_B^{(i)} = C_{fix,B} + m_B \cdot N_B^{(i)} \tag{1}$$

$$C_{PV}^{(i)} = C_{fix,PV} + m_{PV} \cdot N_{PV}^{(i)} \tag{2}$$

From the total CAPEX for every nanogrid, the LCOE can be calculated by dividing with the energy produced by the PV respectively the total energy supplied by both battery and PV over the expected lifespan (see Eqs. (3) and (4)). Since lead–acid batteries are only expected to last 3.5 years, each battery is likely to be replaced at least twice during the expected 10-year lifespan of the PV. Since our calculations spanned a three-month (90 days) time frame, the demand and PV production is multiplied by four (for a whole year) and by ten (for the expected lifetime). The LCOE calculation is:

$$LCOE_{PV}^{(i)} = \frac{C_{PV}^{(i)}}{\sum_{t \in Nt} E_{PV} \cdot 40} \tag{3}$$

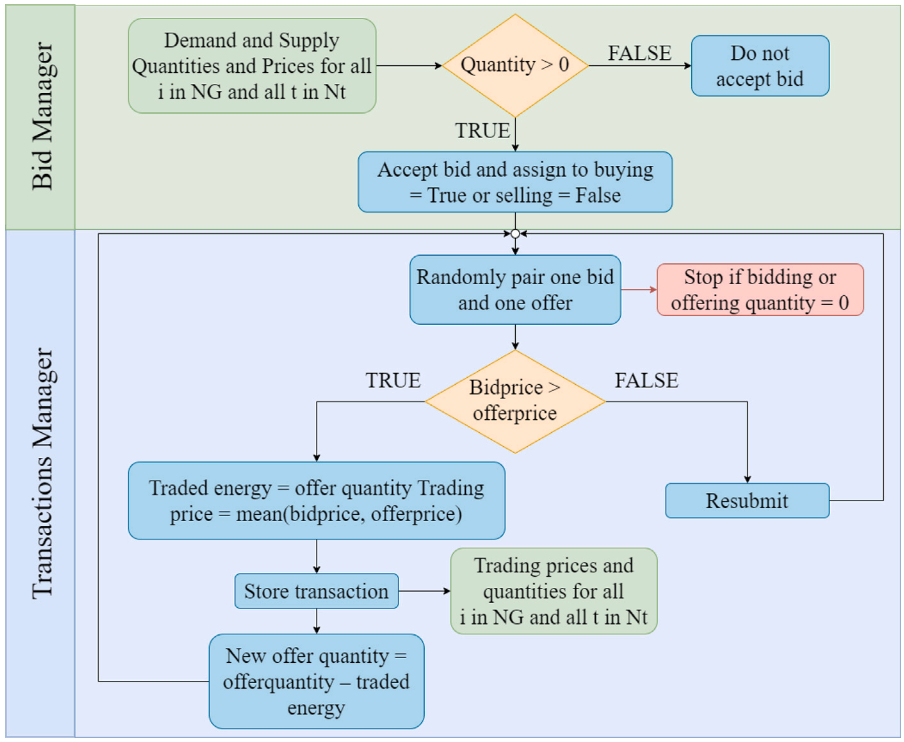


Fig. 3. Flow chart for 'P2P' algorithm in bilateral trading.

$$LCOE^{(i)}_{total} = \frac{C^{(i)}_{PV} + 3 \cdot C^{(i)}_{B}}{\sum_{t \in N_t} E_D \cdot 40} \tag{4}$$

The supply price function is then set up with the total LCOE for the first six hours and last six hours of the day, while the LCOE of the PV determines the supply price in the hours between those two times. The demand price function on the other hand does not vary with time. The end-user tariff per nanogrid is then calculated by determining the energy supply and the corresponding price for every consumer and building the average of all prices in Euro per kWh.

The demand function sent to the market contains the bidding quantity for each nanogrid over each time step and the corresponding demand price. The supply function sent to the market contains the selling quantities for each nanogrid over each time step with the corresponding supply price set by the LCOE of either the PV or the entire generation (PV and battery).

3.2. Bilateral trading

To implement a market for bilateral trading in Madagascar, a bid matching algorithm is used to match buyers and sellers based on their respective bids. One example of such an algorithm is the P2P algorithm implemented by Hashemipour et al. (2021) with the PyMarket[1]. This offers a simple environment to test, simulate, compare and visualize different market mechanisms. It is more focused on the engineering side, as compared to its more mature alternatives, like (Chiarella et al., 2002) and LeBaron (2001), which have a more financial focus.

The bilateral trading process within the P2P algorithm, which consists of two main components – the bid manager and the transaction manager – is shown in Fig. 3.

In Fig. 3, the process is depicted with green boxes to represent input and output data, blue boxes to indicate actions, and orange 'diamonds' to represent conditional statements.

In the algorithm, a market is set up using a bid manager who creates, buys, and sell bids based on their quantities (if the quantity is greater than zero) and their prices. Buying bids will be stored as TRUE and selling bids or offers stored as FALSE. A transaction manager is then employed to identify bilateral transactions by randomly matching bids and offers, and pairing them when the bid price exceeds the offer price. In most cases where the quantities are uneven, the remaining quantity will be carried over to the next iteration for consideration in future assignments. The traded energy is set by the offering quantity. The trading prices are set at the midpoint between the offering and bidding prices, resulting in individual prices for each transaction. These results are stored in a result data frame. If there is zero demand or zero supply from all nanogrids within one time step, no trading will occur, and the price will be set to zero, indicating no trading activity. Otherwise, the process will stop if no more bids and offers can be paired.

The P2P algorithm generates transactions for each time step and match, determining the traded energy and corresponding price. To facilitate comparison, the average price per time step, as well as the average price over the entire duration, can be calculated.

3.3. Central clearing

In the creation of a LEM using the central clearing approach, the main component is the intersection of the supply and demand curves, which determines the market clearing price for that time step, as shown in Fig. 4. In the context of a microgrid without an external grid connection, the demand is relatively inelastic, and the bidding strategy determines the demand price function, which is typically higher than the supply curve determined by the LCOE. The central trading price for each time step is obtained at the intersection of the demand and supply curve. This price is uniform for all participants engaged in energy transactions at that moment, distinguishing it from the bilateral trading price, which is negotiated separately for each deal between selling and buying nanogrids.

