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To Enhance the Operational Planning of an Independent Microgrid Using a Novel Combination of Demand Response Programs

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ABSTRACT

Providing electricity in rural or isolated areas involves high capital costs due to the cost of constructing transmission and distribution facilities. An independent Microgrid consisting of distributed generations (including both renewable and non-renewable energy sources) near the load could be an effective alternative. However, the unpredictability of renewable energy sources like wind and solar creates a problem in Microgrid operation, as there are instances when generation may not be enough to satisfy peak demand. Energy storage technology is generally employed to address this uncertainty. The Demand Response Program (DRP) is another technique that makes the Microgrid operation reliable and safe by lowering peak demand and switching it to low-load periods. This article addresses the short-term Unit Commitment Economic Dispatch (UCED) problem for an Independent Microgrid to reduce the overall operating costs using various DRPs. This paper presents a novel combination of DRP to enhance Microgrid's operation and financial effectiveness and benefit its users. DRP modeling is done based on price elasticity and consumer benefit models. Mixed-integer nonlinear programming (MINLP) is used to formulate and solve the UCED problem in the GAMS software. 11-Bus Microgrid is considered for demonstration. According to the optimization results, implementation of TOU-RTP-CPP-DLC DRPs reduces the operating cost by 13.68%, 13.31%, 17.16%, and 8.41%, respectively, with reduced load shedding. Consumers get benefits only in DLC-DRP. The proposed TOU+DLC-DRP combination reduces the operating costs by 13.48% with increased consumer benefits compared to DLC-DRP alone. Therefore, the proposed method is profitable for both the Microgrid operator and its users.

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1. INTRODUCTION

In today's global context, distributed generation (DG) is prioritized over conventional generation due to increased electricity demand, decreased fossil fuel resources, and a reduced carbon footprint. DGs include renewable energy sources (RES) like solar, wind, etc., and non-renewable energy sources like micro-turbines, combined heat and power systems, etc. DGs have many benefits, including improved power quality, reduced power losses, and improved reliability. However, they harm the safety and security of the power grid [1]. Microgrids are considered a solution for these issues. Microgrids are compact power networks consisting of distributed generators, an electricity storage system, controllable demands, and a control unit. Typically, they are linked to the larger grid, but in an emergency, they can be detached from the mains and work independently in an isolated mode [2-6]. Recently, more attention has been given to Independent Microgrids to supply reliable and economical power supply and grid connection problems from green energy sources. Also, the power shortage problem in remote and mountainous areas can be solved [7]. In previous work, researchers have focused on the design, optimization, and simulation of an Independent Microgrid [8-9].

Battery energy storage is an essential component in an independent Microgrid to handle variable renewable power generation and ensure the stable operation of the Microgrid, [10]. Another solution is to implement the DR Program (DRP). As per the US Department of Energy (DOE), DRP is stated as variation in end-user energy consumption through electricity price changes or the incentive given to them to lower energy use at times of high market prices [11-12]. DRP reduces the power demand in peak periods and shifts it to low-load periods, thereby avoiding the need for expensive generators in standby mode that will reduce the operational cost [13-14]. DRPs are categorized into Price-based and Incentive-based DRPs. In Price-based DRP, consumers vary their electricity usage patterns depending on prices, and in an Incentive-based DRP, the changes are made depending on an incentive given to consumers during peak periods [15]. A DRP model based on price elasticity is presented in [16].

To improve the operation of Microgrid and increase its economic efficiency, unit commitment (UC) is performed. The UC problem determines the on/off status of the power production units for the specified demand [17]. The power output of committed units is then calculated using economic dispatch (ED) to satisfy the demand with minimum operating costs. In Ref. [18], dynamic economic dispatch is performed with a Price-based DRP (TOU). An emergency DRP (EDRP) and TOU DRP are modeled in [19-20] without considering an objective to reduce the operating cost for 24-hours. The decomposition technique is used to model the real-time pricing (RTP) DRP to benefit consumers by changing electricity use depending on dynamic prices [21]. Ref. [22] examined the impact of EDRP on Microgrid reliability considering the generator outage. Ref. [23] proposes a dual optimization model to lower the operating price and transmission losses in grid-connected Microgrids using TOU and RTP DRPs. Ref. [24] presents a stochastic optimization model to maximize the profit of an independent Microgrid using an Incentive-based DRP to improve the reliability of the Microgrid.

A new methodology for implementing Incentive-based DRP in the day-ahead market is proposed in [25]. This work differs from the previous one as variable incentives are given to the participating consumers, depending on the hourly peak intensity. Both types of DRP are incorporated into Microgrid operations [26]. Ref. [27] used fuzzy self-adaptive particle swarm optimization (FSAPSO) to perform economic-emission dispatch in Microgrid, which outperforms other evolutionary techniques like PSO and Genetic Algorithm (GA). The impact of different numbers of customers and installed wind capacity based on various Microgrid operational factors has been studied [28]. Various types of DRPs based on the exponential model are used in [29] for scaling Microgrids. Operation management of a Microgrid tied to the utility grid is provided in [30] to reduce running costs and pollution using an Incentive-based DRP model with an exponential function. Ref. [31] introduces an optimal scheduling approach to lower a grid-tied hybrid system’s overall operational cost by utilizing various Microgrid components like DR, EV, and battery.

Ref. [32] presents a literature review on Microgrid planning considering consumer participation in DRP. Long-term planning and short-term operation of a residential Microgrid are performed using HOMER software, considering environmental aspects [33]. Unlike existing work, which employed mainly Time-of-use (TOU) DRP for Microgrid sizing, the presented work analyzes the impact of dynamic pricing on Microgrid planning results. Ref. [34] presents a stochastic unit commitment model to minimize the total production cost for an independent Microgrid considering the demand forecasting error. However, this paper does not consider the uncertainty of renewable generation. Ref. [35] used mixed integer programming (MIP) to perform day-ahead scheduling of isolated Microgrids incorporating an incentive-based DRP. The authors also introduce a cost model for vanadium redox batteries to enhance the efficiency of Microgrids. The authors confirm the superiority of the proposed model over GA. Ref. [36] used Mixed Integer Linear Programming (MILP) to develop an optimization model that reduces the cost of buying energy from the grid and DR implementation costs. The authors use the p-efficient method to convert the uncertain solar output to a deterministic one. Ref. [37] presents a two-level optimization approach using an Improved Genetic Algorithm and MILP for EMS in Microgrid planning. The proposed model does not incorporate the DR program.

