Multi-Objective Dynamic Economic Emission Dispatch of Microgrid Using Novel Efficient Demand Response And Zero Energy Balance Approach

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Abstract- Energy management system (EMS) in microgrids (MGs) encompasses both dynamic economic dispatch (DED) and dynamic emission dispatch problems, known as dynamic economic emission dispatch (DEED). In this paper, this system is implemented for an MG with different distributed generations. The aim of 24-hour-cycle scheduling is to determine the generation level of diesel generators (DGs), participation rate of responsive loads and their incentives, charging/discharging status of the battery, and the amount of exchanged energy with the main grid. The scheduling task is performed with the objectives of minimizing operation costs and emissions and maximizing the benefit of MG operator (MGO) resulting from the demand response (DR). Due to their interactive operation, the customers' behavioral model and the relevant cost functions have significant impacts on the optimal operation. In this paper, the cost function of customers is developed in the incentive-based DR program (DRP) with the aim of receiving a more realistic incentive and then it is further combined with DEED. Finally, the zero energy balance (ZEB) interaction between the MG and the main grid is proposed as a solution. Regarding the multi-objective and nonlinear optimization problem, the proposed method, with the help of whale optimization algorithm (WOA), is implemented on a small-scale MG in MATLAB software, where electrical loads are also taken into account. Simulation results highlight the fact that the integration of DR into DEED along with import/export ZEB between the MG and the main grid leads to optimal operation and reduced imported power from the main grid, and helps maintain the load/generation balance.

Keywords- Demand response (DR), Dynamic economic emission dispatch (DEED), Energy management system (EMS), Microgrid, Whale Optimization Algorithm (WOA), Zero Energy Balance (ZEB)

Nomenclature

Indices

I	number of diesel generators
T	number of dispatch intervals
J	total number of consumers

Parameters

$p_{\text{utility}}{}^{max}$	maximum power transferable between the main grid and microgrid
$\lambda_{import,t}$	price of power bought from the main grid at time t
$\lambda_{export,t}$	the price of the power sold to the main grid at time t
$p_{wind}{}^{max}$	upper power output limit of WT
$v_{hub,t}$	hourly wind speed at the desired height at time t
ρ_{air}	air density
c_p	power coefficient of the wind turbine
a_{wind}	area of the WT rotor swept surface
η_{wind}	efficiency of the wind generator
$p_{pv}{}^{max}$	upper power output limit of the PV panel
η_{pv}	efficiency of the PV system
a_{pv}	area of the PV array
$i_{pv,t}$	hourly solar irradiation incident on the solar PV array at time t
$p_i{}^{min}$	the minimum capacity of DG i

p_i^{max}	the maximum capacity of DG i
dr_i	the maximum ramp-down rates of DG i
ur_i	maximum ramp-up rates of DG i
a_i , b_i	fuel cost coefficients of DG i
α_i , β_i	emission function coefficients of DG i
$p_{demand,t}$	total system demand at time t
$\theta_{j,t}$	the type of customer based on level of satisfaction to curtail power
$\varphi_{j,t}$	the type of customer based on level of satisfaction to consume power.
pc^{pro}	amount of power curtailment limit proposed by customer j at time t
ob	microgrid operator's total budget
w_1, w, w_3	objective function weights
f_1, f_2, f_3	objective functions
$k_{1,j}$, $k_{2,j}$	outage cost function coefficients of participant customer j
$\lambda_{j,t}$	value of interrupted power calculated via OPF (LMP)
σ	price of battery operation
μ	incentive payment coefficient for mandatory power reduction
ξ	self-discharge coefficients of the battery unit
η_{ch} , η_{dis}	charge/ discharge efficiencies of the battery unit
c_{bat}	capacity of the battery unit
soc^0	initial state of charge for battery unit
soc^{min}	minimum state of charge for battery unit
soc^{max}	maximum state of charge for battery unit
soc_t	state of charge for battery unit at time t
$p_{ch,t}{}^{max}$	maximum charging rate for battery unit
$p_{dis,t}{}^{max}$	maximum discharging rate for battery unit
cb_t	cost of charging/discharging the battery unit at time t
ct_t	microgrid operator cost for trading transferable power at time t
bo_t	benefit function of the microgrid operator at time t
$cf_{i,t}$	fuel cost of DG i at time t
$ce_{i,t}$	emission cost of DG i at time t
$bc_{j,t}$	benefit function of customer j at time t
$\overrightarrow{b}, \vec{v}$	coefficient vectors of the whale algorithm
$\overrightarrow{p^*}(K)$	position vector of the best solution obtained so far
$\vec{p}$	position vector of the whale algorithm
$\overrightarrow{p_r}(k)$	a random whale position vector
r	a value linearly decreased from 2 to 0 over the course of iterations
$\vec{c}$	a random vector in [0,1]
δ	a random number in [0,1]
$\vec{s}$	distance of the i^{th} whale to the prey (best solution obtained so far)
d	a constant for defining the shape of the logarithmic spiral
f	a random number in $[-1,1]$