To gain a better understanding of how the market clearing process is implemented in a Python algorithm, the steps involved in obtaining

[1] https://pymarket.readthedocs.io/en/latest/examples.html

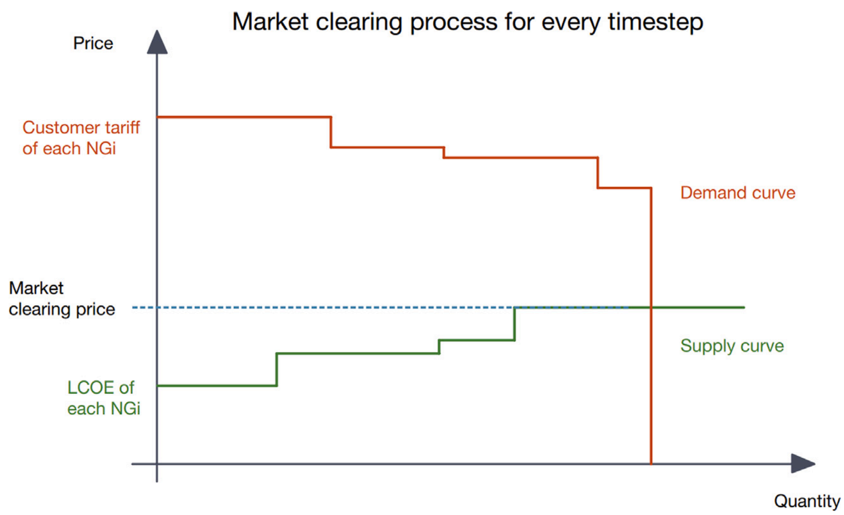


Fig. 4. Schematic approach for central market clearing.

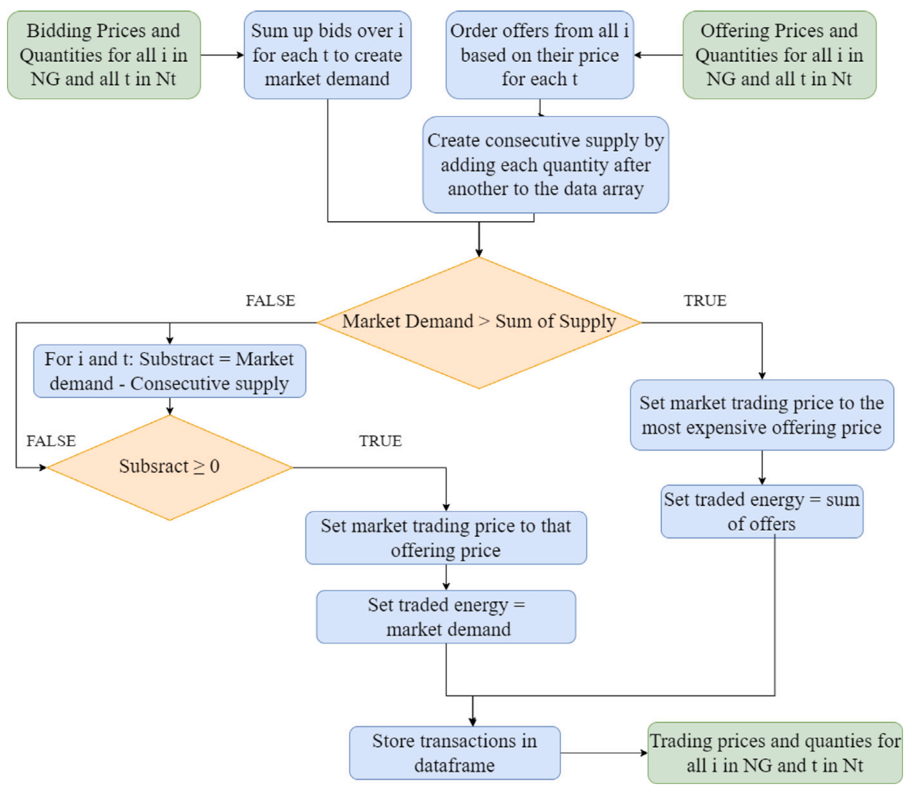


Fig. 5. Flow chart for simulation of central clearing.

trading prices and quantities are shown in Fig. 5. The bidding strategy values for each nanogrid and time step serve as input data, similar to bilateral trading. However, in contrast to bilateral trading, the bidding quantities are aggregated and treated as a single market demand per time step, disregarding different bidding prices. Furthermore, the offer quantities are not considered individually but instead ordered based on their LCOE (from lowest to highest), and a cumulative supply is calculated by progressively summing the quantities offered by each nanogrid.

If the market demand exceeds the total offered energy, the trading price will be determined by the nanogrid with the highest offering price. Alternatively, if the market demand is lower than the supply, the difference between the market demand and cumulative supply will be calculated for each nanogrid across all time steps. The calculation will help to identify the last nanogrid that can meet the remaining demand. When the difference is negative or equal to zero, indicating that all demand is satisfied, the trading price will be set based on the offering price in that specific row. The traded energy is precisely determined as the demand fulfilled by all nanogrids with the same or lower offering prices. The process continues until a trading price and traded energy are determined for each time step, which can be exported to a result data frame. In cases where no trading occurs, the trading price is set to zero (‘0’) to indicate visually the absence of trading.

3.4. Tariff design

After establishing a market clearing model and determining the trading price, the next step is to develop a new tariff structure that incorporates the insights gained from energy trading in the microgrid. The objective is to create a bottom-up tariff structure that determines the minimum price per unit of energy to cover all costs of supply. This minimum price should be set at the entry level of the power subscription, offering an affordable entry-level price. As the power limits increase, the energy price should increase too, in order to generate more revenue opportunities. This is justified by the higher need for balancing with rising power needs. The new tariff should establish a straightforward relationship between price and power.

To develop a cost-reflective tariff, it is important to consider the various components that contribute to the price. Such components include the costs associated with local generation from each PV and battery system, the costs of importing energy from trading, the maintenance costs covered by the entrepreneur, and a revenue margin for entrepreneurs. Furthermore, the revenue obtained from trading energy should be incorporated into the price. The underlying calculation is presented in Eq. (5):

$$\begin{aligned} \mathrm{C_E} = & \underbrace{(\mathrm{E_D} - \mathrm{E_I}) \cdot \mathrm{LCOE}}_{\text{cost of local generation}} \\ & + \underbrace{\mathrm{E_I} \cdot (\mathrm{tf_{grid}} + \mathrm{p_{trade}})}_{\text{cost for importing energy}} \\ & + \underbrace{\mathrm{M_{rev}}}_{\text{revenue from trading}} \\ & - \underbrace{\mathrm{E_{Ex}} \cdot \mathrm{p_{trade}}}_{\text{revenue from trading}} \end{aligned} \tag{5}$$

The objective of the new tariff structure is to ensure fairness among nanogrid consumers. It is designed to equalize prices for all nanogrids by considering the concept of high LCOE leading to higher costs for local generation, which in turn should result in higher revenues and lower costs from trading energy. The goal is to set up one price per unit of energy and power limit for all nanogrids, and thus promote equitable access to energy.

