

# Renewable Integration in Fossil-Fuel-Powered Microgrids under Market Power Conditions

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**Abstract**— Microgrids offer an alternative electricity supply in developing countries like Lebanon, where the public grid is unreliable. Privately owned microgrids often prioritize fossil fuel generation over integrating renewable energy from microgrid-owned units or prosumers. This study employs a mixed-integer linear programming model to optimize microgrid operation under fossil-fuel market power conditions, analyzing interactions between the microgrid owners, household consumers, and prosumers. Results indicate a shift from diesel generators to solar photovoltaic systems, yet most generation capacity remains microgrid-owned, limiting prosumer contributions. The unutilized rooftop PV generation capacity is reduced, yet the reduction remains limited. Profit-driven disconnections of unprofitable prosumers increase with increasing penalty on unsatisfied demand. The findings highlight that additional policy interventions are required to further reduce the unutilized PV generation potential on household rooftops and to ensure proper access for all customers.

**Index Terms**— Solar PV, Microgrid, Market Power, Developing Country, Optimization

## I. INTRODUCTION

Many governments in developing countries fail to provide reliable electricity supply to their citizens [1]. Lebanon is one such example, where the public grid has experienced a near-total collapse due to political instability and economic crises, originating well in advance of the recent war [2]. Thus, private initiatives flourished to substitute the national supply during periods of public grid failure. On one hand, small, parallel local grids developed, centered around one or more private diesel generators serving a single neighborhood or village [3]. These local grids can be classified as diesel-based microgrids. In this setting, the diesel generator owners exercise full control over energy distribution and customers' access to the microgrid, with minimal regulatory oversight. On the other hand, and to gain more control on their electricity access, households have resorted to renewable energy systems, namely rooftop solar PV with battery storage [4]. However, their self-production

conflicts with the interests of the microgrid owners, who seek to increase the utilization of their diesel generators to maximize profit. The integration of renewable energy into diesel-based microgrids—whether through renewable energy systems owned by the microgrid owners or through tying in the rooftop PV output of prosumers—remains uncertain in Lebanon's energy system. This challenge is also present in other countries with similar conditions such as Nigeria and Yemen [5][6].

The case of microgrids combining fossil-fuel sources to distributed energy resources like photovoltaic and wind systems has been widely covered in the literature [7][8][9]. Case studies on developing countries such as Iraq reveal the potential that well-regulated microgrids hold for providing reliable and sustainable energy [10]. The integration of solar PV and wind turbines into a diesel-based system is studied in [11], presenting microgrids as a cost-effective solution to the electrification crisis. While microgrids are widely recognized as a viable solution for enhancing electrification in developing countries, literature often fails to consider the market and policy differences separating them from the developed ones. Studies particularly tend to overlook the control and ownership aspects in developing countries where regulatory oversight is minimal [12]. Understanding ownership dynamics in private-sector-based models is the first step in efficiently planning and managing microgrids [13].

This work analyzes the integration of renewable energy sources into microgrids primarily powered by fossil fuel generation in developing countries considering the existence of household-owned rooftop solar PV systems. It considers the microgrid owner's full control over grid access and energy distribution by the ability to adjust the customer base and control demand fulfillment. A mixed-integer linear programming (MILP) model is employed to optimize the generation portfolio and operation of a microgrid across a long-term planning horizon.

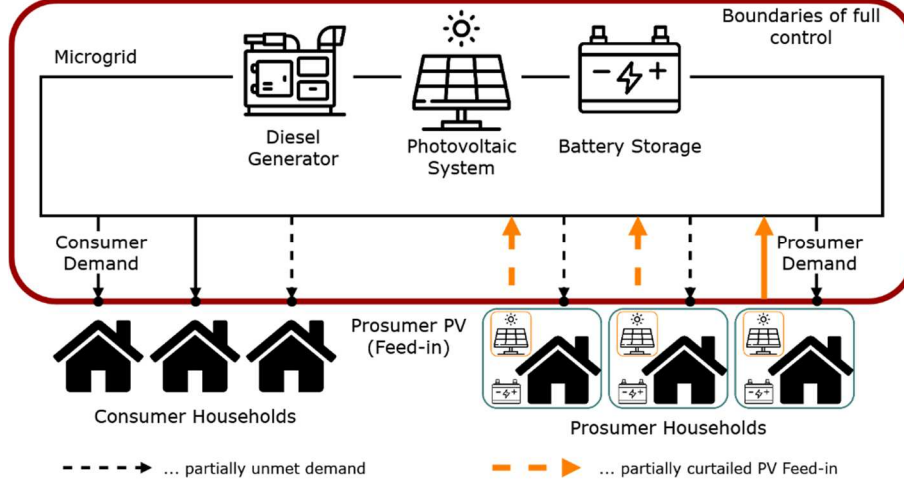


Figure 1: Main concept of the studied microgrid

Figure 1 illustrates the microgrid's structure and deployable assets. While maximizing profit, the owner can decide to: 1) increase the generation assets under their control including diesel, PV and batteries, 2) connect or disconnect consumers, 3) connect or disconnect prosumers while allowing or not allowing them to feed-in electricity into the microgrid, and 4) decide on the dispatch schedule to serve the demand of the connected households. Any unserved demand will be subject to a penalty.