Ref. [38] used AIMMS software to reduce the daily operating costs of networked Microgrids implementing an Incentive-based DRP using AIMMS software. However, the impact of the different levels of consumer participation in Microgrid operations has not been studied. A bi-level scheduling method utilizing a real-time pricing DRP was suggested in [39]. The upper and lower-level goals are to reduce operating costs and user costs, respectively. The authors developed the Jaya-IPM by adding the interior point method to the Jaya algorithm and confirmed that it was better than the hybrid intelligent algorithm and CPLEX solver. To reduce the annual cost and sizing, optimization of an independent Microgrid consisting of

PV-Wind-PHEV is performed in [40] using DRP. To model the uncertainty in renewable generations, the authors used the Latin hypercube sampling (LHS) method to generate various scenarios, and the generated scenarios are reduced by using the K-mean clustering algorithm. Price-based DRP is used considering the classified load model of consumer equipment. Ref. [41] proposes a stochastic energy and reserve scheduling of the WT-PV-PAFC-MT-battery Microgrid connected to the grid. The authors used differential evolutionary (DE) and modified PSO algorithms to reduce operating costs and emissions by incorporating demand bidding, ancillary service market program, and TOU DRP. The simulation is performed for both deterministic and stochastic scenarios. Power dispatch of isolated and grid-tied Microgrid is presented in [42], using DRPs, to reduce operational costs, emissions, and power losses. The multi-objective optimization problem is formulated using MILP and solved in the GAMS environment. Battery charge and discharge are determined using fuzzy logic. Simulation is performed for different evolutionary algorithms such as PSO, GA, TS, ABC, etc., and the author confirmed that the proposed method outperforms. Ref. [43] proposes daily energy management for Microgrids to reduce operational costs, emissions, and power losses using incentive-based DRP. The ED problem is solved using a mix of PSO and fuzzy. The 2-point estimate method is used to control the uncertainty in renewable generations and load. Ref. [44] proposes a novel CSAJAYA algorithm (combination of the crow search algorithm and the JAYA algorithm) to perform economic-emission scheduling using TOU DRP. The presented algorithm has superiority due to low standard deviation and fast search.

It is evident from the literature analysis that DRPs have been implemented to solve the UCED problem in Microgrid operations in independent or grid-connected mode with multiple objectives, such as minimizing operating costs and emissions and increasing system reliability, etc. To optimize the Microgrid operation, most of the existing work has used classical, evolutionary, and heuristic techniques using either Price-based (TOU, RTP, CPP) DRPs or Incentive-based (DLC, EDRP, I/C, CAP) DRPs alone. In a Price-based DRP, operating costs are reduced, but consumers' profit is negative (monetary loss), whereas in an Incentive-based DRP, the consumers receive a benefit. Therefore, this article's primary goal is to solve the UCED problem for an Independent Microgrid to reduce overall operating costs by introducing a combination of Price-based and Incentive-based DRP. The optimization problem is solved using GAMS (General Algebraic Modeling System), whose performance is better than other evolutionary techniques, as found from literature analysis. Hence, this article's contribution comprises

1. A new combination of DRPs for an independent Microgrid is proposed to reduce operating costs and increase consumers' benefits.
2. Various DRPs have been implemented to reduce Microgrid load shedding.
3. Evaluated the impact of running an increased level of DRPs on Microgrid operation.
4. The proposed program is also applicable to Microgrids in grid-connected mode.

2. RESEARCH METHOD

2.1. Microgrid Configuration

This article considers an Isolated Microgrid for power generation, which includes a microturbine (MT), fuel cell (FC), wind turbine (WT), solar photovoltaic (PV), and a battery [26, 27]. Table I gives the power capacity of all sources of considered Microgrid. The capacity of wind and solar units is 15 KW and 25 KW.

Fig. 1 gives the estimated demand for Microgrid, wind, and solar power output per unit for 24 hours. For a specific day, the total demand of the Microgrid is 1152 KW with a peak load of 90 KW. The demand curve is segregated into three parts: a low-load period (1-7 and 20-24), an off-peak load period (8 and 17-19), and a peak load period (9-16). Figure 2 displays the real-time electricity prices of Microgrid for energy trading.

Table 1. Installed Power Sources [27]

Power Sources	Minimum Power (KW)	Maximum Power (KW)	Bids (€ct/kWh)	Start-up/ Shutdown Cost (€ct)
Microturbine	6	30	0.457	0.96
Fuel cell	3	30	0.294	1.65
Photovoltaic	0	25	2.584	0
Wind turbine	0	15	1.073	0
Battery	-15	15	0.200	0

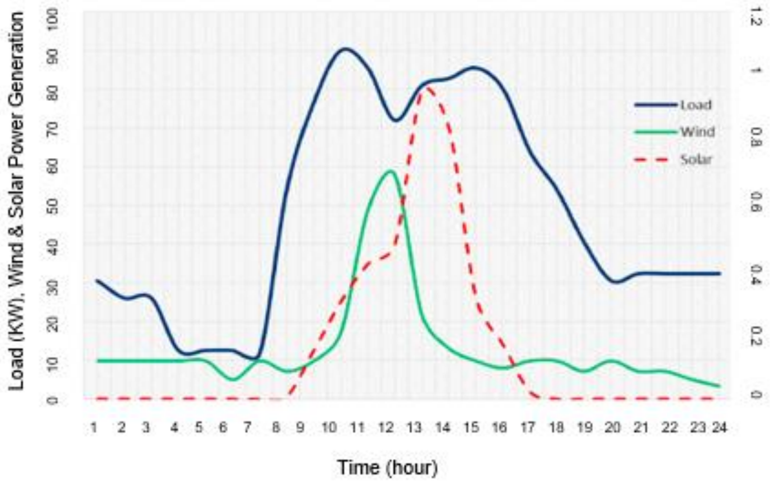

Figure 1. Estimated Load curve and solar and wind power generation in p.u. of the 11-bus Microgrid [26]