While some components, such as import and export energy, demand, LCOE, and trading price, can be directly obtained from previous simulations, the grid tariffs need to be calculated from scratch. These tariffs should reflect the costs associated with using the microgrid to trade one kilowatt-hour of energy. The calculation of the CAPEX will be based on a pilot study implemented in Madagascar. The resulting CAPEX will then be divided by the amount of energy traded within the expected lifespan of the microgrid. The price per energy in €/kWh is derived by dividing the cost of energy supply by the amount of energy consumption, as shown in Eq. (6):

$$\mathrm{p_E} = \frac{\mathrm{C_E}}{E_D} \tag{6}$$

Eq. (7) represents a linear function of the tariff, which allows for an increase in prices between the lower and upper power limits. In this formula, the variable x represents the power subscription measured in kilowatts (kW). A linear model is used for the tariff function to ensure that the end-user tariff predictably rises with increasing power consumption, making it straightforward for implementation and easily comprehensible to users.

$$\mathrm{tf}(x) = \underbrace{\mathrm{tf_{min}} - \frac{(\mathrm{tf_{max}} - \mathrm{tf_{min}})}{x_{\max} - x_{\min}} \cdot (\mathrm{tf_{min}} - 0) +}_{\text{Y-axis intercept}} \underbrace{\frac{(\mathrm{tf_{max}} - \mathrm{tf_{min}})}{x_{\max} - x_{\min}}}_{\text{Gradient of linear function}} \cdot x \tag{7}$$

4. Nanogrids in Madagascar - a case study

In the Diana Region of Madagascar, the French-Malagasy company Nanoé[2] installed 31 small electric nanogrids, giving initial energy access to the region. These off-grid nanogrids consist of four to six households sharing one PV system and one lead–acid battery. The demand for electrical energy in the Diana Region is relatively low, as electric devices are mainly light bulbs or chargers for phones. The consumers can choose different energy tariffs according to their particular needs. The tariffs can be paid on a daily, weekly, or monthly basis via a Bluetooth connection between their phone and a controller in the nanogrid, and they (the tariffs) not only give rise to energy limitations but also to power limitations. Power limits vary between 10 and 125 Watts, while the average tariff is at 30 Watt and costs 0.33 € per day for an maximum of five hour supply. Nanoé's long-term vision is to pursue a bottom-up electrification approach. Over the coming few years, the nanogrids will be interconnected to form microgrids, allowing energy trading between 15 and 30 nanogrids. Subsequently, the microgrids will be connected to create minigrids, which might eventually connect to the main grid, and thereby possibly provide renewable energy surplus to the national system. This incremental expansion will enable the inclusion of more users, including those with higher power demands, while enhancing the reliability and stability of the system.

To gain a better understanding of the real-world application of the nanogrids in Madagascar, the installed nanogrids and the planned interconnection between them are shown in Fig. 6.

4.1. System setup

In the set up for the studied case, each nanogrid is considered an individual 'prosumer' with its own solar PV production and battery storage capacity. The trading of energy occurs between the interconnected nanogrids, rather than within the nanogrids themselves. The operator of the nanogrid, also referred to as a franchisee by Nanoé, is responsible for balancing demand and production, in addition to trading in the local electricity market. The operator is paid by each consumer for the delivery of energy and can either buy energy from the market or sell energy to it.

On the technical side, local demand is initially met by the PV generation and battery storage within each nanogrid, thus ensuring self-consumption and balancing of energy. Any surplus energy generated beyond the local demand can be supplied to the microgrid, while any deficit in energy can be sourced from the microgrid. Nanoé has developed the control of the technical system based on the voltage level of the microgrid and the state of charge (SOC) of each local battery as presented by Richard et al. (2022). This control mechanism does not require a sophisticated smart infrastructure, hence simplifying the implementation and operation of the system.

On the economic side, the current state of the interconnected nanogrid system lacks a designed local electricity market. To address this gap, suitable market mechanisms will be designed. The aim is to develop a market structure and framework that facilitates efficient energy trading among the interconnected nanogrids and maximizes the benefits for all stakeholders involved.

By combining technical and economic aspects, the aim behind the interconnected nanogrid system is to create a reliable and economically viable energy infrastructure by optimizing the allocation of energy resources, and by striving to empower local communities and promote sustainable development. The main technical and economic specifications relating to the case study are presented in Table 1.

4.2. Demand and production data

We used real-life measured data in our models. Nanoé, the company responsible for setting up the nanogrids in Madagascar, provided load data for each consumer at a resolution of 10 min. The case study reported in this papers covered a three-month period and contained 18 different nanogrids. The average power consumption of each nanogrid

[2] https://www.nanoe.net/

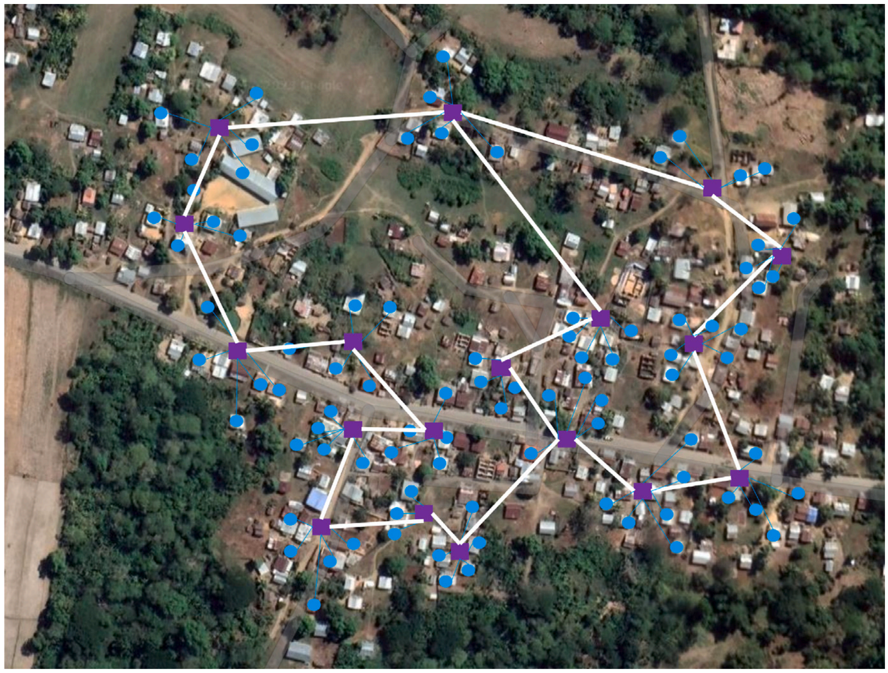


Fig. 6. Satelite image of one planned microgrid in Madagascar.

Table 1
List of technical and economic specifications.