## II. METHODOLOGY

In this section, we provide a description of the MILP model, focusing on its key aspects. A comprehensive description, including the code and further details, can be found in a GitHub repository in [14]. We first start by discussing the objective function then highlight the balance constraint. To accurately model the hourly chronological operations while ensuring the tractability of the model over the long-term horizon, we utilize representative operating days. Each representative day is modeled on an hourly basis and scaled by the number of days  $\omega_d$  that it represents in a year. In the following framework, index  $y$  represents a year, while  $d$  denotes a representative day and  $h$  an hour.

### A. Objective Function: Profit Maximization

The objective function maximizes the net present value (NPV) of profits using an annual interest rate  $\xi$ :

$$\max_x \sum_y \left[ (R_y - (C_y^C + C_y^{OF} + C_y^{OV} + C_y^{FI} + C_y^{UD})) * \frac{1}{(1+\xi)^y} \right] \quad (1)$$

Revenues  $R_y$  are derived from supplying electricity via a microgrid controlled generation technology  $g$  in  $disp_{g,y,d,h}$  or from battery discharge  $b_{y,d,h}^{out}$  to grid customers at a set tariff  $\rho$ . Annual capital costs  $C_y^C$  for new generation capacity stem from the annually added capacity  $a_{g,y}$  multiplied by its unit capital cost  $\lambda_g^C$ . Similarly, annual fixed operation costs  $C_y^{OF}$  are

determined by the installed capacity  $c_{g,y}$  within the microgrid, multiplied by its unit fixed operation cost  $\lambda_g^{OF}$ . Annual variable operation costs  $C_y^{OV}$  account for the electricity dispatched from microgrid-controlled generation technologies, as well as battery charging and discharging  $b_{y,d,h}^{in}$ ,  $b_{y,d,h}^{out}$  multiplied by the respective unit variable operation costs  $\lambda_g^{OV}$ . The variable operational costs also include fuel expenses for the diesel generator, which are modeled by multiplying electricity dispatch from the diesel generators  $disp_{g=DG,y,d,h}$  with the diesel price  $\pi$  and a binary variable  $bin_{k,y,d,h}^{DG}$  to determine the fuel consumption based on a two-step curve  $\alpha_k$ . This approach accounts for the increased fuel consumption at lower utilization levels.  $C_y^{FI}$  represents expenses incurred from purchasing excess electricity from prosumers  $f_{i,y,d,h}$  at a set feed-in-tariff  $\tau$ . Costs sustained from not satisfying demand  $C_y^{UD}$  occur when demand from customers goes unmet  $ud_{y,d,h}$  at a penalty  $\epsilon$ .

$$R_y = \rho * \sum_d \omega_d \sum_h ((\sum_g disp_{g,y,d,h}) + b_{y,d,h}^{out} - b_{y,d,h}^{in}) \quad (2)$$

$$C_y^C = \sum_g a_{g,y} * \lambda_g^C \quad (3)$$

$$C_y^{OF} = \sum_g c_{g,y} * \lambda_g^{OF} \quad (4)$$

$$C_y^{OV} = \sum_d \omega_d \sum_h ((\sum_g disp_{g,y,d,h} * \lambda_g^{OV}) + (b_{y,d,h}^{in} + b_{y,d,h}^{out}) * \lambda_{g=B}^{OV} + (disp_{g=DG,y,d,h} * (\sum_k bin_{k,y,d,h}^{DG} * \alpha_k) * \pi)) \quad (5)$$

$$C_y^{FI} = \sum_i f_{i,y,d,h} * \tau \quad (6)$$

$$C_y^{UD} = \sum_d \omega_d \sum_h ud_{y,d,h} * \epsilon \quad (7)$$

$$bin_{k,y,d,h}^{DG} \in [0,1] \quad (8)$$

$$x \in [disp_{g,y,d,h}, b_{y,d,h}^{out}, b_{y,d,h}^{in}, a_{g,y}, c_{g,y}, f_{i,y,d,h}, ud_{y,d,h}, n_{i,y}^{house}] \quad (9)$$

$$x \geq 0 \quad (10)$$

### B. Demand Coverage: Supply / No Supply

Equation (11) enforces the hourly balance between power consumption (left hand side) and generation (right hand side) while accounting for unmet demand. The microgrid consumption includes the demand from household types  $i$ , represented by  $\mu_{i,d,h}$ , multiplied by the number of grid-connected households of that type in year  $y$ ,  $n_{i,y}^{house}$ . The boundaries of control of the microgrid, depicted in Figure 1, include the grid's connections to its customers, allowing the grid owner to adjust the number  $n_{i,y}^{house}$  for all household types  $i$  and years  $y$ . In addition to supplying household demand, the microgrid also consumes energy through battery charging. Energy supply can originate from a microgrid controlled generation technology  $g$  (diesel, microgrid-owned PV or prosumer surplus PV feed-in) or from battery discharge.