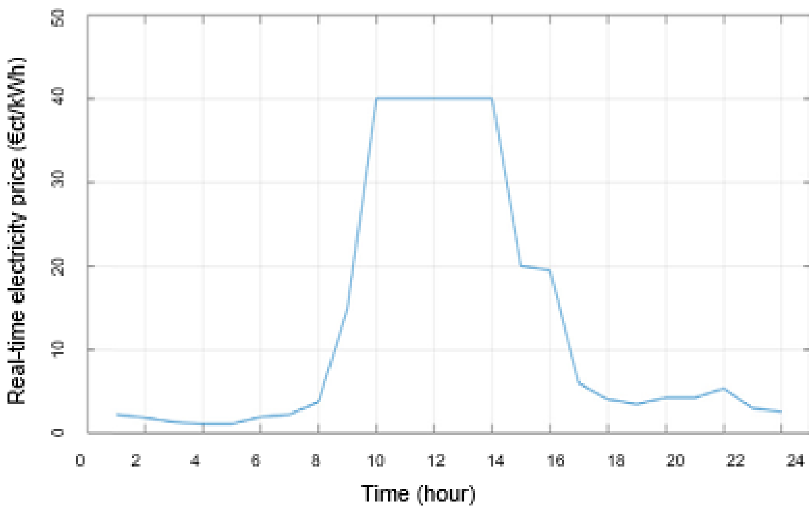

Figure 2. Real-time electricity prices [26]

For Microgrid operation to be reliable, a 30kWh battery is used with a minimum charge and discharge rate of 15 KW. The battery's initial state is 20 kWh with 95% charging and discharging efficiency. To make the operation secure during peak demand hours, the Microgrid operator shades some load, and in return, it pays a high amount of money to consumers referred to as the Value of Lost Load (VOLL). Due to VOLL, the operating cost of Microgrid increases. So, it is desirable to reduce load shedding (LS). The VOLL and average energy price of the Microgrid are considered as 4 €ct/kWh and 0.15 €ct/kWh, respectively. The author assumed 20% of the load, as critical and remaining as non-critical for which load shedding can occur. For DRP implementation, it is assumed that 20% of consumers of Microgrid actively participate. Table 2 represents the elasticity of consumers to implement DRP.

Table 2. Self and cross elasticity of load [27]

	Low	Off-peak	Peak
Low	-0.10	0.032	0.024
Off-peak	0.032	-0.10	0.02
Peak	0.024	0.02	-0.10

2.2. DRP Modelling

In the power market, the electricity demand decreases with an increase in electricity price, and vice versa. This relationship between demand and price is modeled in terms of elasticity (E), interpreted as the demand sensitivity toward the electricity price.

$$E = \frac{\text{Percent change in demand}}{\text{Percent change in price}} = \frac{\Delta q/q_0}{\Delta\rho/\rho_0}$$

$$E = \frac{\rho_0}{q_0}.\frac{\Delta q}{\Delta \rho} \quad (1)$$

Where ρ_0 and q_0 are the initial cost of electricity ($/kWh) and Initial demand (kW), $\Delta\rho$ change in price and Δq refers to the respective change in demand for this change in price. For a small price change, $\frac{\Delta q}{\Delta \rho}$ can be approximated by the derivative $\frac{dq}{d\rho}$. Thus eq. (1) can be rewritten as

$$E = \frac{dq/q_0}{d\rho/\rho_0}$$

$$E = \frac{\partial q}{\partial \rho} = \frac{\rho_0}{q_0}\frac{dq}{dp} \quad (2)$$

When electricity prices vary, demand reacts in two ways;

i. Some of the loads, can only be turned on or off. These loads cannot transfer from one period to another and have sensitivity in one period, measured by self-elasticity.

$$E_{tt} = \frac{\partial q_t}{\partial \rho_t} \leq 0$$

∂q_t – Percentage variation in demand in t period, $\partial\rho_t$– Percentage variation in price in t period

ii. Some loads, can be transferred to another period due to price fluctuation in one period. These loads have multi-period sensitivity measured by cross-elasticity.

$$E_{tt'} = \frac{\Delta q_t}{\Delta \rho_{t'}} \geq 0$$

∂q_t - Percentage variation in demand in t period, $\partial\rho_{t'}$- Percentage variation in price in t′ period

In DRP, consumers reduce their demand during peak hours and shift it to off-peak hours due to these elasticities. The changed demand after implementing DRP is given by

$$P_{L,DRP}(t) = P_L(t) \cdot \{1+E(t,t) \cdot \frac{[P(t)-P_0(t)+A(t)]}{P_0(t)} + \sum_{\substack{t'=1 \\ t'\neq t}}^{24} E(t,t') \cdot \frac{[P(t')-P_0(t')+A(t')]}{P_0(t')} \quad (3)$$

where $P_0(t)$-initial electricity prices, $P(t)$-spot electricity prices, A(t)-incentive given to consumers for DRP implementation, P_L-Demand before applying DRP, $P_{L,DRP}$-Changed demand after implementing DRP. In this equation, the second term is due to self-elasticity E(t,t), and the third term is due to cross-elasticity $E(t,t')$. DRP modeling in detail is provided in references [16-18-25-26-28].

2.3. Problem Formulation

2.3.1. Goal

The goal is to reduce the Microgrid's overall operating costs, which include the cost of fuel and startup/shutdown costs of generating sources (represented by the 1st term), the operating cost of battery storage (2nd term), the cost of energy not delivered to consumers (3rd term), and the cost of implementing DRP (4th term).

$$\text{Min } F = \sum_{t=1}^{T}\{\sum_{i=1}^{N_g}[P_{geni}(t)b_{gi}(t)u_i(t) + s_{gi}(u_i(t) - u_i(t-1))] + P_{esj}(t)b_{esj}(t) + \sum_{t=1}^{T} VOLL * ls(t) + \sum_{t=1}^{T} C_{DRP} \quad (4)$$

Where T-total operating period of 24-hr (Δt=1h), N_g-number of generating units, u_i -status of unit i, P_{geni}& P_{esj} - output power of generating unit & battery storage, b_{gi}& b_{esj}-bids of generating unit and battery storage, S_{gi}-startup/shutdown costs of ith generating unit, LS -load shedding, VOLL-amount for energy not supplied and $C_{DRP}(t)$ -the cost of implementing DRP at time t.