Parameter	Value	Unit
Battery		
Max charge level	80	%
Max discharge level	30	%
(Dis-) charge rate	10	W/Wh
Voltage		
Microgrid voltage level	60	V
Nanogrid voltage level	12	V
Investment costs		
Costs for 100 Wp PV	54	€
Costs for 90 Ah lead–acid battery	108	€
Nanogrid set-up incl. controller, cables, labour etc.	288	€

ranged from 1.5 W to 21 W, with a mean value of 10 W. As anticipated, the power demand in the villages in the Diana Region was exceptionally low compared to European standards. The villages had previously lacked access to electricity and had relied on diesel generators. Consequently, their energy requirements were minimal and were primarily limited to basic lighting and the charging of appliances. There was no use of energy for refrigeration, heating, cooling, or electric cooking, and consequently there was an average daily energy consumption of 230 Wh per nanogrid, with 34 Wh for the nanogrid with least consumption and 423 Wh for the nanogrid with the highest consumption.

Solar production in Madagascar benefits from the country's proximity to the Equator, which results in minimal seasonality. With sunrise and sunset consistently around 6 a.m. and 6 p.m. throughout the year, along with stable temperatures, Madagascar experiences advantageous conditions. The 10-minute resolution data for demand and production of all nanogrids over a three-month period (90 days) are shown in Fig. 7. Overall, it is evident that despite the significant reduction in PV sizes, the daily production, on average, exceeded the demand by more than twice that of the nanogrids collectively.

The ENERGICA project[3] provided valuable data regarding customer subscriptions, PV and battery sizes per nanogrid, and investment costs for energy assets.

4.3. *Asset sizes and trading energy*

Modelling the LEM relies on the specific sizes of PV and battery systems, as they determine the surplus and deficit energy of each nanogrid. The battery and PV sizes are shown in Table 2, together with their reduction retrieved from previous calculations, based on the work of Bertram (2023) and the total amount of deficit and surplus energy of each nanogrid. It is important to note that the deficit energy serves as buying bids and surplus energy as selling bids, but the quantities do not necessarily balance out, as market clearing uses these quantities to calculate the actual energy traded.

The correlation between battery size and the generation of selling and buying bids is shown in Table 2. A larger battery capacity allows for a greater amount of energy to be offered or demanded in the market, as the specific charge and discharge rates depend on the capacity, and the submission of buying and selling relies on the SoC of each battery. Also, nanogrids with small battery sizes and small PV sizes (e.g. O, N, Q) show small amounts of buying and selling quantities, thus supporting the correlation.

5. Results and analysis

In this section we present the findings relating to the two different market approaches by comparing them in terms of trading prices and traded energy. Based on the findings, we present the resulting energy-based tariff structure.

[3] Energy Access in Rural and urban Africa, see https://energica-h2020.eu/.

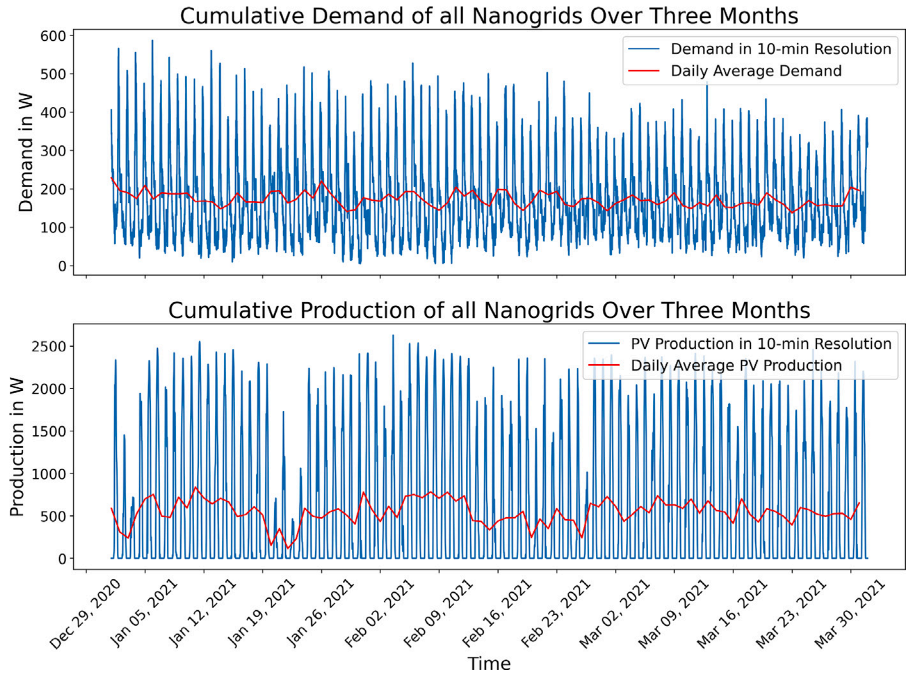


Fig. 7. Input data (production and load) for all nanogrids over time period.

Table 2
Asset sizes and available energy for trading.

NG	Battery (Wh)	PV (W)	Deficit energy (kWh)	Surplus energy (kWh)
A	1100	100	329	393
B	400	160	107	194
C	2500	670	558	1282
D	800	190	188	372
E	700	290	177	361
F	1200	390	294	602
G	600	130	189	224
H	700	150	199	287
I	800	160	208	347
J	500	80	166	168
K	700	180	197	302
L	700	90	223	239
M	300	50	92	112
N	100	50	38	42
O	100	50	27	54
P	1300	110	489	356
Q	100	50	53	28
R	200	50	68	70
Average	**711**	**164**	**200**	**302**

Table 3
Demand and supply prices for market clearing process (in €/kWh).

NG	Bid price	LCOE total	LCOE PV
A	2.10	0.71	0.07
B	1.85	0.55	0.06
C	2.01	1.08	0.04
D	1.83	0.52	0.05
E	1.93	0.70	0.05
F	1.87	0.66	0.04
G	1.93	0.45	0.06
H	1.93	0.52	0.06
I	1.93	0.69	0.06
J	2.44	0.51	0.08
K	1.97	0.55	0.05
L	2.34	0.50	0.08
M	1.68	0.81	0.10
N	2.49	0.30	0.10
O	2.40	0.71	0.11
P	2.20	0.54	0.06
Q	2.29	1.37	0.10
R	2.75	0.59	0.11
Average	**2.11 €/kWh**	**0.65 €/kWh**	**0.07 €/kWh**

5.1. Local electricity market design

As a first step in setting up a local electricity market, the bidding strategy calculated by LCOEs and demand prices in price per energy was calculated for use for the market clearing process. The results of these calculations for every nanogrid are shown in Table 3.

