(IJACSA) International Journal of Advanced Computer Science and Applications,
Vol. 15, No. 10, 2024

Advanced Techniques for Optimizing Demand-Side Management in Microgrids Through Load-Based Strategies

Ramia Ouederni[1], Bechir Bouaziz[2], Faouzi Bacha[3]
Computer Laboratory for Electrical Systems, LR11ES26, INSAT, University of Carthage, Tunisia[1, 2, 3]
Electronics & Telecommunications Department, ISIMG, University of Gabes, Tunisia[2]
Electrical Department, ENSIT, University of Tunis, Tunisia[3]

***Abstract*—Microgrids are crucial for ensuring reliable electricity in remote areas, but integrating renewable sources like photovoltaic (PV) systems presents challenges due to supply intermittency and demand fluctuations. Demand-side management (DSM) addresses these issues by adjusting consumption patterns. This article explores a DSM strategy combining load shifting (shifting demand to periods of high PV generation), peak clipping (limiting maximum load), and valley filling (redistributing load during low-demand periods). Implemented in MATLAB and tested on a PV-battery microgrid, the strategy significantly reduces peak demand, improves the peak-to-average demand ratio (PAR), and enhances system stability and flexibility, particularly with the inclusion of deferrable loads.**

***Keywords*—Demand side management; microgrid; load shifting; peak clipping; valley fill**

I. INTRODUCTION

In recent decennials, an evolution in conventional power grid structure has taken place due to uncertain distributed renewable generation (URG) and advanced communication and control technologies [1], [2]. The increased utilization of deep penetration URGs and the improvement of demand-side resources (DSR) development have been seen as two important technological advances for supporting the sustainable expansion of today's energy infrastructure, enabled by the objective of total cost reduction [3]. A microgrid (MG) that can be incorporated with various URGs, advanced energy storage systems (ESS), and DSRs represents a sustainable way to deliver renewable, clean electricity as a vital part of the power transformation of conventional electricity production systems [4].

Microgrids (MGs) are stand-alone systems that support the integration of distributed power resources (DERs) and renewable energies for both reliability and profitability [4]. They are important components of intelligent energy transmission and distribution networks that regulate the electrical system's resilience under unfavorable conditions.

The various solutions for supplying rural areas with electricity are extensions of the national grid, autonomous systems, or microgrids [5]. Microgrids, or small electrical networks, have become a major solution because they can function independently. They are essential to developing an electrical infrastructure built around locally available renewable energy technologies at considerably reduced costs. In addition, they can accelerate access to electricity in areas where it is impossible to extend the grid in the short or long term.

To ensure that the electrical system becomes more reliable and robust, the peak demand is considered as opposed to the average demand. As a result, environmental resources are being wasted and production systems are being under-used. Rapid-response power generators (e.g. gas and oil-fired units), employed to satisfy the demand peak, not only cost a lot of money, they also generate high levels of carbon emissions. As a response, various packages were presented to help users shape their energy use profiles. These programs aim to make efficient use of the generation available so that new transmission and generation infrastructure is installed as little as possible. Such programs, referred to as demand-side management (DSM) programs, are designed to program consumption or reduce it [6].

A DSM program provides support for power grid functionalities in various areas, such as electricity market control, infrastructure maintenance, and management of decentralized energy resources [7]. In electricity markets, it informs the load controller about the latest load schedule and possible load reduction capabilities for each time step of the next day. Using this procedure, it schedules the load according to the objectives of interest associated with the power distribution systems [8], [9]. The load shapes indicate industrial or residential consumers' daily or seasonal electricity demands between peak hours (PHs) and off-peak hours (OPHs). These shapes can be modified by six techniques [9], [10]: peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape.

Both peak clipping and valley filling are techniques for controlling loads directly. While peak shaving is concerned with peak load reduction, valley filling takes into consideration load shaping on off-peak loads. The best and widely employed method of managing load in today's electricity networks is load shifting. It involves shifting the load from the PH to the OPH. In the case of conservation strategy [10], demand reduction methods are used at the customer's end to obtain optimal charging patterns. If the load requirement is greater, the daily response is optimized using distributed energy resource load augmentation techniques [11], [12].

The principal aims of the DSM are to remodel a load profile and regulate the highest and lowest day-to-day power requirements to make the most of power sources and prevent the need to construct new generation power plants. This may result in the consumption of electricity. Many DSM technologies are designed to maximize efficiency to avoid or reduce the need to build more power plants. Further reasons to implement DSM techniques include social relations and environmental considerations, by modifying customers' power consumption patterns at peak and off-peak times to conserve power [13].

In this paper, three DSM methods were applied for a microgrid of model photovoltaic solar panels with real measured demand as well as radiance data to show the benefits of energy efficiency which is currently lacking on the island of Djerba, Tunisia. A model system was simulated in the MATLAB software using the DSM load-carrying capability. The principal research contributions of this work are summarized in detail below.

- The DSM methods of load shifting, load capping, and valley filling were applied on a microgrid model of the island of Djerba, Tunisia.
- Substantial power consumption savings can be realized through corresponding generation and load demand requirements without deep-discharging of battery storage.
- The global load profile is enhanced by exploiting available renewable energy resources to a large extent, thus minimizing total reliance on the storage system.