2.3.2. Contraints

Demand-Supply balance

For the power system operation to be reliable, power generated from the generating units, battery (+ve when charging and –ve when discharging), and the load shedding, should be equal to the load after implementing DRP.

$$\sum_{i=1}^{N_g} P_{geni}(t) + P_{esj}(t) + ls(t) = P_{L,DRP}(t) \quad (5)$$

Power production limit

Power output from generating units and battery is controlled by their minimum/maximum limit.

$$P_{geni,Min}(t) * u_i(t) \leq P_{geni}(t) \leq P_{geni,Max}(t) * u_i(t) \quad (6)$$

$$P_{esj,Min}(t) \leq P_{esj}(t) \leq P_{esj,Max}(t) \quad (7)$$

Battery storage limits

Various battery constraints are given below:

The state of charge (soc) of the battery at any instant t is given by the soc at the previous interval and the battery charge (P_c) and discharge power (P_d) multiplied by their respective efficiencies,

$$soc(t) = soc(t-1) + P_c(t)\eta_c - P_d(t)/\eta_d \quad (8)$$

Limits on soc are given by

$$soc_{Min}(t) \leq soc(t) \leq soc_{Max}(t) \quad (9)$$

The battery charging and discharging power are limited by their maximum limit.

$$P_{ch}(t) \leq P_{ch,Max} \quad (10)$$

$$P_{dch}(t) \leq P_{dch,Max} \quad (11)$$

Load Shedding

The load that could be shed by the Microgrid operator is provided by

$$0 \leq LS(t) \leq (1 - Cl(t))P_L \quad (12)$$

Where Cl- a critical load that needs to be supplied all the time.

3. RESULTS & DISCUSSION

In this presented work, various DRPs are modeled in Microgrid operation and compared. Simulation is done under a scenario when renewable generation is operating at its maximum capacity. Formulate the system problem using MINLP and solve it in the GAMS environment.

3.1. With No DRP

In this case, simulation is performed without running DRP in Microgrid operation. Fig.3 displays the power output from different generating sources. During the initial hour, when demand is low, the FC mainly supply the load due to its lower bid, and battery also charges during this period. With the increase in load, the MT unit starts to operate, and the battery discharges during peak hours to meet the load demand.

In this case, the operating cost is 429.87 €ct, and 17.68 kWh load is shaved throughout 24 hours to maintain the power supply-demand balance.

3.2. With Time of Use (TOU) DRP

In this case, instead of using a fixed energy price of 0.15 €ct /kWh, 0.05, 0.20 & 0.40 €ct /kWh are used for low load, off-peak load & peak load periods accordingly. During low load hours (1-7), the FC unit operates due to its lower bid, while the MT unit remains off. Also, the battery gets charged due to surplus power. After implementing TOU DRP, demand during peak and off-peak hours is curtailed and transferred to low-load hours. The battery is discharged during intervals 9-11 and 15-17 and charged during intervals 1-4, 12-14, and 19-24. Since the battery is not operating continuously during the remaining hours, this will also increase the battery lifespan. Fig. 4 shows the power output from different sources. During initial hours, the load is majorly satisfied by the FC, WT, and PV. When the load increases, the MT unit starts to operate to meet the demand.

The total operating cost in this case is 371.04 €ct, and the quantity of shaded load is 1.09 kWh. The cost of running DRP is zero because no incentive is given to consumers. Consumer's benefit is found negative in this DRP.

3.3. With Real-Time Pricing (RTP) DRP

In this case, real-time electricity prices are applied for 24 hours (which are the prices for buying electricity from the upper grid in grid-connected mode) so that the customer can get the most of its benefits. Following the implementation of the RTP program, demand during peak hours (9-16) and off-peak hours (8 & 17-19) is reduced and moved to low load hours. The battery is charged during 4, 12-14, 20-24 hours and discharged during hours 9, 10, 15 & 16. For the remaining hours, the battery is not in a usable state.

The overall operating cost is 372.62 €ct, and the amount of the load curtailed is 1.22 kWh. Just like in the preceding case, there is no cost to implementing the DRP. Power output from different generating sources for this case is displayed in Fig. 5.

3.4. With Critical Peak Pricing (CPP) DRP

This DRP is applied when there is an unexpected increase in demand. Except for time intervals 9, 10, and 11 where prices are very high i.e., 0.60 €ct/kWh, TOU rates are applied for the rest hours. The operating cost is 356.08 €ct/kWh. There is no load shedding to satisfy the power supply-demand balance condition. In this program, there is no cost of applying DRP. Fig. 6 displays the power output from different generating sources in this case.

3.5. With Direct Load Control (DLC) DRP

In this program, the utility or Microgrid operator has the authority to curtail some of the load of consumer's load in case of system contingency, and the consumer gets benefits either in terms of incentive payment or decreases in electricity bill. This program is voluntary, so no penalty is given to consumers if they don't shed the load.

The Microgrid operator makes a contract with consumers to give them an incentive of 0.20 €ct/kWh for reducing their demand during peak hours. The consumers are encouraged to decrease peak demand by the provided incentive. The total cost for this program is 393.68 €ct including 223ct for implementing DRP, and the shaded load is 7.8 kWh. In this case, the consumers' benefit due to the incentive is 129.1 cents. Fig. 7 shows the power output from different generating sources.