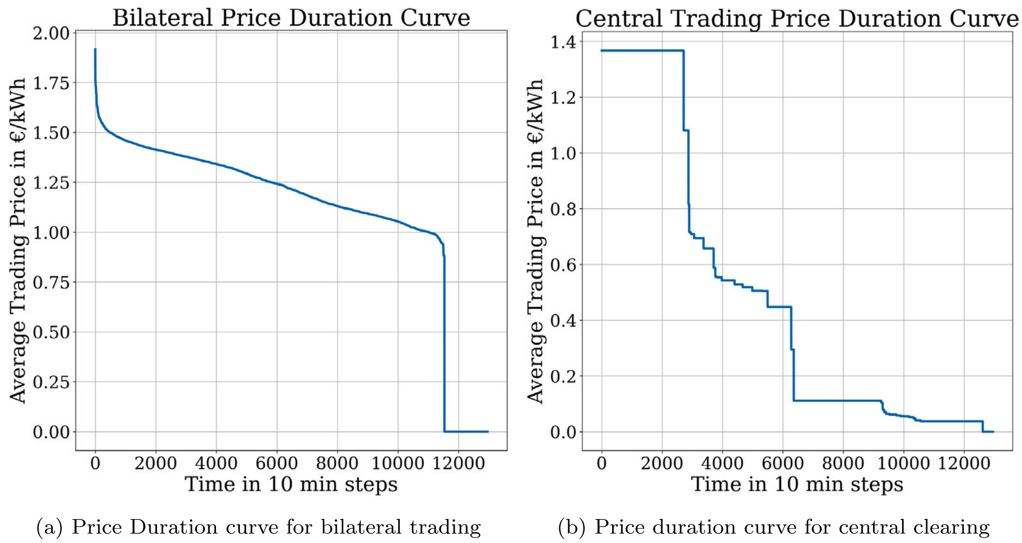
Table 3 shows bid prices that, at an average of 2.1 €/kWh, are significantly higher than bid prices at the daytime price level of 0.07 €/kWh and nighttime price level of 0.65 €/kWh. Based on the results of the bidding strategy, the market simulations for all 18 nanogrids were performed and analysed in order to compare the two markets in the context of implementation of the strategy in Madagascar.

5.1.1. Trading price

The main result used to compare both markets was the trading price determined by each algorithm. The trading prices over the 12,960 time steps (three months in 10 min steps) are shown in Fig. 8, ranked from highest to lowest price. A trading price of zero (‘0’) indicates no trading occurred during that hour, due either to no supply or no demand.

Fig. 8(a) shows a smooth curve transitioning from around 1.8 €/kWh for a very short duration to just below 1 €/kWh. By contrast, Fig. 8(b) shows a ‘step-shaped’ price duration curve. It reveals distinct levels at 1.37 €/kWh, 0.11 €/kWh, and at around 0.05 €/kWh. The plot highlights both levels of trading prices resulting from the LCOE of PV systems and PV systems combined with battery storage, and demonstrates similar levels of day trading (total c. 1,130 h) and night trading (total c. 1,030 h). With this understanding, we can delve deeper into the comparison of the trading price and explore the differences between the two market clearing algorithms.

The behaviour of the trading price on an average day over the three-month period (90 days) is shown in Fig. 9, which highlights the distinctions between the central clearing and bilateral trading approaches. Although both curves exhibit distinct patterns with significant fluctuations between day and night price levels, they also



(a) Price Duration curve for bilateral trading (b) Price duration curve for central clearing

Fig. 8. Comparison of price duration curves for different trading methods.

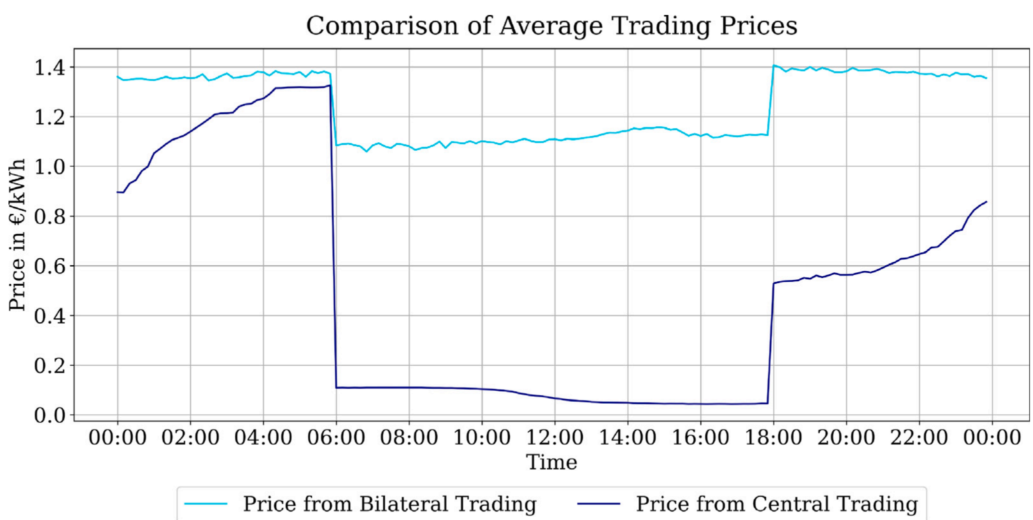


Fig. 9. Comparison of both trading prices on average daily distribution.

have noticeable differences, particularly in the day trading price. The variations can be attributed to the price setting mechanism in both the central clearing, which is determined by the offering price, and in bilateral trading, which involves both offering and demanding prices.

In central clearing, the price increases towards the end of the night, suggesting that nanogrids with higher battery capacity have more energy available for trading towards the end of the night, due to their larger battery size and the associated higher LCOE. As the sun rises and PV power is generated, the price level drops from over 1.37 €/kWh to around 0.1 €/kWh. Daytime trading prices gradually decrease, suggesting that cheaper PV systems offer their energy later, as they have lower surplus energy. At around 6 p.m., the price rises back to the night level, starting at 0.6 €/kWh and gradually increasing, for the same reasons as given for the early hours of the day.

In bilateral trading, the average day shows similar shaped curves for day and night price levels, but, in contrast to in central clearing, with a smaller difference between both levels, as prices are not solely dependent on the LCOE but on the demand prices too. During the night time the price in bilateral trading also stays at a similar level just above central clearing price, but only goes down to around 1.1 €/kWh during the daytime.

5.1.2. Traded energy

To provide an overview of energy flows, Fig. 10 showcases the aggregated values calculated by summing all nanogrids and taking the average over all days. This approach provided insights into the patterns across the entire system.