The remaining sections in this paper are structured in the following way. In Section II, we describe the configuration of the microgrid, in Section III we present the DSM method and its features, and in Section IV we present the DSM problem. Section V presents the detailed results and discussion, while Section VI concludes the paper.

II. CONFIGURATION OF A MICROGRID SYSTEM

A schematic representation of the proposed microgrid system is shown in Fig. 1. This system comprises three different groups of units. The first includes energy production units with photovoltaic panels. The second is comprised of energy consumption units, principally residential electrical loads. The third is dedicated to energy storage, as represented by a typical battery bank.

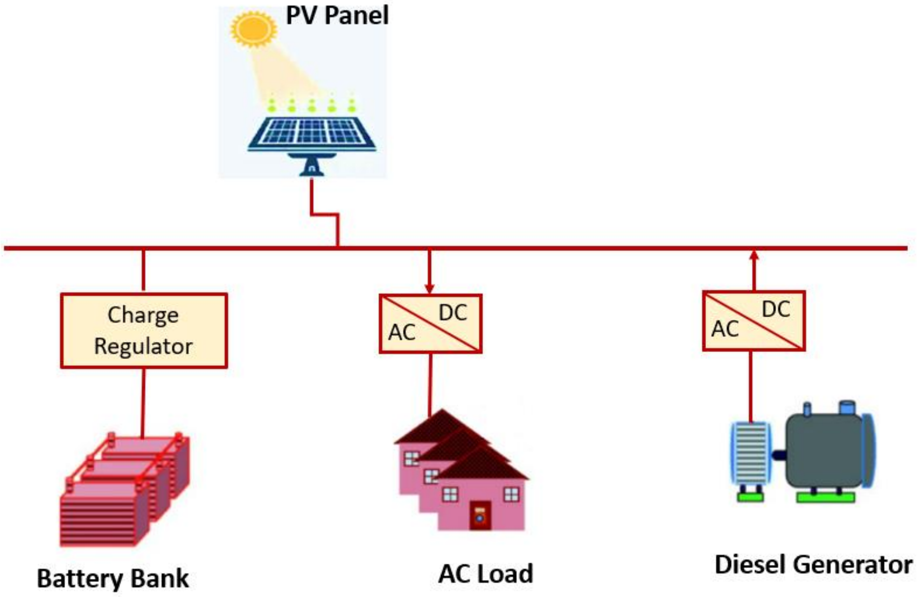

Fig. 1. Schematic representation of the proposed microgrid system.

III. DEMAND SIDE MANAGEMENT

Demand side management (DSM), also known as energy demand management, consists of implementing strategies and procedures to improve the efficiency of an energy system on the supply and demand side. It enables us to manage, control, influence, and generally minimize power consumption, giving us a better perspective on the potential of renewable energy systems, or making effective use of those systems that have been installed. Such strategies can provide substantial financial advantages to energy end-users and reduce carbon emissions. The measures aimed at reducing energy consumption do not necessarily have to be costly, and can often even be provided free of charge, making them easy to implement in development regions [14]. According to the [15] definition of demand-side management, DSM comprises three main concepts: demand response, energy efficiency, and energy conservation.

The demand response (DR) approach involves modifying customer electricity consumption, shifting load from periods of peak demand to off-peak times, and using active demand pricing strategies: by modifying electricity prices over time (when it's off-peak, it's less expensive) or through inducement payments, these offer customers an incentive to reduce their demand for energy at a particular period of the day. DR is usually linked to advanced energy metering technologies that provide information to end-users on their consumption of energy.

DSM can be implemented in several ways, and Fig. 2 shows several categorizations of DSM with associated load shapes. Peak clipping aims at reducing demand during peak hours. Utilities achieve this control by incentivizing customers not to consume power during peak hours, directly controlling loads, or setting up higher prices. The method is helpful in cases with no possibility of setting up or installing new power plants [16]. Valley filling focuses on raising usage during periods of very low electricity profile to keep demand and supply balanced, avoiding the startup and ramp-up costs of generators [17]. Load growth is more common when using electric vehicles, where customers are encouraged to increase usage up to a certain threshold for grid stability [18]. Load shifting gives consumers options to shift their usage pattern to off-peak hours based on cheap tariffs.

It is the combination of load clipping and valley filling [19], [20]. Flexible load shaping is when consumers are flexible enough to shift their loads to different low-usage slots. Usually, customers willing to participate in this are identified and incentivized for their participation [16]. Energy efficiency is when the overall load profile is lowered throughout the day by using more energy-efficient devices or through cyclic operation [21].