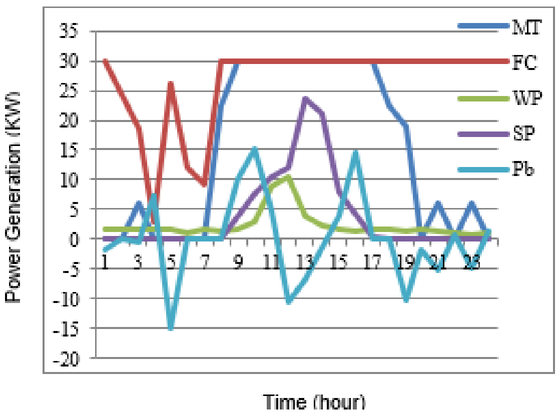

Figure 3. Power output of generating sources with No DRP

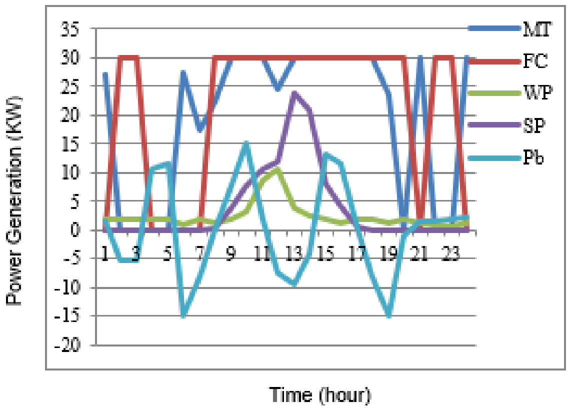

Figure 4. Power output of generating sources with TOU-DRP

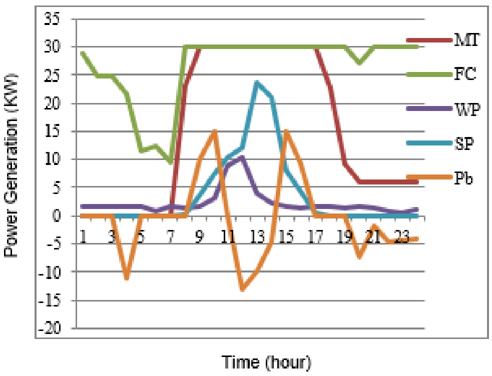

Figure 5. Power output of generating sources with RTP-DRP

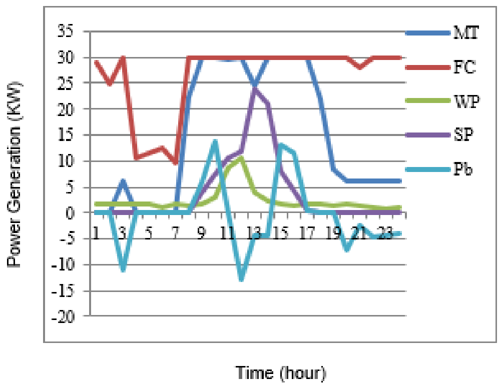

Figure 6. Power output of generating sources with CPP DRP

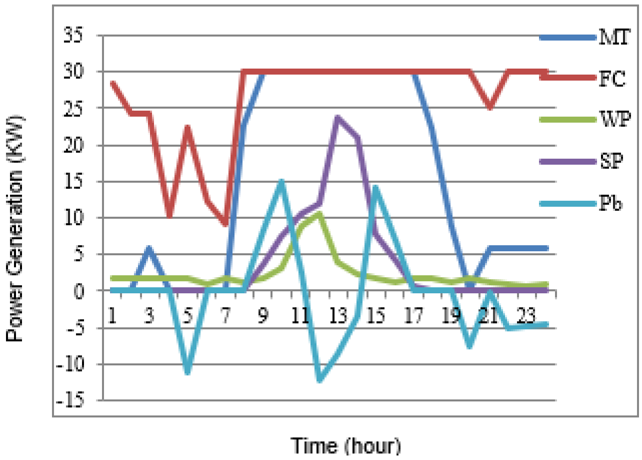

Figure 7. Power output of generating sources with DLC DRP

Table 3 depicts the optimization results for TOU, RTP, CPP (Price-based), and DLC-DRP (Incentive-based) DRPs in tabular form. It is visible that the maximum reduction in operating cost occurs in CPP-DRP with the highest financial loss for consumers. Figure 8 shows the change in the demand curve after implementing various DRPs. It is visible that during peak periods 9-16, demand is reduced in all programs and shifted to low-load periods. Figures 9 and 10 demonstrate the two main attributes needed to implement DRP: peak reduction and peak-to-valley reduction. It is clear from these figures that maximum peak reduction, as well as peak-to-valley gap reduction, occurs in the CPP-DRP.

Table 3. Simulation results for 20% of consumers' participation under various DRPs

	Without DRP	Various DRPs			
		TOU	RTP	CPP	DLC
Operating Cost(€ct)	429.87	371.04	372.62	356.08	393.68
Load Shedding (kWh)	17.68	1.09	1.22	0	7.8
Consumers' Profit (ct)	0	-361.3	-217.86	-500.8	129.1

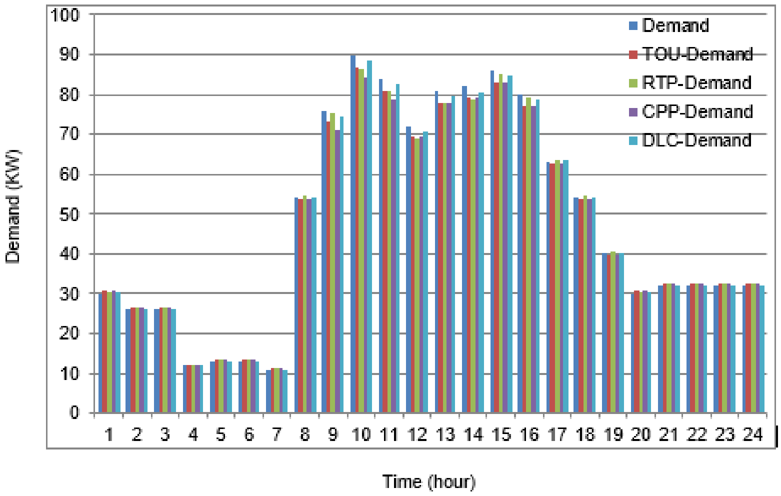

Figure 8. Modified demand after implementing various DRPs

In Ref. [26], the same Microgrid operates in grid-connected mode while implementing Price-based or an Incentive-based DRP alone to the Microgrid operation. In the presented work, this Microgrid is working in independent mode, and a new combination of DRP is presented to benefit both the Microgrid operator and its consumers.

In all DRPs, demand decreases during peak hours and increases during off-peak and low-load hours. Although the operating cost is reduced after implementing TOU-RTP-CPP DRPs, consumers suffer a monetary loss. Whereas in the DLC program, the operating cost is higher, but consumers get benefits. The CPP has the lowest operating cost with the highest consumer expenses, so the next option is TOU-DRP. Therefore, in this work, a combination of two (TOU+DLC-DRP), is simulated to reduce overall operating costs.