$$(\sum_g n_{i,y}^{house} * \mu_{i,d,h}) + b_{y,d,h}^{in} = (\sum_g disp_{g,y,d,h}) + b_{y,d,h}^{out} + ud_{y,d,h} \quad (11) \quad \forall y, d, h$$

## III. RESULTS

In this section, we present selected findings of the analyzed Lebanese case study, emphasizing the integration of renewable energy and prosumer households into the microgrid. Accordingly, we focus on the number of households connected to the network and the extent of unmet customer demand. As an illustrative example, we select a typical autumn day to visualize the utilization of the generation portfolio and the unfulfilled demand in an hourly resolution.

### A. Microgrid Operation over a Representative Day

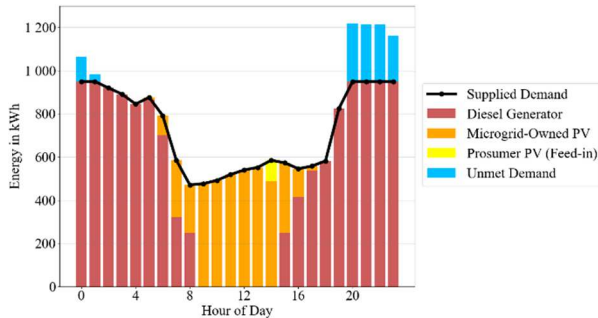


Figure 2: Daily demand coverage for all connected households in the microgrid for a representative day in autumn

PV electricity generation completely fulfills the microgrid demand during its peak availability in hours 9 to 14 as shown in Figure 2. The majority of PV-generated electricity within the microgrid is sourced from microgrid-owned systems as opposed to supply from prosumer households. The diesel generator primarily supplies the demand during periods lacking PV production. Notably, no microgrid-owned battery systems are installed. Furthermore, the results show that nighttime demand peaks are better left unmet, despite incurring a penalty of 0.1 \$/kWh as highlighted in Figure 2 by the blue bars. The extent of unmet demand is driven by the penalty parameter.

In the following section, we present different sensitivities regarding its impact and examine the conditions under which households are disconnected from the microgrid.

### B. Connected and Disconnected Customers

A sensitivity analysis of the penalty for unmet demand, presented in Figure 3, illustrates the range of connected and disconnected households in the microgrid. The figure is divided into two parts: (top) displays the number of connected consumer and prosumer households, while (bottom) illustrates the total energy demand not delivered to the different household types in the microgrid. The selected penalty value for the main optimization appears in the figure as *Base Scenario*. Following notable observations emerge from the analysis:

The number of consumers within the microgrid (represented by the blue line in the upper figure) remains unaffected by variations in the penalty for unmet demand. Regardless of the penalty parameter, it remains optimal for the microgrid owner to connect all consumers to the grid. In contrast, the number of prosumers shows a significant dependence on the penalty parameter. When the penalty is low (e.g., 0.05 \$/kWh), the number of connected prosumer households is maximized at 550. As the penalty increases, this number decreases, reaching 130 at a penalty of 0.35 \$/kWh. Increasing the penalty beyond this threshold does not lead to further reductions in the number of prosumers. Additionally, the unmet demand of connected customers is also highly sensitive to the penalty parameter. With a penalty of 0.05 \$/kWh (or lower), the unmet demand is the highest at 900 MWh/year. As the penalty increases, this value decreases progressively, reaching 350 MWh/year at a penalty of 0.1 \$/kWh and reducing to zero (0 MWh/year) at a penalty of 0.35 \$/kWh. It is important to note that this unmet demand refers only to customers that are connected, excluding those who are completely disconnected.

The disconnection of up to 420 prosumer households results in a significant loss of grid demand and excess PV generation. We quantify these metrics for an individual prosumer household in the following subsection.