A demand curve is formed by various DSM technologies [21], as illustrated in Fig. 2, additionally, but without limitation:

- Load shifting: The main objective of load shifting is the transfer of load from peak to off-peak hours.
- Conservation: The best-known approach to reduce global consumption of electricity, and not only at peak periods.
- Peak clipping: The main aim of this strategy is to reduce demand at peak times (e.g. 7 p.m.). Energy consumption is reduced by the control of equipment that can be switched off, like air conditioners or heaters, by the customer or the electricity supplier.
- Valley fill: Under valley fill, the demand for load increases in off-peak hours and reduces during peak hours.
- Load growth: Unlike the conservation approach, with load expansion, the overall amount of electricity sold (off-peak and on-peak) increases.
- Load Shape Flexibility: With this technique, the utilities have the power to discontinue loading as required, and without notifying the customer. Changes in the quality or quantity of service are generally described as flexible load shapes.

Practically all the DSM programs are designed and implemented to optimize the use of existing power plants. Another crucial objective is to avoid, defer, or delay the construction of much-needed new power plants (both renewable and conventional).

A. Demand Response

These programs are recent developments in demand-side management, involving consumers' participation in improving their energy consumption patterns in response to instantaneous price variations [21]. They are seen as an effective solution to some of the problems of deregulated power systems.

Demand response enables industrial, commercial, and residential customers to optimize their electricity consumption to obtain reasonable prices and improve grid reliability. In other words, it can modify electrical energy consumption to reduce peak loads and shift consumption to off-peak hours [22]. Demand response methods generally fall into two categories: electricity price-based programs and incentive-based programs. Fig. 3 illustrates this classification.

In this article, among the various demand management programs, the load shifting program has been used to reduce peak load and increase load during periods of low demand (i.e. peak load reduction and load trough filling). There are also restrictions on time-of-use shifting for each of the loads.

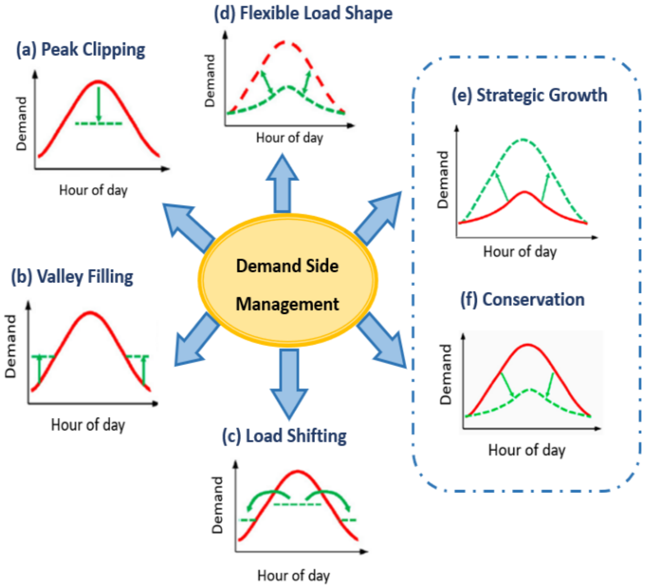

Fig. 2. Classification strategies for demand-side management.

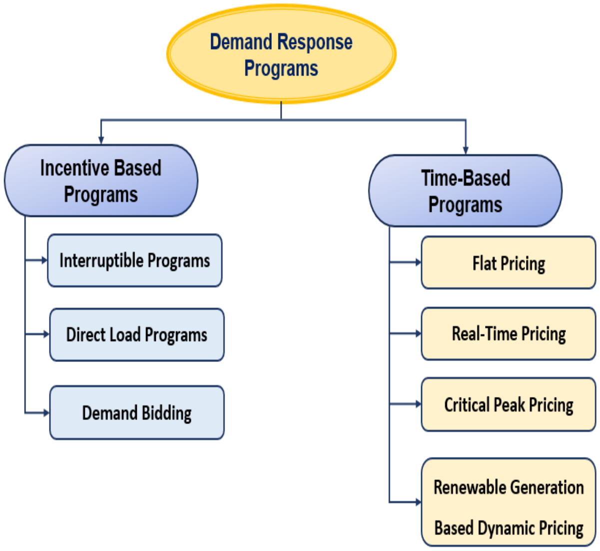

Fig. 3. Different types of demand response programs.

To illustrate the process of implementing the Demand Side Management (DSM) method, the following pseudo-algorithm describes the key steps in the approach used:

Algorithm 1: Pseudo-code of the DSM proposed algorithm

```
Step 1
Enter data, including renewable energy production (solar irradiance), load demands, system parameters (PV area, yield), and threshold values for demand-side management (DSM).
Step 2
Calculate hourly energy production using input data and system parameters.
Step 3
Initialize load curve for DSM operations (load shifting and peak shaving).
Step 4
Identify periods with significant energy production.
Determine the time of maximum energy production.
Step 5
For each period of the load curve:
If the load exceeds the DSM threshold:
Calculate excess load above a threshold.
Reduce the load to a threshold level.
Redistribute excess load to adjacent periods with sufficient energy production (Load Shifting).
Step 6
For each period of the modified load curve:
If the load still exceeds the threshold:
Limit load to threshold level using Peak Clipping.
Step 7
Apply the Valley Fill method:
Identify periods of low demand (valleys) in the load curve.
Redistribute non-critical load from high-demand periods (after Load Shifting and Peak Clipping) to these low-demand periods to smooth the load curve.
Step 8
Repeat steps 5, 6, and 7 until the load curve is optimized.
Step 9
Return the optimized load curve and analyze the results.
End
```