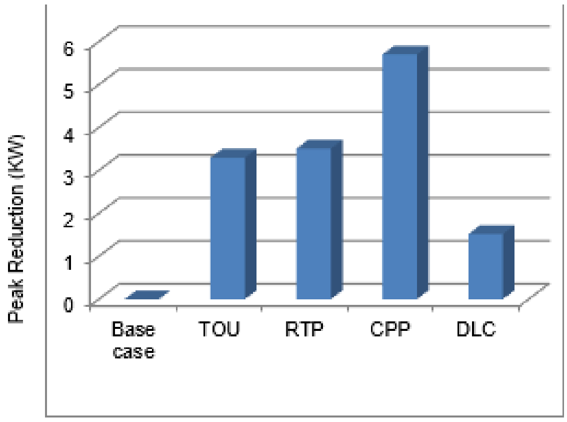

Figure 9. Peak reduction in various DRPs

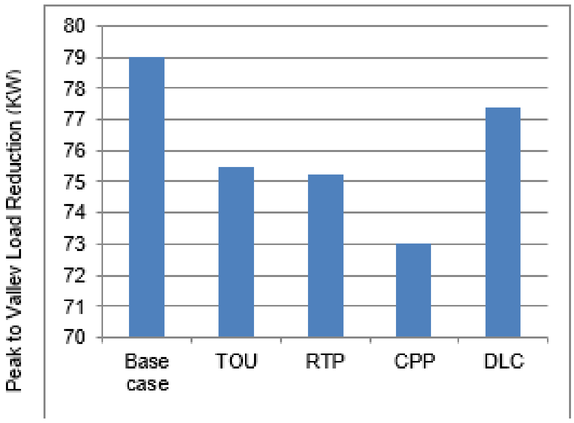

Figure 10. Peak-to-valley load reduction using various DRPs

3.6. Impact of Different Percentages of Consumer Participation

To illustrate the significance of consumers' involvement in Microgrid operation, the same procedure is repeated with 50%. As visible from Table 4, operating costs and load shedding are further reduced compared to 20% of consumers' participation.

Table 4. Optimization results for 50% of consumers' participation in various DRPs

Various DRPs	Operating Cost (€ct)	Load Shedding (kWh)
TOU	349.24	0.67
RTP	346.03	0
CPP	349.27	0
DLC	364.76	1.36

3.7. Implementing a Novel TOU+DLC DRP

In this program, electricity prices are the same as TOU, and consumers are provided an incentive of 0.20 €ct/kWh if they agree to curtail their energy consumption. Due to higher bids, the MT units mainly remain off during low-load hours. The FC and renewable generation supply the majority of the load, and the battery charges with the surplus power. The MT unit turns on with the increase in load, and the battery discharges.

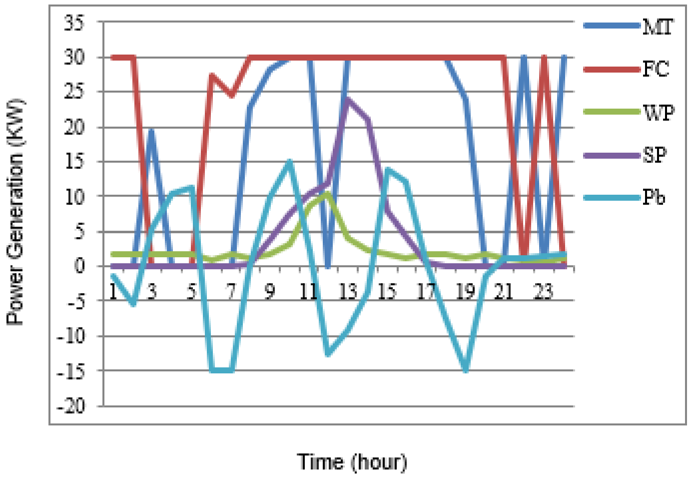

Figure 11. Power output of different generating units after implementing TOU+DLC DRP

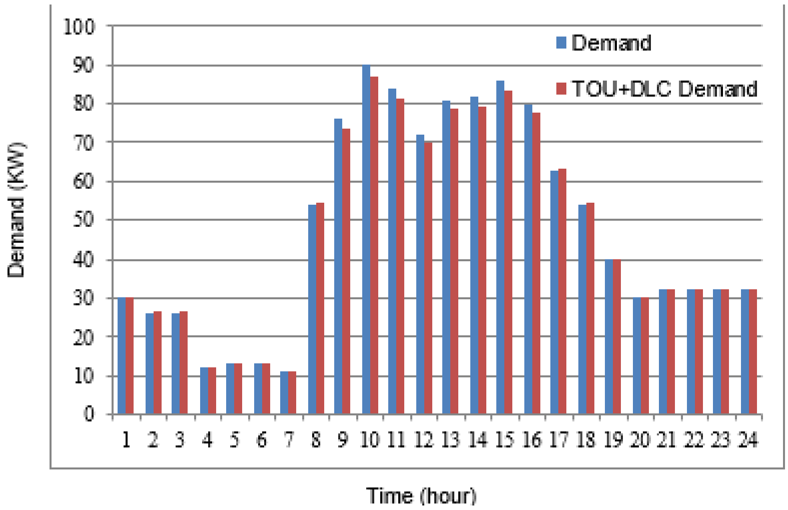

Figure 12. Change in demand after implementing TOU+DLC DRP

Table 5. Simulation Results for 20% Consumers' Participation after Implementing TOU+DLC DRP

TOU+DLC DRP	Operating Cost (€ct)	Load Shedding (kWh)	Customers' Profit (ct)
	371.89	1.69	270

The operating cost in this case is 371.89 €ct, and the load shaved is 1.69 kWh. Consumers make a profit of 270 cents. As a result, this program offers the benefit of both price and incentive-based DRP. Fig. 11 shows the power output from different generating sources. Fig. 12 depicts the change in demand after implementing this program with a maximum peak reduction is 2.7KW.

As illustrated in Table 5, combining DRPs significantly reduces operating costs and load shedding, and boosts consumers' benefit compared to implementing only one type of DRP.