As discussed with regard to the model and presented in Section 3.1, buying bids are generated when demand exceeds production or if the SoC is below 50% of its capacity. Conversely, selling offers are generated when production exceeds demand or if the SoC is above 50%, thus explaining the behaviour of the bidding and offering curves. Given the average battery capacity of 711 Wh, the SoC does not go below 40%, thus supporting the priority of self-supply and the minimum level of charge set to 30% of the capacity. In Fig. 10, the green lines represent both traded energy curves as the intersection between the demand and supply in the market. When the traded energy exceeds the load represented by the blue line, it indicates that energy is being traded for the purpose of battery balancing. Additionally, Fig. 10 gives an insight into overall demand patterns, with a peak of energy demand above 400 Wh in the evening and a low demand of around 100 Wh in the morning hours between 8 a.m. and 1 p.m.

Moreover, it is important to note that the bidding quantity for the market differs significantly from the actual demand of all nanogrids,

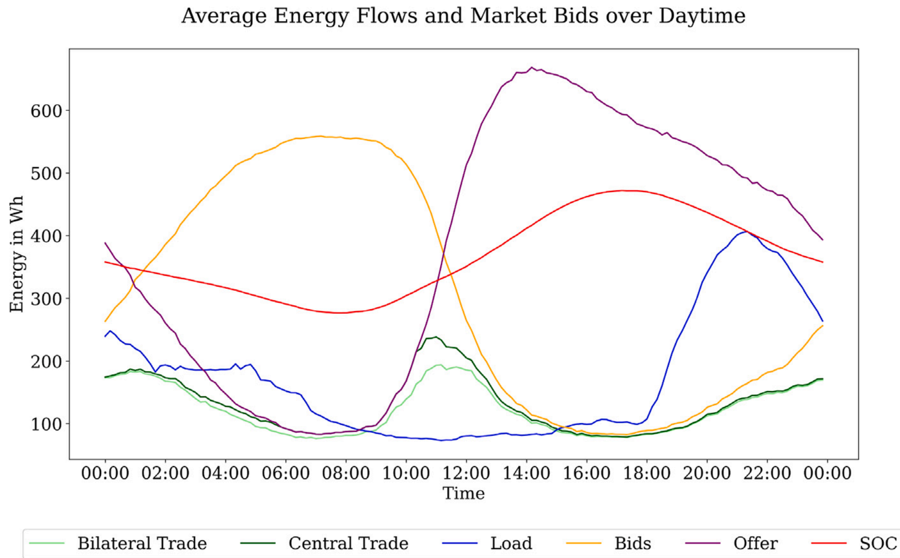


Fig. 10. Energy flows, storage level and market quantities.

Table 4
Summary of prices.

Metric	Unit	Bilateral	Central
Average price	€/kWh	1.24	0.49
Average day price	€/kWh	1.11	0.07
Average night price	€/kWh	1.37	0.90
Standard deviation	€/kWh	0.39	0.58
Traded energy	kWh	1,588	1,698

primarily due to the bidding quantity's dependency on the SoC. The same holds true for the relationship between the offering quantities and PV production.

From a comparison of both models in terms of traded energy, it can be seen that the central clearing approach is generally more capable of following bids and offers, and therefore trades more technically available energy, while the bilateral trading mechanism lags behind during the middle of the day, with a peak of 193 Wh compared to a 238 Wh peak for the central clearing. This indicates that there are some unsuccessful bid matches in the bilateral trading where, due to the level of randomness in this model, some technically available energy cannot be traded by the market.

5.1.3. Comparison of market designs

A comparison of the key findings from both market clearing methods with respect to various measures is shown in Table 4. Significant differences can be seem in the trading price, both during night trading and day trading. There is a 60% difference between the average prices for bilateral trading and central clearing. The standard deviation, as a measure of price variation, is 0.39 €/kWh for bilateral trading and 0.58 €/kWh for central clearing, indicating higher price predictability in bilateral trading.

To facilitate a discussion of the findings relating to the local electricity market designs, we defined specific criteria to compare and evaluate the market designs.

The criteria serve as a framework for assessing the performance of each market design and providing valuable insights into the market designs' strengths, weaknesses, and suitability for P2P electricity trading in Madagascar. These criteria provide a framework for evaluating and comparing the performance and effectiveness of different local electricity market designs. Evaluating the market designs against these criteria enabled us to perform a comprehensive analysis and present a meaningful discussion of their respective outcomes. The criteria are as follows:

- **Security of supply:** Ensure a reliable and continuous energy supply to all nanogrids without instances of energy shortages or blackouts within the microgrid system.
- **Transparency:** Provide market participants with clear and accessible information about the pricing factors, market rules, and trading processes to enable informed decision-making among market participants.
- **Market efficiency:** Promote fair and efficient trading of energy between participants with equal opportunities while maximizing overall economic welfare.
- **Flexibility:** Participants' ability to trade surplus and deficit energy effectively, thereby enabling them to respond and adapt to changing market conditions and optimize their energy transactions.
- **Resource efficiency:** Optimal use and allocation of resources involved in energy generation, storage, and distribution.
- **Scalability**: Allows for successful implementation and operation across different microgrid projects and varying scales of energy generation and consumption.

The evaluation of the local energy market criteria is conducted qualitatively, taking into consideration various market behaviours, the quantity of energy exchanged in each market-clearing process, and the intricacies of the trading price, including its fluctuations and average. These aspects collectively contribute to the assessment of the market's performance.

Table 5 shows a detailed comparison of the LEM design criteria for both market clearing algorithms. By comparing and analysing this table, two significant differences between both market algorithms can be summarized with regard to the ability to trade technically available energy and the method of setting the price:

1. *Ability to trade all available energy*: The central market clearing algorithm allows for the trading of all technically available energy, ensuring efficient use of resources. By contrast, the bilateral trading algorithm may result in unmatched trading, leading to the inability to trade all available energy.
2. *Price setting approach*: The bilateral trading algorithm sets the price based on a random bid matching and between offering and buying prices. By contrast, the central market clearing algorithm sets the price to the LCOE of the most expensive demand-meeting nanogrid by neglecting different bidding prices and

Table 5
Comparison of market models in serving LEM criteria.

Criteria	Central clearing	Bilateral trading
Security of supply	The market enables trading if it is technically feasible to meet the demand.	The bilateral mechanism may not meet all demand if buying and selling partners are suboptimally paired.
Transparency	Full transparency on price determination based on offering LCOE.	Lack of full transparency as bids and offers are randomly paired, and prices are set between the paired prices.
Market efficiency	The market promotes the lowest possible prices and maximizes consumer surplus.	The market tends to promote prices that are more favourable for producers.
Flexibility	Offering demand-side flexibility is incentivized by low trading prices.	Offering supply-side flexibility is incentivized by high trading prices.
Resource efficiency	Battery and PV power are used efficiently.	Resources are not optimally utilized due to unmatched trading.
Scalability	Scalable market approach to promote low trading prices and incentivize consumers to participate.	Scalable market approach to promote higher producer surplus and incentivize producers to participate.

quantities of each nanogrid. Central clearing promotes full transparency in price finding, ensuring fair and efficient trading, as well as the highest consumer surplus.

