An Energy Trading Model for a Lab-Scale PV Microgrid in the Tunisian Context

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Abstract

The paper proposes an energy trading strategy that emulates residential building electrification through a lab-scale microgrid in Tunisia. A Mid-Market Rate (MMR) model is proposed for a 10kW grid-connected PV microgrid including battery storage and emulated loads. The trading algorithm proposes a uniform trading price for both electricity export and import within the microgrid. Multiple scenarios are formulated with regard to load profile, system sizing, and electricity market conditions. The results are analyzed and a set of Key Performance Indicators (KPIs) are defined to compare the proposed scenarios. The preliminary analysis shows that the proposed algorithm reduces the CO_2 emissions of the microgrid by 24% and improves the self-consumption of the locally generated energy. The model can be scaled up to include local communities effectively.

Keywords: energy trading, energy management strategy, microgrid, mid-market rate, peer-to-peer.

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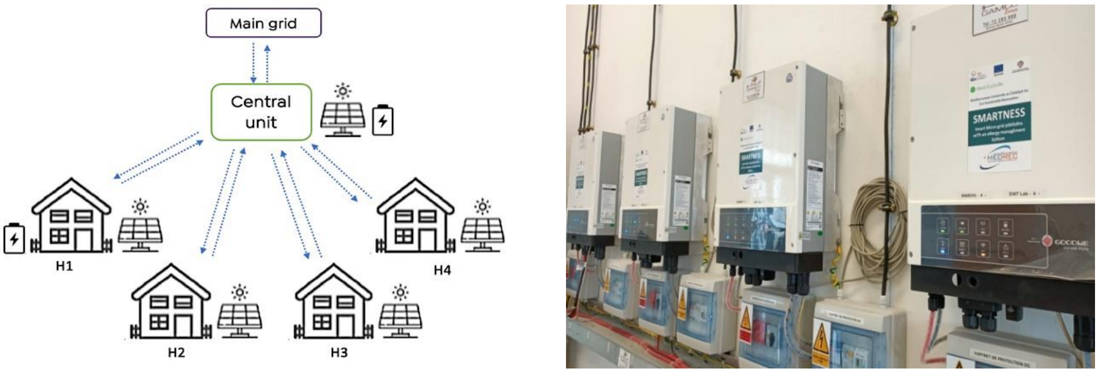
1. Introduction

Microgrids operate in distribution markets, which differ from the wholesale market not only in the size of the bids for energy trading, but also in the source of their energy –mainly from renewable sources with near-zero marginal cost. The transition into smarter and greener energy networks requires the utilization of new technologies and market models, thus, bringing the innovative business model of Peer-to-Peer (P2P) energy trading into context. The main objectives of the use of the P2P energy trading model are the maximization of the benefits of the users and the energy balance of the grid.(Yang et al., 2019)

Many models have been developed in recent years and multiple authors have compared and analyzed the performance of such energy trading mechanisms. Zhang et al. compared three pricing models: Double Auction, MMR, and Supply and Demand Ratio, and proposed a P2P energy trading framework considering a dynamic retail price and a forecasting agent to predict prices and energy production(Zhang et al., 2019). Long et al. compared three different P2P energy trading structures, namely, a Bill Sharing; MMR, and Auction-based Pricing Strategy. The clearing price mechanism of each of these market paradigms is tested in a PV-powered microgrid model with 10 households connected to the grid. The simulation resulted in a substantial reduction in energy prices (Long et al., 2017). Kuruseelan et al. used a Bill Sharing and MMR approach to study the performance of different market structures in P2P energy trading and compared them with a traditional Peer-to-Grid (P2G) scenario. These markets were designed and applied to a microgrid composed of three prosumers with PV generation and one non-PV consumer. The study showed that the income perceived by the prosumers is greater when MMR is used as the clearing-price mechanism (Subburaj and C, 2019).However, these findings cannot be adopted in various cases, given that the simulation is highly dependent on the local context. The present study focuses on adapting MMR algorithm to the Tunisian electricity market conditions while considering local scenarios and constraints.