IV. PROBLEMATIC DEMAND MANAGEMENT SYSTEM

For a microgrid system that includes the use of photovoltaic (PV) generation, optimization of power consumption is a crucial factor in reducing costs and maximizing the utilization of renewable resources. Two strategies commonly used to meet this objective are demand-side management (DSM):

- Peak Clipping: The purpose of this strategy is to reduce the maximum power requirement by clipping and reducing loads above a specific level.
- Load Shifting: With this approach, loads are shifted during peak periods to periods when photovoltaic generation is most available, thus minimizing dependence on conventional sources.
- Valley Fill: In this method, the loads in periods when demand is low are increased to fill the valley of demand, thus leveling out demand and optimizing the use of available resources, thereby minimizing variations and dependence on traditional sources of energy.

A. System Modeling Equations

1) Power generated by the photovoltaic system: The output generated by the photovoltaic panels, P_{PV} (t), is given in the equation below:

$$P_{PV}(t) = \eta_{PV} \times A_{PV} \times I_{rr}(t) \tag{1}$$

Where:

η_{PV}: representing the efficiency of the photovoltaic panels.

A_{PV}: represents the overall area of the panels in m2.

$I_{rr}(t)$: represents the solar radiation in W/m2 at the time t.

2) Peak clipping strategy: The peak reduction is achieved by setting a maximal limit P_{seuil} above which the load output is restricted:

$$P_{load\_clipped}(t) = \min(P_{load}(t), P_{seuil}) \tag{2}$$

Where:

$P_{load}(t)$: is the initial load at the current time.

P_{seuil}: is the limit value selected.

3) Load shifting strategy: The load shift consists of shifting the surplus charge from the peak times to the times when the photovoltaic generation is highest. If at a given time t, the $P_{load}(t)$ load is above the limit, the $P_{exces}(t)$ surplus is determined as described below:

$$P_{exces}(t) = P_{load}(t) - P_{seuil} \tag{3}$$

This excess is allocated to the hours of most significant PV generation (defined as more than 50% of the maximum PV generation):

$$P_{load\_shifted}(h) = P_{load\_shifted}(h) + \frac{P_{exces}(t)}{N_{PV}} \tag{4}$$

Where:

h: denotes a time selected for redistribution.

N_{PV}: is the total number of hours selected for redistribution.

4) Valley-filling strategy: A valley fill approach involves the redistribution of under-utilized capacity at times of low demand (off-peak hours) to cover the valleys in the load curve. If the load $P_{load}(t)$ is less than a predetermined level at a given time t, the load deficit $P_{deficit}(t)$ is calculated in the following equation:

$$P_{deficit}(t) = P_{seuil} - P_{load}(t) \tag{5}$$

To smooth demand, this deficitis then assigned to the periods of lowest photovoltaic production (defined as less than 50% of peak photovoltaic output):

$$P_{load\_filled}(h) = P_{load\_filled}(h) + \frac{P_{deficit}(t)}{N_{low\_PV}} \tag{6}$$

Where:

h: represents a period selected for the redistribution.

N_{low_PV}: represents the number of total hours selected for the redistribution when the photovoltaic output is low.

5) Mathematical formulation of optimization: The general objective of the problem is to minimize the peak loads and maximize the utilization of renewable energy. The problem can be expressed in the following terms:

$$\min\left(\max P_{load\_final}(t)\right) \tag{7}$$

With the constraints below for peak clipping:

$$P_{load\_final}(t) \leq P_{seuil} \tag{8}$$

Excess load is redistributed in a balanced manner during load shifting, with consideration of PV generation. This approach ensures that load adjustments align with solar energy production, optimizing efficiency and reducing reliance on non-renewable sources

V. RESULTS AND DISCUSSION

A. *Basic Case*

This study utilized a dataset from a microgrid located on the island of Djerba in Tunisia, with a maximum solar power capacity of 889.128 kW. This remote microgrid is designed to supply power to the island's communities, contributing to the region's energy independence and sustainability. The analysis was conducted over a week during which irradiance measurements were taken, to assess the load profile and irradiance patterns to evaluate the solar power generation of the system. Fig. 4 illustrates the power consumption over this period, Fig. 5 presents the irradiance data, and Fig. 6 represents the photovoltaic system’s power output. Comparing these results with similar studies in microgrid systems reveals consistent trends in power production and consumption patterns, particularly in remote island contexts. Studies conducted in other island communities show similar variability in solar irradiance and load profiles. However, our findings suggest that the Djerba microgrid demonstrates higher efficiency in converting solar energy, likely due to optimized PV system design and favorable climatic conditions. This has important consequences for isolated microgrid design and operations, underlining the necessity for an enhanced energy control strategy. In comparison to earlier research, this study underscores the potential for enhancing load-shifting techniques and optimizing storage systems, which could further reduce reliance on backup generators and improve overall energy efficiency in isolated microgrids.