4. CONCLUSION

In the presented work, power production from different power sources is optimally scheduled for an Independent Microgrid by running various Time-based and Incentive-based DRPs. A new combination of these two DRPs has been presented to reduce the overall 24-hour operating costs using the GAMS software. According to the optimization results, without running DRP, the operating cost and load shedding would be 429.87 €ct and 17.18 kWh with zero consumer benefit. When TOU, RTP, CPP (Time-based), and DLC (Incentive-based) DRPs are implemented with 20% consumer involvement, operating costs are reduced by 13.68%, 13.31%, 17.16%, and 8.41% with a reduction in load shedding from 17.18 kWh to 1.09, 1.22, 0 & 7.8 kWh. Therefore, from the Microgrid operator's perspective, CPP-DRP is a top priority due to the highest reduction in operating cost, load shedding, and peak reduction, while DLC is at least due to the expense of implementing DRP. The optimization results confirm that consumers experience a financial loss in TOU-RTP-CPP DRPs, with the highest occurring in CPP-DRP, and they get benefits only in DLC-DRP.

Therefore, the highlight of this article is the simulation of a new combined TOU+DLC DRP made up of two DRPs, which reduces the operating cost by 13.48% with a load shedding of only 1.69 kWh. The consumers' benefit increases from 0 to 270 ct. Therefore, the suggested combination is beneficial for both the Microgrid operator and its consumers. The increase in the percentage of consumer participation results in a significant reduction in operating costs.

For future work, we intend to expand the optimization model to a multi-objective stochastic model for grid-connected microgrids to reduce annual costs and emissions while incorporating other combinations of DRPs.

REFERENCES

[1] H. Kuang, S. Li, Z. Wu., "Discussion on Advantages and Disadvantages of Distributed Generation Connected to the Grid," *2011 International Conference on Electrical and Control Engineering*, pp. 170-173, 2011.
[2] N. W. A. Lidula, A. D. Rajapakse, "Microgrid Research: A Review of Experimental Microgrids and Test Systems," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 186-202, 2010.

[3] G. Ferruzzi, F. Jacobone, "Optimal Bidding in A Day-Ahead Energy Market for Microgrid under Uncertainty in Renewable Energy Production," *Energy*, vol. 106, pp.194–202, 2016.

[4] J. Lu, M. Niu, "Overview on Microgrid Research and Development," *in International Conference on Information Computing and Application, ICICA 2010*, pp. 161-168, 2010.

[5] H. M. Kim, T. Kinoshita, M.C. Shin, "A Multiagent System for Autonomous Operation of Islanded Microgrids Based on A Power Market Environment," *Energies*, vol. 3, no. 12, pp. 1972-1990, 2010.

[6] Y. You, G. Wang, C. H. Zhang, J. R. Lian., "An Improved Frequency Control Method for Microgrid in Islanded Operation," *in 2nd International Symposium on Instrumentation and Measurement, Sensor Network and Automation*, pp. 296-299, 2013.

[7] R. Dufo-López, L José, B. Agustín, "Multi-Objective Design of PV-Wind-Diesel Hydrogen-Battery Systems," *Renewable Energy*, vol. 33, no.12, pp. 2559-2572, 2008.

[8] L., Jose, B. Agustín and R. Dufo-López., "Simulation and Optimization of Stand-Alone Hybrid Renewable Energy Systems," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2111-2118, 2009.

[9] R. Siddaiah, R.P. Saini. "A Review on Planning, Configurations, Modeling and Optimization Techniques of Hybrid Renewable Energy Systems for Off-Grid Applications," *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 376–396, 2016.

[10] X. Tan, Q. Li, H. Wang, "Advances and Trends of Energy Storage Technology in Microgrid," *International Journal Electrical Power Energy System*, vol. 44, no. 1, pp. 179-91, 2013.

[11] H. Babazadeh, W. Gao, Z. Wu., "Optimal Energy Management of Wind Power Generation System in Islanded Microgrid System," *in North American Power Symposium 2013, NAPS 2013*, pp.1–5, 2013.

[12] U.S. Department of Energy. *Energy Policy Act of 2005*. section 1252, 2006.

[13] M. P. Moghaddam, A. Abdollahi, M. Rashidinejad, "Flexible Demand Response Programs Modeling in Competitive Electricity Markets," *Applied Energy*, vol. 88, no. 9, pp. 3257–3269, 2011.

[14] M. Rahmani-Vanderbilt, "Modeling Nonlinear Incentive-Based and Price-Based Demand Response Programs and Implementing on Real Power Markets," *Electr. Power System Research*, vol. 132, pp. 115–124, 2016.

[15] H. Du, S. Liu, Q. Kong, W. Zhao and D. Zhao, "A Microgrid Energy Management System with Demand Response", 2014 China *International Conference on Electricity Distribution. CICED 2014*, pp. 551-554, 2014.

[16] H. A. Aalami, M.P. Moghaddam and G. R. Yousefi, "Demand Response Modeling Considering Interruptible/Curtailable Loads and Capacity Market Programs," *Applied Energy*, vol. 87, no. 1, pp. 243–250, 2010.

[17] C. Deckmyn, J. V. Vyver, T. L. Vandoorn, B. Meersman, J. Desmet, and L. Vandevelde, "Day-Ahead Unit Commitment Model for Microgrids," *IET Generation, Transmission & Distribution*, vol. 11, no. 1, pp. 1-9, 2017.

[18] E. Dehnavi, H. Abdi, "Optimal Pricing in Time of Use Demand Response by Integrating with Dynamic Economic Dispatch Problem," *Energy*, vol. 109, pp. 1086–1094, 2016.

[19] H. Aalami, G.R. Yousefi, M. P. Moghadam, "Demand Response Model Considering EDRP and TOU Programs," *IEEE/PES Transmission and Distribution Conference and Exposition*, pp. 21-24, 2008.

[20] A. Asadinejad, K. Tomsovic, "Optimal Use of Incentive and Price Based Demand Response to Reduce Costs and Price Volatility," *Electric Power System Research*, vol. 144, pp. 215–223, 2017.