Overall, the bilateral trading algorithm in the LEM design incentivizes nanogrids to install more generation capacity, as it offers high revenue opportunities through high market prices. This design is suitable when energy tariffs are relatively low or when either investor or operators tend to use small asset sizes and additional revenue is needed to cover the investment costs of energy assets. However, the central market clearing algorithm promotes a local electricity market design that is favourable for the consumption of energy from the microgrid. It provides incentives to minimize the size of energy assets while still meeting demand. This approach is particularly useful in microgrids with relatively high energy tariffs and oversized assets, as it allows for the reduction of overall energy costs by importing a portion of energy from the microgrid at a comparatively lower price. It ensures the optimal use of available energy and facilitates fair price determination.

5.2. Energy-based tariff

Continuing from the outcomes of the market clearing process, the subsequent phase involves formulating a novel tariff for end users that takes into account market trading prices and the potential revenue from P2P trading for each nanogrid. In contrast to the existing tariff structure, which relies on fixed prices linked to specific power and energy limits, along with optional rentals for electrical devices, this endeavour can be characterized as a bottom-up approach aimed at establishing a simplified energy-based tariff framework.

As described in Section 3.4, the energy-based tariff should depend not only on import, export, and demand with prices for trading and generation (LCOE) but also on the costs of using the grid. An overview of the total costs of a microgrid is provided based on a pilot study executed by Nanoé (Table 6). These example costs were applied to 18 nanogrids in the Diana Region and thus serve as a realistic reference value.

The grid tariff results from the CAPEX of each microgrid divided by the total energy expected to be traded during the lifespan of the microgrid over ten years (see Eq. (8)). The total traded energy was derived from the energy trade in central clearing scaled up to ten years.

$$\mathrm{tf}_{\mathrm{grid}} = \frac{\mathrm{CAPEX}}{\sum_{t\in N_t} E_{Ex}} \qquad \mathrm{tf}_{\mathrm{grid}} = \frac{9,480\,€}{49,720\,\mathrm{kWh}} = 0.19\,€/\mathrm{kWh} \tag{8}$$

Table 6
Microgrid costs.

Modules	Total cost
Interconnection	3,860 €
Distribution	4,850 €
Transport & Labour	770 €
SUM	9,480 €

Table 7
Costs, revenue, and profit margin for various products.

NG	LCOE (€/kWh)	Import (kWh)	Export (kWh)	Yearly Load (kWh)	Cost (€)	Price (€/kWh)
A	0.72	185	117	2,834	2,783	0.98
B	0.56	25	92	2,010	1,518	0.76
C	1.08	430	67	4,568	6,724	1.47
D	0.53	91	98	3,295	2,400	0.73
E	0.71	64	116	2,470	2,390	0.97
F	0.66	151	81	3,997	3,645	0.91
G	0.45	73	110	3,031	1,862	0.61
H	0.52	65	110	2,956	2,100	0.71
I	0.69	90	105	2,439	2,315	0.95
J	0.51	35	152	2,247	1,516	0.67
K	0.55	53	123	2,852	2,154	0.76
L	0.50	71	185	2,852	1,931	0.68
M	0.82	11	69	981	1,083	1.10
N	0.30	2	36	1,740	699	0.40
O	0.71	1	33	719	701	0.97
P	0.54	164	71	4,304	3,261	0.76
Q	1.37	2	43	375	694	1.85
R	0.59	6	49	1,117	894	0.80
					AVERAGE	0.89 €/kWh

Using Eqs. (5), (6), and (7), we computed the price per kWh for each nanogrid, as shown in Table 7. Given variations in LCOE, import/export quantities, and load across different nanogrids, the minimum energy price varies too. However, it is possible to derive an average value that serves as the overall minimum price per unit of energy.

In Table 7, it is noticeable that nanogrid C has the highest annual demand and imports, resulting in the highest annual costs. This is also reflected in the price per kWh, which is at a comparably high value of 1.47 €/kWh. By contrast, nanogrid Q has lower values for imports, load, and costs, but an even higher energy price of 1.85 €/kWh. Moreover, nanogrid N consumers have the lowest retail tariff at only 0.4 €/kWh, which corresponds to the lowest LCOE of 0.3 €/kWh.

With an average minimum energy price of 0.89 €/kWh the price for energy in the nanogrids could be lowered by 58% compared to the previous tariff used by Nanoé, which was 2.11 €/kWh on average. Similar to the tariff structure used by Nanoé, which distinguishes between different power subscriptions, the suggested minimum energy price could be set as the tariff for the lowest power subscription of 10 W.

From a new tariff structure based on the above-presented findings, a linear function can be derived to set energy-based tariffs that increase over power subscriptions to incorporate a price of ensuring enough capacity. Considering that the recent highest power subscription at 125 W is available for an average price of 1.22 €/kWh and setting this price as an upper limit, the tariff can be structured by a linear function as between 10 W at 0.89 €/kWh and 125 W at 1.22 €/kWh. This would resulting in a linear function:

$$\mathrm{tf}(x) = \underbrace{\mathrm{tf}_{\min} - \frac{(\mathrm{tf}_{\max} - \mathrm{tf}_{\min})}{x_{\max} - x_{\min}} \cdot (\mathrm{tf}_{\min} - 0)}_{\text{Y-axis intercept}} + \underbrace{\frac{(\mathrm{tf}_{\max} - \mathrm{tf}_{\min})}{x_{\max} - x_{\min}}}_{\text{Gradient of function}} \cdot x$$
$$\mathrm{tf}(x) = (0.89 - \frac{1.22 - 0.89}{0.125 - 0.01} \cdot 0.01) + \frac{1.22 - 0.89}{0.125 - 0.01} \cdot x$$
$$\mathrm{tf}(x) = 0.86 + 2.87 \cdot x \tag{9}$$

where $0.01 \leq x \leq 0.125$ in [kW]

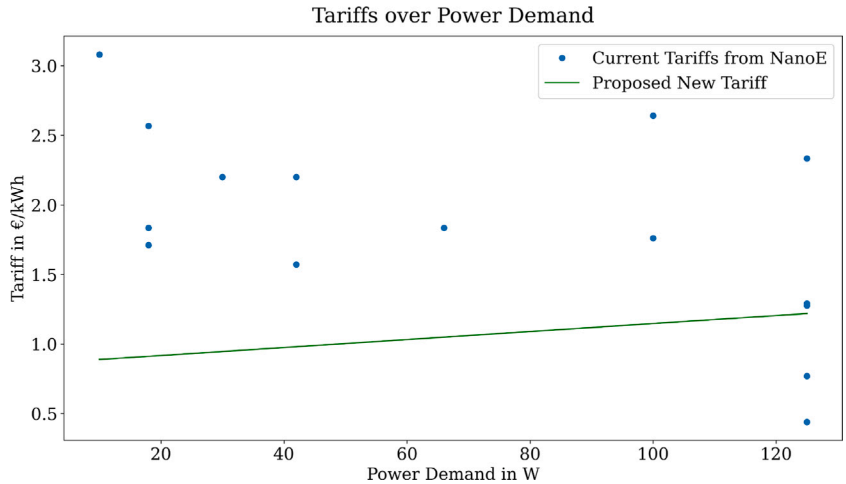


Fig. 11. Comparison of old and new tariff structured by power limits.