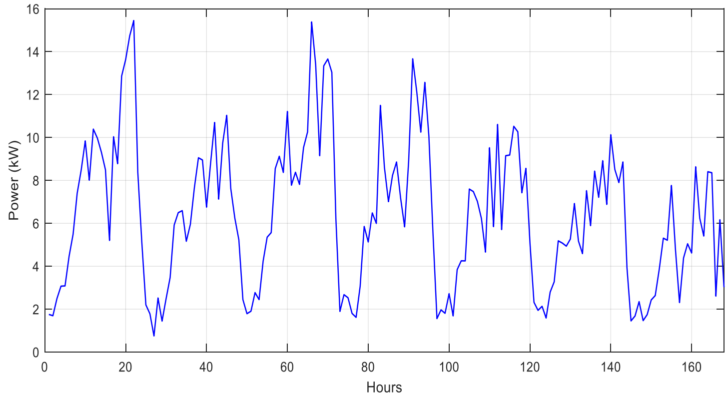

Fig. 4. Weekly load power analysis.

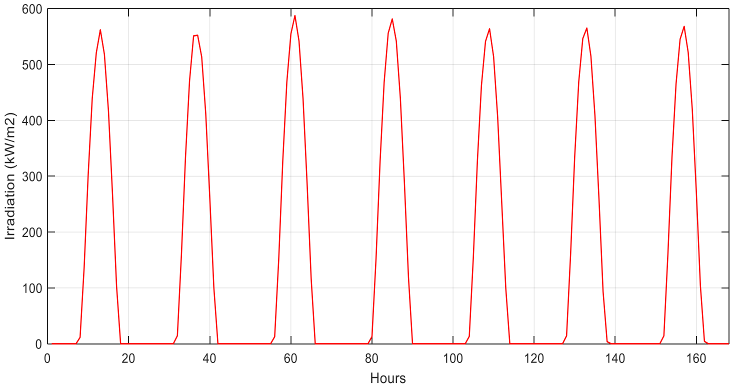

Fig. 5. Weekly analysis of solar irradiation levels.

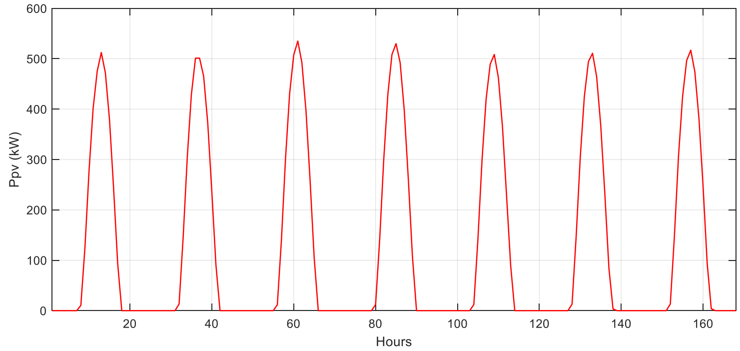

Fig. 6. Weekly performance analysis of photovoltaic power system.

B. Effect of Peak Clipping

A controller or switching equipment carries out the peak clipping process. The consumption is continuously supervised and when it rises to levels that give reason for concern, the controller can switch off specific loads to minimize the demand. The loads that can be disconnected are ranked in order of priority, and classified as transferable and non-transferable.

Fig. 7 illustrates the impact that peak clipping has on the hourly load. The blue curve shows the initial load, with significant daily fluctuations. The second curve represents the load after peak shaving, with load values restricted to a 10-kW threshold. The peak clipping process limits the peak consumption to a specified threshold, thereby preventing system surges and stabilizing the energy demand. It effectively holds the load below a monitored level, thus minimizing the potential for power system instability and overloading.

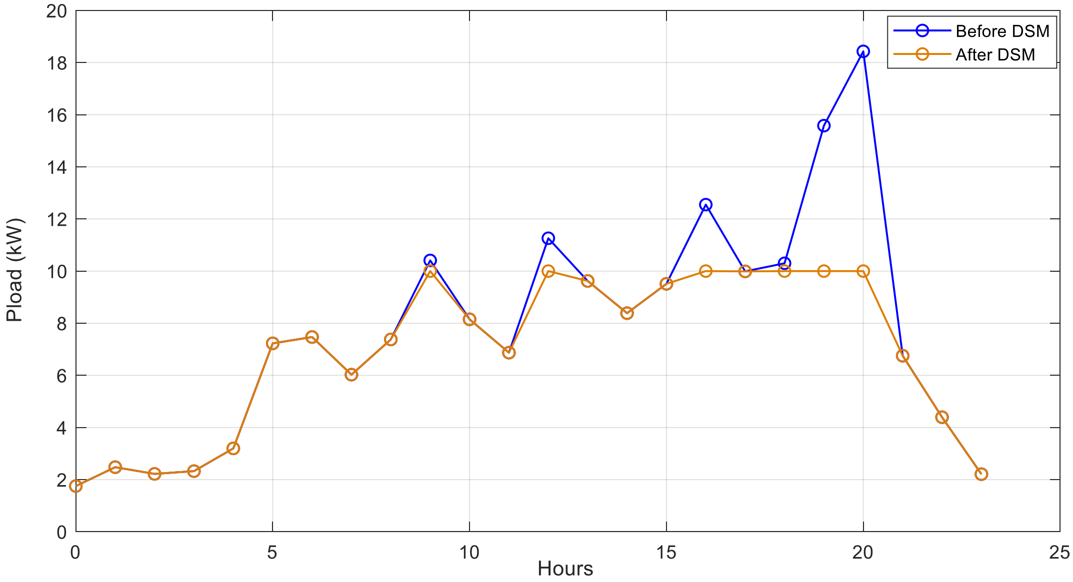

Fig. 7. Impact of peak clipping DSM on load profile.