doi:10.18086/eurosun.2022.01.02 Available at http://proceedings.ises.org

This paper assesses the performance and techno-economic viability of a lab-scale microgrid system, SMARTNESS (Smart Micro-grid plAtfoRm wiTh an eNergy managEment SyStem), implemented at the National Engineering School of Tunis, El Manar, Tunisia, in the framework of the Euro-Mediterranean project Med-EcoSuRe ("Med-EcoSuRe," n.d.). It explores the feasibility of social cooperation between prosumers within the energy network in establishing their sustainable participation in a P2P energy trading setup. The microgrid is composed of four households with an individual PV installation and a Li-ion battery for one of the houses. Moreover, a central unit, with a PV installation and two battery modules acts as the operator of the microgrid and deals with the energy management and exchange of power with the grid. The microgrid architecture and real photo are demonstrated in Figure 1.



(a) **(b)**

Figure 1: SMARTNESS microgrid. (a) Microgrid architecture. (b) Real photo ("Med-EcoSuRe," n.d.).

2. Methodology

A MMR method was developed based on the economic models proposed by (Long et al., 2017) and (Subburaj and C, 2019). This model consists of setting an internal price of electricity to trade energy inside the microgrid and is defined as the simple average of the retail prices to sell energy to the grid and buy energy from the grid, ensuring that every agent is treated equally. The MMR is developed for the hypothetical case of a Feed-in Tariff (FiT) scheme in the Tunisian electricity market, contrary to the net-metering system currently in place. Moreover, the retail price paid by the consumer is calculated according to a tier tariff scheme based on the amount of electricity consumption as established by the Tunisian Society of Electricity and Gas (STEG) ("STEG: Les tarifs d'électricité," 2019). The electricity tariff as of 2021 can be seen in Table 1.

Table 1. Low voltage electricity tariff in Tunisia. ("STEG: Les tarifs d'électricité," 2019)

Sector	1 – 200 kWh	201 – 300 kWh	301 – 500 kWh	501 or more kWh
Residential (mill/kWh)	176	218	341	414

2.1 Mid-Market Rate Model

The internal price of electricity is computed as per the MMR methodology as follows:

$$C_{P2P} = \frac{C_{BFG} + C_{STG}}{2} \quad \text{(Eq. 1)}$$

Where:
C_{P2P} : Internal Price in P2P Microgrid.
C_{STG}: Retail price of Energy, Sell To Grid (STG).

C_{BFG}: Retail price of Energy, Buy From Grid (BFG).According to the power balance between the load and the power generation, there may exist three different cases which will affect the internal price of energy; an energy balance between generation and demand (scenario 1), an excess of energy generated (scenario 2), or a lack of energy generated (scenario 3) within the microgrid. With each case, the MMR remains the same, but the price to import or export electricity will be determined according to the energy balance in a given timeslot. The model considers one-hour timesteps to perform the power balance of the system and the amount of energy imports and exports, and the change of tier in the tariff scheme, will affect the electricity bill of each prosumer differently.

The power production in the microgrid is considered as the power exported from the houses to either the central battery or the main grid, and the power exported from central PV and central battery to the houses and or grid:

$$P_{prod}(t) = \sum_{n=1}^{N} (P_{PV}^{n}(t)) + P_{CB\_to\_houses}(t) \quad \text{(Eq. 2)}$$

Where:
$P_{prod}(t)$: Total PV production within the Microgrid in kW at timestep (t)
$P_{PV}^{n}(t)$: PV production of each prosumer “n” in kW for timestep (t)
$P_{CB\_to\_houses}(t)$: Power exported from the Central battery to the prosumers in kW for timestep (t)

The load in the microgrid will, thus, be the sum of the houses’ imports and the local consumption of the central unit plus the power delivered to the central battery. Given that the central battery is considered in the load computation, it is possible to characterize the central battery as a dynamic load balancing the microgrid:

$$L(t) = \sum_{n=1}^{N} L^{n}(t) + L_{CB}(t) \quad \text{(Eq. 3)}$$

Where:
$L(t)$: Total Load within the Microgrid in kW for timestep (t).
$L^{n}(t)$: Load of user “n” (including Central consumption) in kW for timestep (t).
$L_{CB}(t)$: Load of the Central Battery in kW for timestep (t).