The common energy tariff in Madagascar, Eclairage Plus, with a 30 W subscription and a previous energy limit of 150 Wh, was offered at 0.33 €/day resp. 2.2 €/kWh and would then be offered at 0.95 €/kWh without energy or time restrictions. A comparison of both tariff options according to the power subscription is shown in Fig. 11.

The current tariff (blue dots in Fig. 11) exhibits multiple energy prices for certain power levels, and the lack of a consistent increase or decrease in energy prices as power limits increase. This due to the fact that some tariffs include a rental charge for electrical appliances, such as light bulbs or screens with high energy saving properties. Hence, the tariffs are normally not structured as prices per energy but as fixed prices per subscription. By contrast, the proposed new tariff (shown in green in Fig. 11) suggests a clear linear tariff structure, ranging from 0.89 €/kWh to 1.22 €/kWh for the highest power level of 125 W. The objective is to offer the lowest possible energy price for lower power subscriptions, facilitating affordable entry-level electrification, while recognizing the need for higher power limits for improved economic welfare. This objective could be met by reducing the energy price at the lowest power demand from 3.1 €/kWh to 0.89 €/kWh.

In Madagascar, the implementation of significantly reduced tariffs has created an opportunity for franchisees to generate profits. The average costs of setting up a nanogrid with reduced assets, which has been made possible through the LEM enabling trading, are now 2,148 €, compared to the previous cost of 4,390 € for separately installed nanogrids. This reduction in costs is also evident in the cost-covering energy price, which has decreased from 2.30 €/kWh to 0.89 €/kWh. To ensure that all costs are covered and to allow for profit margins, a linear increase in tariffs has been introduced. The difference between the linear function and the 0.89 €/kWh represents the profit margin.

Despite the significant reduction in tariffs, franchisees now have an increased opportunity to earn profits due to the lower set-up costs and the introduction of a linear tariff structure. This approach enables cost recovery while maintaining profit margins.

5.3. Discussion and limitations

Market clearing process

The proposed time dynamic approach to market clearing while also considering the intersection of demand and supply may be too complex for implementation in the microgrid in Madagascar, given the lack of reliable telecommunication infrastructure. Simplifying the market rules is crucial to facilitate revenue generation from surplus energy without extensive trading optimization. Our findings relating to the market trading prices can be used to establish simple market rules, such as different day and night prices based on the LCOE. This approach ensures cost coverage, while remaining easily understandable. To adapt to the evolving energy landscape, market prices can be annually adjusted based on traded energy volume and changes in the LCOE, allowing for a responsive market.

Tariff structure

When considering the implementation of a new tariff structure, key considerations include whether the tariff should increase or decrease with higher power limits and whether it should incorporate fixed prices or be calculated by using a formula based on power. Offering lower prices for smaller power subscriptions enables broad electrification at a small power supply scale, while higher energy prices for larger power subscriptions reflect increased economic welfare. A decreasing tariff structure can account for lower willingness to pay and lower opportunity costs for higher power subscriptions. Different tariffs for private and industrial use could be considered, with private tariffs increasing up to the maximum household supply level and decreasing within the range of industrial users. Rental fees for electrical appliances could be billed separately to enhance pricing transparency.

6. Conclusion

In this paper we have focused on the development of a LEM design and a new tariff structure aimed at achieving a reliable, affordable, and sustainable energy supply. To evaluate the performance of this approach, we compared the microgrid with P2P trading to the scenarios of disconnected nanogrids currently prevalent in the Diana Region of Madagascar and the absence of access to electricity still prevalent in many rural regions of Madagascar and in other sub-Saharan countries, and worldwide.

Both the separated nanogrids and the microgrid system using P2P trading offer significant advantages compared to the absence of electricity access (Table 8). However, the microgrid system stands out as the more advantageous solution across all three criteria, ensuring a reliable, sustainable, and affordable energy supply for the project in Madagascar and serving as a proof of concept for rural electrification.

From our comparison of two market models, central clearing and bilateral trading, we conclude that the central clearing approach offers advantages in terms of transparency, market efficiency, security of supply, and resource efficiency. It also promotes lower overall trading prices. However, bilateral trading can be beneficial if operators tend to undersize their assets or withhold energy from trading as it forms higher market prices.

The introduction of a new tariff design with a low entry level can be very beneficial, as it allows small businesses that rely on electricity to

Table 8
Comparison of energy access solutions.

Criteria	No electricity access	Separated nanogrids	Microgrid using P2P trading
Affordability	Expensive energy supply through diesel, fire wood or candles.	Different tariffs offer different energy price, but the average tariff is at 2.1 €/kWh.	Tariffs increase with power limits, but start at an energy price of 0.89 €/kWh.
Reliability	High dependency on availability of fuels.	Energy supply is secured through large battery capacities.	Energy demand is reliably met through trading surplus and deficit energy.
Sustainability	High CO2 emissions and pollution from fuel burning.	Renewable energy generation is prevalent, but the use of resources is inefficient.	Optimal use of available resources through P2P trading.

locate, thereby creating opportunities for economic growth and social prosperity. This approach not only supports business development in rural areas, but also contributes to overall social and economic prosperity by ensuring financially sustainable and affordable energy access. The main findings of our study are as follows:

- The microgrid system using P2P trading provides affordable, reliable and sustainable energy supply in the context of initial energy access.
- Central clearing facilitates low trading prices and ensures the use of all available energy, while bilateral trading tends to benefit producers with higher prices.
- The implementation of a new tariff structure would promote accessible energy entry levels, thereby reducing barriers to energy access.

Future work should explore the implementation and impact of different energy sources, such as biomass or wind, on reliability, affordability, and sustainability criteria. Additionally, investigating the long-term vision of connecting nanogrids to the main grid and its effects on P2P trading would shed light on the objectives and challenges of such connections in rural areas of sub-Saharan Africa.

CRediT authorship contribution statement

Lea Bertram: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ida Fuchs:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Victor Banuls Ramirez:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation. **Pedro Crespo del Granado:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Sergio Balderrama:** Writing – review & editing, Supervision.

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.

Data availability

The authors do not have permission to share data.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of the revised manuscript the author(s) used ChatGPT in order to improve language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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