C. Effect of Load Shifting

Fig. 8 presents an example of demand-side management (DSM) implementation through load shifting. An analysis of the results indicates that load shifting has been strategically applied over 24 hours, with most operations scheduled during peak solar irradiation to minimize the need for energy storage. By aligning load utilization with times of highest production, the system maintains a sufficient margin to supply critical loads during peak demand periods, thereby enhancing system stability and preventing overloads. The impact of load shifting on hourly load is illustrated in Fig. 8. The initial load, shown in blue, reveals significant peaks during high-demand periods, while the second curve represents the load after implementing load shifting, where consumption peaks have been effectively smoothed out. This method redistributes surplus load to hours of higher photovoltaic production, resulting in a more uniform demand distribution. Comparative analysis with similar studies shows that load shifting is a widely recognized strategy for optimizing energy consumption in microgrids, demonstrating its effectiveness in reducing peak loads and alleviating pressure on the power supply system. Our findings corroborate previous research, highlighting that load shifting not only enhances system reliability but also supports sustainability efforts by maximizing the utilization of renewable energy resources.

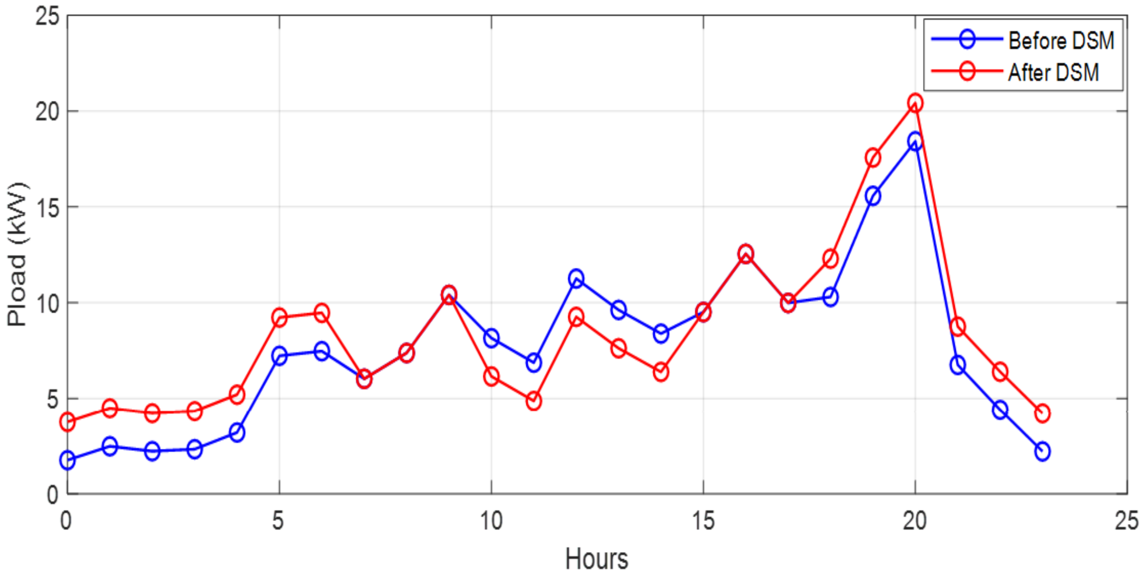

Fig. 8. Impact of Load Shifting DSM on 24-Hour Load Profile.

D. Effect of Valley Fill

The Valley Fill approach is implemented in the form of an intentional increase in load during times of reduced demand, usually monitored by an appropriate controller or energy management system. As consumption falls to a critical level, a controller may enable supplementary loads, prioritized based on their ability to transfer loads without affecting the global system. The loads that can be shifted are increased to compensate for any dips in the power curve.

Fig. 9 shows the effect of the Valley Fill method on the load per hour. The initial blue curve represents the load, characterized by steep peaks and troughs during certain periods of the day. The other curve shows the load after Valley Fill has been applied, with the troughs filled to smooth demand. This stabilizes power demand by preventing excess fluctuations, thus reducing the risk of under-utilizing the available energy resources and improving global system efficiency.