The first scenario occurs when the power produced is exactly equal to the load of the microgrid. This may occur when the batteries and loads can absorb the energy exported by all the other agents. In this case, both the import and export prices for each prosumer will be equal to the internal price:

$$C_{im}(t) = C_{P2P} \quad \text{(Eq. 4)}$$

$$C_{ex}(t) = C_{P2P} \quad \text{(Eq. 5)}$$

Where:
$C_{im}(t)$: Price of Imported Energy
$C_{ex}(t)$: Price of Exported Energy

The second scenario occurs when the power production is higher than the demand, the remaining of the power production will be exported to the main grid at the sell-to-grid price, lowering the final price of energy:

$$C_{im}(t) = C_{P2P} \quad \text{(Eq. 6)}$$

$$C_{ex}(t) = \frac{L(t) * C_{P2P} + \ (P_{prod}(t) - L(t)) * C_{STG}}{P_{prod}(t)} \tag{Eq. 7}$$

The third and final scenario proceeds when the energy production is lower than the demand, in this case, all the energy produced is consumed by the prosumers, while the remaining of the load is supplied by the main grid, causing the prices of electricity to increase inside the microgrid.

$$C_{ex}(t) = C_{P2P} \tag{Eq. 8}$$

$$C_{im}(t) = \frac{L(t) * C_{P2P} + \ (L(t) \ - \ P_{prod}(t)) * C_{BFG}}{L(t)} \tag{Eq. 9}$$

As the prices vary on an hourly basis depending on the ratio of energy imported from or exported to the main grid, the electricity bill for each individual household is calculated by considering the different prices and consumption levels at each timestep as follows:

$$C_j = \sum_{t=0}^{T} (P_{im}^{j}(t) * t * C_{im}(t)) - \sum_{t=0}^{T} (P_{ex}^{j}(t) * t * C_{ex}(t)) \tag{Eq. 10}$$

Where:

$P_{im}^{j}(t)$: Imported Power of User “j”

$P_{ex}^{j}(t)$: Exported Power of User “j”

The electricity bill for the Central Unit will be calculated differently as it needs to have an overall earning to pay for operation and maintenance expenses, therefore, the central battery is arbitrarily considered to export energy to the prosumers at buy-from-grid price and import energy at the internal price of energy:

$$\begin{aligned} C_{Central} = & \sum_{t=0T} (P_{im}^{Central}(t) * t * C_{im}(t)) \\ & - \sum_{t=0T} (P_{PV}^{Central}(t) * t * C_{ex}(t) + (P_{CB\_exports}^{Central}(t) * t * C_{STG}\ ) \end{aligned} \tag{Eq. 11}$$

Where:

$P_{im}^{Central}(t)$: Imported Power of Central Unit in kW for timestep (t)

$P_{PV}^{Central}(t)$: Exported PV Power of Central Unit in kW for timestep (t)

$P_{CB_{exports}}^{Central}(t)$: Central Battery exports in kW for timestep (t)

2.2 Microgrid Scenarios

For a comprehensive analysis, multiple scenarios of microgrid configurations are defined to evaluate the trading algorithm. These scenarios evaluate the impact of changing microgrid parameters such as BFG prices, load profiles and PV production on energy trading. Typical load profile values were obtained from OpenEL developed by the US Department of Energy and used for the houses in the microgrid (OpenEI, n.d.). Moreover, the PV generation profile was obtained for the city of Tunis from NREL data (NREL, n.d.).The baseline scenario is designed to be run with STG price of zero and central battery capacity of 4.8 kWh. Other scenarios include increasing the battery capacity, modifying the BFG and STG prices and changing the load profiles of individual prosumers.