[21] J. Wang, C. Kang, "Distributed Real-Time Demand Response Based on Lagrangian Multiplier Optimal Selection Approach," *Applied Energy*, vol. 190, pp. 949–959, 2017.

[22] J. Aghaei, M.I. Alizadeh, P. Siano, and A. Heidari, "Contribution of Emergency Demand Response Programs in Power System Reliability," *Energy*, vol. 103, pp. 688-696, 2016.

[23] A. Ajoulabadi, S. N. Ravadanegh, B. M. Ivatloo, "Flexible Scheduling of Reconfigurable Microgrid-Based Distribution Networks Considering Demand Response Program," *Energy*, vol. 196 (117024), 2020.

[24] T. Khalili, A. Jafari, M. Abapour, B. M. Ivatloo, "Optimal Battery Technology Selection and Incentive-Based Demand Response Program Utilization for Reliability Improvement of an Insular Microgrid," *Energy*, vol. 169, pp. 92-104, 2019.

[25] E. Shahryari, H. Shayeghi, B. M. ivatloo, M. Moradzadeh, "An Improved Incentive-Based Demand Response Program in Day-Ahead and Intra-Day Electricity Market," *Energy*, vol. 155, pp. 205-214, 2018.

[26] M. H. Imani, M. J. Ghadi, S. Ghavidel, L. Li., "Demand Response Modeling in Microgrid Operation: A Review and Application for Incentive-Based and Time-Based Programs," *Renewable and Sustainable Energy Review*, vol. 94, pp. 486–499, 2018.

[27] A. Moghaddam, A. Seifi., T. Niknam, "Multi-Operation Management of a Typical Micro-Grids Using Particle Swarm Optimization: A Comparative Study," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 2, pp. 1268– 1281, 2012.

[28] M. H. Imani, P. Niknejad, M.R. Barzegaran, "Implementing Time-Of-Use Demand Response Program in Microgrid Considering Energy Storage Unit Participation and Different Capacities of Installed Wind Power," *Electrical Power System Research*, vol. 175 (105916), 2019.

[29] A. Maherbani, H. Mardani, M. S. Ghazizadeh, "Optimization of Isolated Microgrid in the Presence of Renewable Energy Sources and Demand Response Programs," *IEEE 11th Smart Grid Conference*, pp. 1-5, 2021.

[30] S. Kakran, S. Chanana., "Operation Management of a Renewable Microgrid Supplying to A Residential Community Under the Effect of Incentive-Based Demand Response Program," *International Journal of Energy and Environmental Engineering*, vol. 10, pp. 121-135, 2019.

[31] S. R. Salkuti, "Optimal Operation of Microgrid Considering Renewable Energy Sources, Electric Vehicles and Demand Response," *E3S Web of Conferences*, vol. 87 (01007), 2019.

[32] J. D. Mina-Casaran, D. F. Echeverry, C. A. Lozano, "Demand Response Integration in Microgrid Planning as A Strategy for Energy Transition in Power Systems," *IET Renewable Power Generation*, vol. 15, no. 4, pp. 889-902, 2021.

[33] Z. X. Yu, M. S. Li, Y. P. Xu, S. Aslam, Y. K. Li. "Techno-Economic Planning and Operation of the Microgrid Considering Real-Time Pricing Demand Response Program," *Energies*, vol. 14, no. 15, 4597, 2021.

[34] L. Barrios, A., Nozal, J., Valreno, I., Vera, J. Martinez-Ramos, "Stochastic Unit Commitment in Microgrids: Influence of the Load Forecasting Error and the Availability of Energy Storage," *Renewable Energy*, vol. 146, pp. 2060-2069, 2020.

[35] N. D. Tuyen, Linh, H.T., T.X. Hung, D.V. Long. "A Mixed-Integer Programming Approach for Unit Commitment in Microgrid with Incentive-Based Demand Response and Battery Energy Storage System," *Energies*, vol. 15, 7192, 2022.

[36] J. Wang, K. J. Li, Y., Liang, Z., Javid, "Optimization of Multi-Energy Microgrid Operation in the Presence of Pv, Heterogenous Energy Storage, and Demand Response," *Applied Science*, vol. 11, 1005, 2021.

[37] M. Nemati, M. Braun, S. Tenbohlen, "Optimization of Unit Commitment and Economic Dispatch in Microgrids Based on Genetic Algorithm and Mixed Integer Linear Programming," *Applied Energy*, vol. 210, pp. 944-963, 2018.

[38] T. R. Olorunfemi, and N. L. Nwulu, "Multi-Agent-Based Optimal Operation of Hybrid Energy Sources with Demand Response Programs," *Sustainability*, vol. 13, no. 14, 7756, 2021.

[39] Y. Li, K., Li, Z., Yang, Y., Yu, R., Xu, M. Yang, "Stochastic Optimal Scheduling of Demand Response- Enabled Microgrid with Renewable Generations: An Analytic Heuristic Approach," *Journal of Cleaner Production*, vol. 330, 129840, 2022.

[40] Mehrabani, H. Mardani, and M. S. Ghazizadeh, "Optimization of Isolated Microgrid in the Presence of Renewable Energy Sources and Demand Response Programs," IEEE 2021 11th Smart Grid Conference, 2021.

[41] M. Sedighizadeha, M. Esmailib, A. Jamshidia and M. H. Ghaderia, "Stochastic Multi-Objective Economic Environmental Energy and Reserve Scheduling of Microgrids Considering Battery Energy Storage System," *Electrical Power and Energy Systems*, vol. 106, pp. 1-16, 2019.

[42] V.V.S.N. Murty, and A. Kumar, "Multi-Objective Energy Management in Microgrids with Hybrid Energy Sources and Battery Energy Storage Systems," *Prot. And Cont. of Modern Power System*, vol. 5, no. 2, pp. 1-20. 2020.

[43] A. R. Battula, S. Vuddanti, S. R. Salkuti, "A Day Ahead Demand Schedule Strategy for Optimal Operation of Microgrid with Uncertainty," *Smart Cities*, vol. 6, pp. 491-509, 2023.

[44] B. Day, S. Mishra, F.P. Marquez, "Microgrid System Energy Management with Demand Response Program for Clean and Economical Operation," *Applied Energy*, vol. 334 (120717), 2023.

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