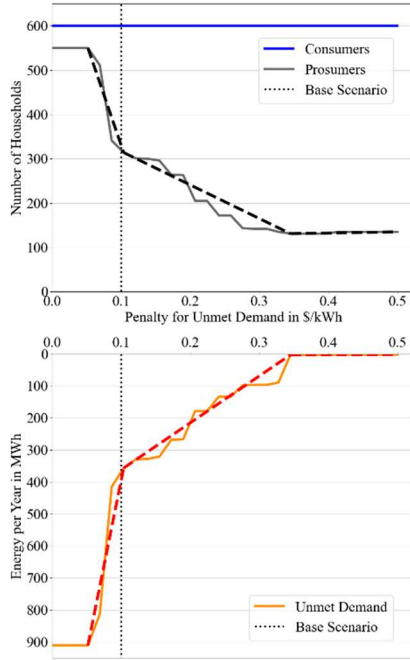


Figure 3:(Top) Number of connected consumer and prosumer households, (Bottom) Total unmet energy demand across different customers as a function of the unmet demand penalty.

### C. Impact of Prosumers

Although prosumer households maintain a reduced demand due to their own energy generation, they still offer economic opportunities for the microgrid. As demonstrated in Table 1, the microgrid supplies 25% of the prosumers' annual household demand, totaling 2 000 kWh. Only 13% of the available surplus PV production is fed into the microgrid, amounting to 70 kWh annually. This leaves 460 kWh of unutilized rooftop PV generation. The feed-in tariff, based on the levelized cost of electricity (LCOE) for PV, contributes to this issue. Its value provides no clear advantage for surplus PV generation by prosumers over microgrid-owned PV systems. The primary reason for low utilization of surplus PV is the limited hours of surplus feed-in availability. This creates an incentive for the microgrid to install its own photovoltaic system.

Table 1: Annual demand coverage and PV utilization of a single prosumer household without- and with microgrid connection

	Demand	Unmet Demand	Unutilized PV Generation
disconnected	7880 kWh	3690 kWh (47%)	530 kWh
connected		1690 kWh (22%)	460 kWh

So far, we have identified a substantial quantity of unused surplus PV generation alongside unmet demand during periods when photovoltaic generation is inactive. The conditions for the installation of battery storage to address this issue are detailed in the next subsection.

### D. Indicators for a Battery Storage

In the base scenario, the model opts not to install a battery storage system in the microgrid. Figure 4 illustrates the installation of a battery storage system for a combination of different input parameters. To include only significant battery system installations by the microgrid, we document only systems that have a capacity of at least 500 kWh.

Base Scenario:		Feed-in Tariff	UD Penalty	Diesel Price		Electricity Price		Number Prosumers	
No Battery Storage		0 \$/kWh	0 \$/kWh	low	high	low	high	low	high
Feed-in Tariff:	0 \$/kWh								
UD Penalty:	0 \$/kWh								
Diesel Price	low								
	high	X			X				
Electricity Price	low								
	high	X	X	X	X		X		
Number Prosumers	low							X	
	high	X	X	X	X		X		X

Figure 4: Battery storage installation in different scenarios  
 X... Installation of a microgrid-owned battery system  
 [Grey]... Infeasible or repetitive scenario

Microgrid-owned battery systems are installed under scenarios characterized by high electricity prices or a high number of prosumers. Similarly, high diesel prices drive the adoption of a battery storage in most scenarios due to the increased operational costs for the competing flexible generation technology. On the other hand, scenarios with no penalty for unmet demand or a low number of prosumers reduce the attractiveness of battery installations. Notably, a low electricity price (0.5 times the base case) has the most significant negative impact on battery storage installation.

However, it is worth highlighting that this electricity price is below the generation costs of all technologies, resulting in no generation technology being deployed within the microgrid.

#### IV. CONCLUSIONS

This paper proposes a Lebanese microgrid model under fossil-fuel market power conditions to explore the opportunities and challenges associated with integrating renewable energy into the supply mix. The focus is on the relationship between prosumer-owned solar PV generation and its impact on the profit-maximizing strategy of the microgrid owner.

We found that the microgrid owner's profit-maximizing strategy leads to an increase in solar PV generation, facilitating a shift from fossil-fuel-based to renewable-based energy supply. This transition presents clear economic benefits for the microgrid owner, even when accounting for efficiency variations associated with diesel generator utilization. However, our analysis reveals that the majority of the solar PV generation comes from the microgrid-owned capacity, rather than from prosumer-owned capacities. Only a small fraction of the generation from prosumers' solar PV systems is integrated into the microgrid's supply mix. A significant portion of potential prosumer-owned solar PV capacity remains unused because a majority of this customer type is disconnected from the grid, as their demand-generation mix is deemed unprofitable for the microgrid owner.

In conclusion, we find that despite the absence of a regulatory authority, microgrids where solar PV systems are considered, including fed-in generation from connected prosumers, offer clear improvements from the current state for all parties. Yet, additional policy interventions are required to further reduce the unutilized PV generation potential on household rooftops.

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Figure 1 has been designed using resources from Flaticon.com.

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