Table 2:Analyzed Microgrid Scenarios

Case	Description	Purpose
Baseline	The load profiles are obtained by multiplying the original data (OpenEI, n.d.) by a random factor ranging from 0.75 to 1.25, the PV profiles(NREL, n.d.) are multiplied by 0.9 to 1.1	To serve as a baseline to compare with all the other scenarios. The random choice of the multiplying factors in load and PV profiles is made so that trading between houses is possible.
Optimum PV production (HOMER)	A simulation of microgrid is run in Homer Pro and optimal values for PV production are obtained, PV production is increased for each user to match these optimal values; load profile remains the same	This represents the best possible case with regards to sizing the PV modules. The effect of higher exports levels at optimum PV production were analyzed
Higher battery capacity	The total battery capacity is doubled	To analyze the effect when energy can be stored or sold to central. Increased battery size will allow energy to be traded between the central unit and individual houses.
One high consumer	One of the prosumers has a load profile 4 times higher than the original, allowing it to absorb most of available energy in the microgrid	To analyze the effect of increased trade within the microgrid. When the demand of one prosumer increases, it will obtain more energy from peers and central unit, causing an increase in trading price.
Various STG prices	STG prices are set at 0, 100, and 200 mill as FiT	To evaluate how changing the tariff will impact the earning and whether it causes a major difference in revenues for stakeholders.
Load Profiles shifted by 12 hours for 2 prosumers	The load profiles of 2 houses are shifted by 12 hours to simulate complementary load profiles inside the microgrid	To increase the energy traded among the prosumers. The amount of energy traded increases with different load profiles
Fixed BFG price	BFG price is a fixed value set equal to the highest value in the tariff scheme i.e., 414 mill and no longer depends on the energy consumption	To evaluate earnings in a flat tariff scheme. In the baseline, the consumer is charged according to its consumption. Once we remove it, we can understand the earnings with a flat tariff structure
Fixed BFG price, 3 Low demand Prosumers & 1 High-demand Prosumer	BFG price is a fixed value set equal to the highest value in the tariff scheme i.e., 414 mill, and no longer depends on the energy consumption. One of the prosumers' demand is 4 times higher than the original and the rest have half the original demand	To evaluate earnings in a flat tariff scheme. This will ensure that consumers are not penalized for additional consumption. Besides, one big consumer and 3 small consumers will increase the energy traded inside the P2P market as the bigger consumer will consume all the energy excess generated by rest

3. Results and Discussion

The P2P energy trading model was analyzed for the scenarios described in Table 2, and the total savings were calculated by comparing the electricity bill for a microgrid with and without P2P trading. For this purpose, three main aspects were considered: environmental impact, electrical performance, and economic evaluation.

For analyzing the environmental impact, the reduction in the carbon dioxide emissions was set as key performance indicator (KPI), which calculates the amount of CO_2reduced by implementing energy trading algorithm inside the microgrid. The grid emission factor taken as a reference specifically for Tunisia was 463 g/kWh. This grid emission factor was multiplied by the amount of energy traded inside the microgrid to calculate the amount of reduction. ("IFI Default Grid Factors 2021 v3.1 | UNFCCC," n.d.; IFI TWG, 2020)

For the electrical performance, the self-consumption level (SCL) and the self-sufficiency level (SSL) are considered. The SCL is the ratio between the total local consumption from the houses and the total amount of locally produced energy, in this case with Renewable Energy sources. It includes the surplus injected to the grid, and indicates which percentage of local generation is used to cover the demand. The SSL is the ratio between the consumption covered by local PV production and the total consumption from the houses. It indicates which percentage of the demand is covered by the local generation.

Finally, for the economic evaluation, the net-present value (NPV) and the bill savings were calculated in Tunisian Dinars (TND). The NPV is the difference between the costs the system incurs over its lifetime and the revenue it earns over its lifetime, with the value at present time, with a discount rate of 6.25%based on Tunisian Central bank rate, and a lifetime of 25 years, the typical duration of a PV project (Reuters, 2022).The bill savings indicate the difference between the cost of producing energy locally and making transactions directly with the grid (Business as Usual), and the cost producing energy locally produced and trading in the microgrid. The results from these KPIs are presented below in Table 3 and Figure 2.