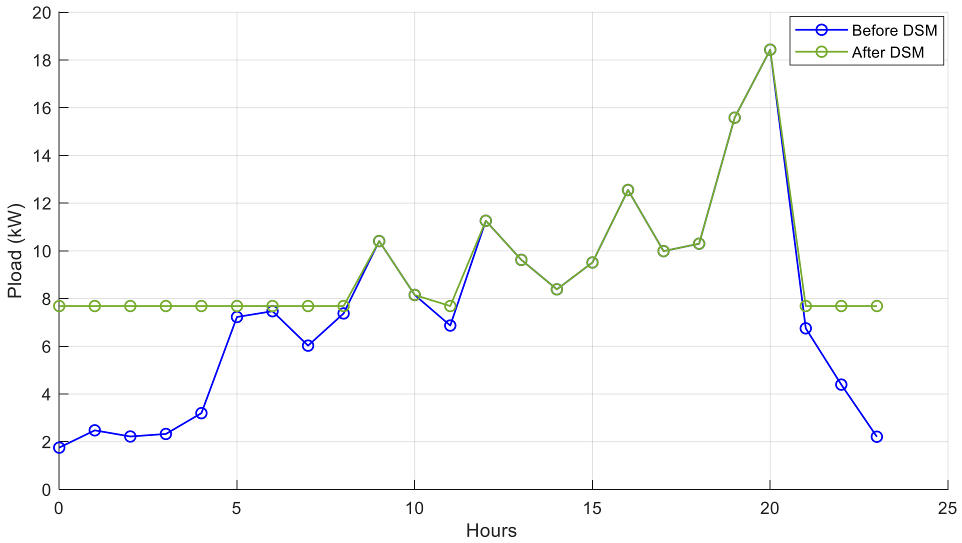

Fig. 9. Load Profile Analysis Before and After Valley Fill DSM.

Shifting reduces power demand and inconvenience in peak hours by switching surplus demand away from the system. Load shifting enables off-peak hours to be rescheduled with a smaller energy consumption reduction, as illustrated in Fig. 10.

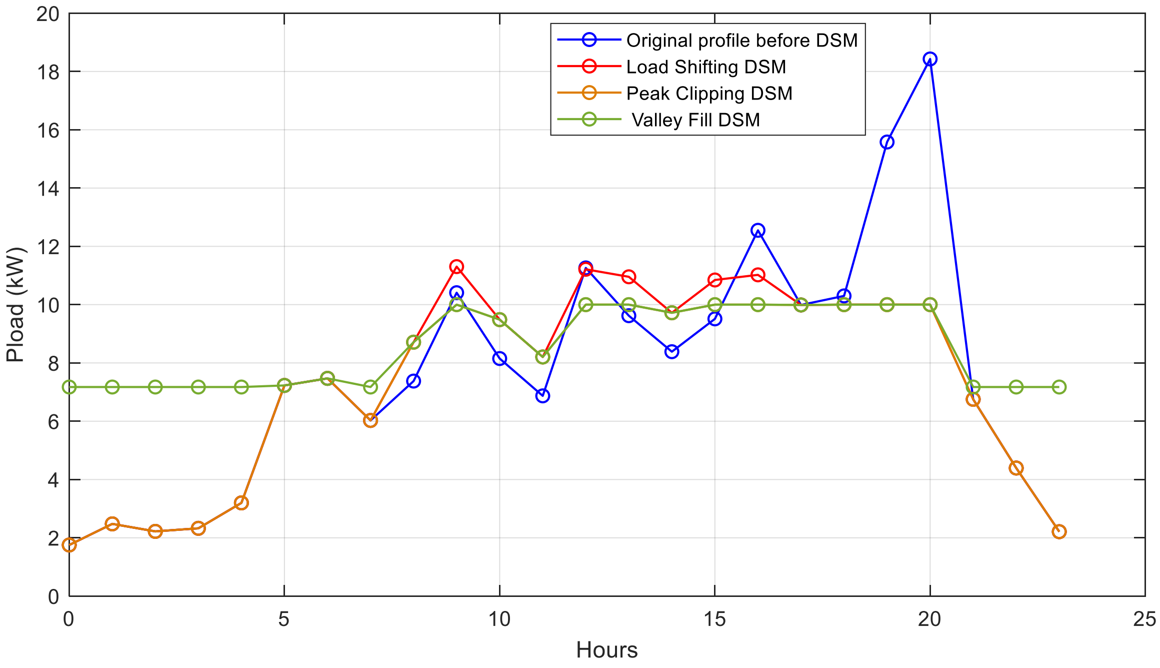

Fig. 10. The impact of DSM strategies on load profile: load shifting, peak clipping, and valley fill.

VI. CONCLUSION

This study examines energy management in a solar-powered microgrid using the Demand Side Management (DSM) method. The DSM approach was applied to a 24-hour solar microgrid on the island of Djerba, Tunisia, utilizing data from NASA. The results show that after implementing DSM strategies, the load profile aligned more closely with solar generation, as much of the energy demand was shifted to periods of higher solar output. This approach provides a framework for achieving more resilient isolated microgrids by optimizing the use of renewable energy. Additionally, reducing energy consumption in the microgrid enhances system stability and offers cost savings. By improving the balance between load and generation, the method also reduces the need for extensive storage capacity, especially during periods of low solar power availability.

REFERENCES

[1] S.Onika, S. Peyghami, A. Sangwongwanich, F. Blaabjerg, “Reliability aspects in microgrid design and planning: Status and power electronics-induced challenges, Renewable and Sustainable Energy Reviews,” vol.159, pp.1364–0321,2022.