The results in Table 3 show that the Homer and higher battery capacity scenario optimize the NPV of the system and leads to a higher self-sufficiency. Both increase the amount of energy available for trading. One high consumer provides the highest savings as more energy trading takes place due to a high demand by the high consumer. Changing the STG prices does not have a significant effect on the KPIs defined. Similarly, shifting the load profile scenario has little impact on KPIs due to the load profile being mostly flat throughout the day. Having a fixed BFG price significantly improves the savings and NPV. In fact, a higher consumption by one of the prosumers causes increased electricity rates for all prosumers in the microgrid due to combined grid imports through one central unit and the tier tariff scheme in force in Tunisia as of 2021. Therefore, a scenario with fixed BFG price is simulated to ensure that the prosumers will not be severely affected by the tier tariff scheme, which resulted into higher savings compared to dynamic BFG price.

The results for SCL show that at least 58.33% of the PV generation is used to cover the demand. These values are in accordance with results presented by other authors (Heilscher et al., 2014). A German study highlights that a PV system producing 1/3 of the annual demand may reach values of self-consumption of 60-90%, which goes in accordance with the scenarios, as for most of the cases the PV generation is almost 1/3 of the annual demand (Heilscher et al., 2014).

From the SSL, it is possible to state that no more than 36% of the demand is locally covered during the year. This means that a major amount of power has to be imported from the Tunisian grid. This can be due to the lack of PV generation during the night which is usually a period of high demand in households, small PV generation in comparison to the load consumption, or lack of sufficient energy storage. A study in Spain shows that the values for self-sufficiency range between 30% and 40% for small consumers like offices and educational buildings (Ordóñez Mendieta and Hernández, 2021). Another study developed in Germany calculated the optimal electrical self-sufficiency for houses which ranges between 30% and up to 70% under specific frameworks (McKenna et al., 2017). The microgrid falls short in most scenarios if it is compared with the German study. This could be because the PV generation is small compared to the load consumption, therefore, the use of batteries is advised to increase this ratio and to match the PV generation with the demand (Ciocia et al., 2021).

Table 3: Results of KPIs for the analyzed scenarios

Scenario	**CO2 emissions avoided by Microgrid (tCO2)**	**CO2 emissions avoided by Microgrid with P2P (tCO2)**	**Additional CO2 emissions avoided**	**SCL**	**SSL**	**NPV (TND)**	**Saving (TND)**
1. Baseline case	6.5	8.1	26%	91%	24%	- 48,005	- 1,375
2. Optimum PV production (HOMER)	11.2	12.5	12%	58%	36%	- 42,659	- 1,582
3. Higher battery capacity	11.4	13.3	16%	58%	36%	- 45,672	- 904
4. One high consumer	12.8	17.7	38%	82%	29%	- 1,653	1,702
5. STG=0	6.5	8.1	26%	91%	24%	- 48,005	- 1,375
6. STG=100	6.5	8.1	26%	91%	24%	- 47,576	- 1,340
7. STG=200	6.5	8.1	26%	91%	24%	- 47,148	- 1,306
8. Load Profiles shifted 12 hours for two prosumers	6.2	8.0	28%	89%	23%	- 46,967	- 1,292
9. Fixed BFG price	6.5	8.1	26%	91%	24%	- 11,175	1,575
10. Fixed BFG price, 3 Low demand Prosumers & 1 High-demand Prosumer	11.2	12.5	12%	97%	18%	987	2,549

Regarding the CO_2 emissions avoided in a P2P market, the results show that using photovoltaic energy and batteries contributes significantly in reducing the carbon footprint, especially in countries like Tunisia that rely heavily on natural gas.