[2] Bouaziz, B., Bacha, F. Direct power decoupling control using optimal switching table combined with virtual flux estimator for PWM rectifier. Electr Eng 106, 1605–1617 (2024). https://doi.org/10.1007/s00202-023-02179-6

[3] F.Yang, and X. Xia,“Techno-economic and environmental optimization of a household photovoltaic-battery hybrid power system within demand side management,” Renew. Energy 108, 132–143,2017.

[4] A.Maleki, Z. Eskandar Filabi, M.ANazari, “Techno-Economic Analysis and Optimization of an Off-Grid Hybrid Photovoltaic–Diesel–Battery System: Effect of Solar Tracker,” Sustainability, vol.14, 7296,2022.

[5] M.Usman, M.Khan, A.Rana, “Techno-economic analysis of hybrid solar-diesel-grid connected power generation system, ” Journal of Electrical Systems and Information Technology,2017.

[6] S. Nanibabu, S. Baskaran, P. Marimuthu, “Realization of Demand Side Management in Smart Grid,” Optimization Techniques for Hybrid Power Systems, 378–406, 2024.

[7] J. Yang, W. Xu, K. Ma, J. Chen, W. Guo, “Integrated demand-side management for multi-energy system based on non-cooperative game and multi-energy pricing,” Sustainable Energy, Grids and Networks, vol.34, 2352–4677,2023.

[8] R. Ouederni, B. Bouaziz and F. Bacha, “Design and evaluation of an island's hybrid renewable energy system in Tunisia,” 2022 5th International Conference on Advanced Systems and Emergent Technologies (IC_ASET), Hammamet, Tunisia, 2022, pp. 418-423,2022.

[9] P.D.Necoechea-Porras, A.López, J.C. Salazar-Elena, “Deregulation in the Energy Sector and Its Economic Effects on the Power Sector: A Literature Review,” Sustainability, vol. 13, 3429,2021.

[10] A.Shewale, A.Mokhade, N.Funde, N.D.Bokde, “A Survey of Efficient Demand-Side Management Techniques for the Residential Appliance Scheduling Problem in Smart Homes,” Energies, vol.15, 2863,2022.

[11] B. Williams, D. Bishop, P.Gallardo, J.G. Chase, “Demand Side Management in Industrial, Commercial, and Residential Sectors: A Review of Constraints and Considerations,” Energies, vol.16, 5155,2023.

[12] R.Ouderni, B.Bouaziz, and F. Bacha, “A Case Study of Hybrid Renewable Energy System Optimization for an Island Community based on Particle Swarm Optimization,” Engineering, Technology & Applied Science Research. vol.14, 3, 14367–14373,2024.

[13] S. N. Bragagnolo, J. C. Vaschetti, and F. Magnago, “A technical and economic criteria comparison on demand side management with multi-level optimization model,” IEEE Latin America Transactions 19(9): 1494–1501,2021.

[14] R. Ouederni, B. Bouaziz, F. Bacha, “ Modeling and cost optimization of an islanded virtual power plant: A case study of Tunisia,” Turk J ElectrPower Energy Syst, 2(2), 168–179, 2022.

[15] MA.Bhaagat, NH.Mirjat, SA.Khatri, A.Mahar, MA.Raza, Demand Side Management for the Energy-Efficient Future of Pakistan Using a Low Emission Analysis Platform, Engineering Proceedings, vol. 46(1):28,2023.

[16] S. Panda, S. Mohanty, P.K.Rout, B.K.Sahu, M.Bajaj, H.M.Zawbaa, S.Kamel, “Residential Demand Side Management Model, Optimization and Future Perspective: A Review,” Energy, vol.8, 3727–3766,2022.

[17] S.Mujeeb, TA.Alghamdi, S.Ullah, A.Fatima, N.Javaid, T.Saba, “Exploiting Deep Learning for Wind Power Forecasting Based on Big Data Analytics,” Applied Sciences, vol. 9(20):4417,2019.

[18] S. Maharjan, Y. Zhang, S. Gjessing, D.H.K. Tsang, “User-Centric Demand Response Management in the Smart Grid with Multiple Providers,” IEEE Trans. Emerg. Top. Comput, vol.5, 494–505,2017.

[19] G.H.Philipo, Y.A.Chande Jande, T.Kivevele, “Demand-Side Management of Solar Microgrid Operation: Effect of Time-of-Use Pricing and Incentives,” J. Renew. Energy 2020, 6956214,2020.

[20] R. Ouederni, B. Bouaziz, F. Bacha, “Optimization of a Hybrid Renewable Energy System Based on Meta-Heuristic Optimization Algorithms,” International Journal of Advanced Computer Science and Applications, vol.15(7), 2024.

[21] P.Palensky, D. Dietrich, “Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads,” IEEE Trans. Ind. Inform, 7, 381–388,2011.

[22] S.Feuerriegel, N.Dirk, “Integration scenarios of Demand Response into electricity markets: Load shifting, financial savings and policy implications,” Energy Policy vol. 96, 231–240,2016.