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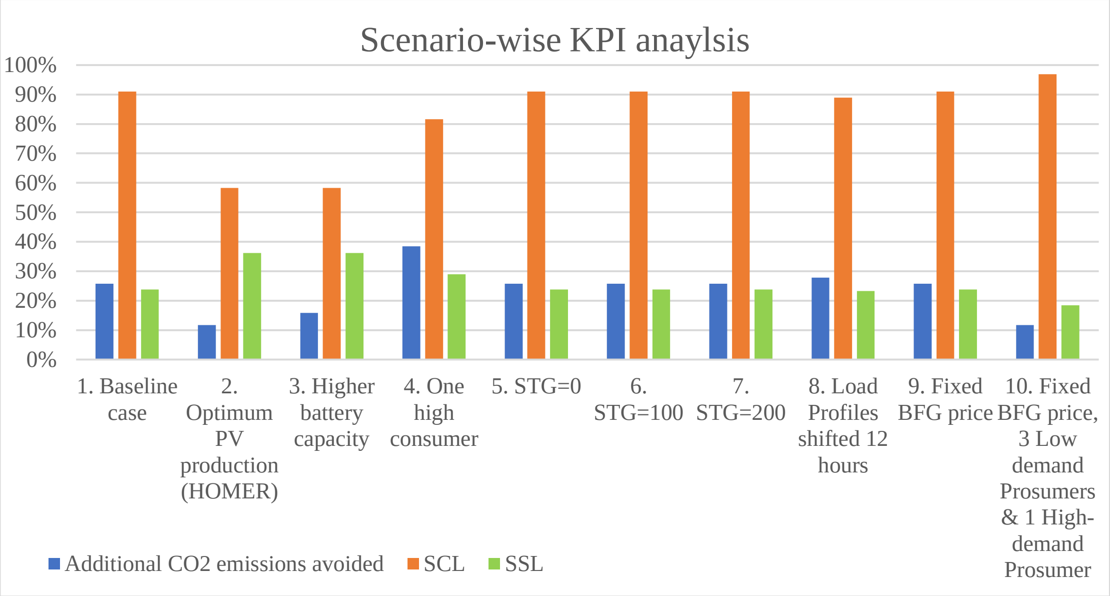

Figure 2: Scenario-wise KPI analysis

Concerning the economic analysis, negative values for NPV and savings represent that the project under those scenario conditions are not financially attractive. The resulting NPVs were mostly influenced by factors as the relatively high cost of investment, the replacement of the inverter every 10 years and the batteries every 15 years, and that the total billing of the microgrid was higher than expected in comparison to an individual configuration. The scenario 10 with one high consumer and fixed BFG price becomes profitable. In fact, under these conditions the prosumers would recover their investment with a small margin of gains, while decreasing their carbon emissions.

In general, it was observed that under a high load profile, there is an overall higher energy import from than export to the grid. This higher import results in increased electricity cost, thus, there is a need to promote self-consumption to increase savings. The savings can be increased when the central battery capacity is expanded, as the central unit can, in this case, store more energy which allows more trading. If one prosumer has a much higher load than the others, there are notable savings in the monthly electricity bill. This is because the excess of energy available during peak sun hours from other prosumers is consumed by the consumer with high load profile.

Implementing the Tunisian tier tariff scheme in the microgrid is challenging as the price of electricity is dependent upon total electricity consumption. A subsidy to the initial investment or a mechanism to promote the trading of the energy inside the microgrid and, hence, increase the savings in the energy billing, would contribute to making the project more economically feasible. Other schemes such as the participation in ancillary services markets could also improve the profitability of a smart microgrid, however, this falls out of the scope of this project.

4. Conclusion

P2P energy trading not only improves the local balance of energy generation and consumption but enable prosumers to move from being passive to active managers of their energy networks. The paper proposes an energy trading algorithm based on a Mid-Market Rate (MMR) for a lab scale microgrid emulating residential buildings in Tunisia. The model is evaluated for multiple scenarios proposed and key performance indicators are calculated for each one of them. The results reveal the environmental benefits of energy trading and highlight the importance of self-consumption. Moreover, the electrical performance of the algorithm is at part with similar projects across the world.

Around 60% of the PV generation is utilized for fulfilling the demand and 36% of the annual demand is covered locally at max. The trading algorithm has a positive environmental impact by reducing the emissions around 6-12% depending upon the scenario. Finally, the economic performance of the project depends upon the exact scenario considered and may or may not be financially lucrative. It is possible to observe a high dependence of revenues and the amount of energy traded inside the microgrid, which is a result of the interaction of the load and PV production profiles chosen for the prosumers. Moreover, a fixed Buy-from-Grid price is favourable for the total savings of the microgrid as it eliminates the negative impact of having consumption-dependant tariffs. A dynamic tariff that depends on time and not on consumption could have also been used and obtained a similar effect. The results can be used as a blueprint for future electricity market legal framework in Tunisia to promote energy trading in local microgrid setups.

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