Variables

$p_{utility,t}$	transferable power between the main grid and microgrid at time t
$p_{import,t}$	amount of power bought from the main grid at time t
$p_{export,t}$	amount of power sold to the main grid at time t
$p_{batt,t}$	power of the battery unit at time t
$p_{ch,t}$	amount of charge power for the battery unit at time t
$p_{dis,t}$	amount of discharge power from the battery unit at time t
$p_{wind,t}$	hourly energy output from the wind generator at time t
$p_{pv,t}$	power generated from the PV at time t
$p_{i,t}$	power generated from DG i at time t
pc^{opt}	quantity of optimum power curtailment by a participant customer j at time t
$pc_{j,t}{}^{norm}$	quantity of normal power curtailment by customer j at time t
$pc_{j,t}{}^{mand}$	quantity of mandatory power curtailment by customer j at time t
$rc_{j,t}$	value of monetary compensation received by customer j at time t
$cc_{j,t}$	incurred cost of reducing normal PC (kW) by customer of type φ or θ
$ccm_{j,t}$	incurred cost of reducing mandatory PC (kW) by customer of type φ or θ

Binary variables

$b_t{}^{batt}$	binary variable for discharging(0) / charging(1) mode of the battery unit at time t
$b_t{}^{u}$	binary variable for exporting (0) and importing(1) mode to/from the main grid at time t

Abbreviations

ED	Economic Dispatch
DED	Dynamic Economic Dispatch
DEED	Dynamic Economic Emission Dispatch
BESS	Battery Energy Storage System
DG	Diesel Generator
DOD	Depth Of Discharge
DR	Demand Response
DRP	Demand Response Program
EMS	Energy Management System
MG	Microgrid
MGO	Microgrid Operator
MOOP	Multi-Objective Optimization Problem
PV	Photovoltaic
RES	Renewable Energy Source
SOC	State of Charge
SOOP	Single-Objective Optimization Problem
WOA	Whale Optimization Algorithm
WT	Wind Turbine
ZEB	Zero Energy Balance
| |	Absolute Value
.	Element-by-element multiplication

1. Introduction

In recent years, with numerous studies conducted on scheduling and optimization of energy in microgrids (MGs), the modern management of dynamic behavior and constraints of MGs has tremendously advanced, paving the way for MGs to eventually replace the conventional power systems [1]. Dynamic economic dispatch (DED) is an important issue in MGs aimed at reducing the operation costs via determining the optimal output active power for different generation units and helping to obtain the economic objective function [2]. It should be noted that DED is a dispatch for a time interval that is influenced by its preceding interval (e.g. by ramp rate limit of diesel generator (DG)), and this differentiates DED from the conventional Economic Dispatch (ED). However, although DED enjoys an accurate formulation, it is often difficult to solve because of its large dimension and therefore is usually solved by employing special algorithms [3].

With the increasing demand for electrical energy, the operators' concerns have been doubled. The main aim of an operator is not merely to analyze the DED, but they should also take care of the dynamic emission dispatch. This transforms DED into a dynamic economic emission dispatch (DEED) problem. DEED is a dynamic problem resulted from the innate dynamics of the power system and large variability of the customers' demand. Thus, DEED can be simultaneously used for the reduction in operation costs and emissions and this is, in fact, a multi-objective optimization problem (MOOP). A reasonable solution for DEED problem is to transform MOOP into single-objective optimization problem (SOOP). Several techniques have already been suggested for solving the DEED problem [4, 5, 6, 7].

On the other hand, demand side management as a potential solution for most technical and commercial problems has provided a research field for operators. In this context, it is necessary to add incentive programs such as electricity demand reduction to the DEED problem so that the customers and the MG operator (MGO) can receive the relevant technical and economic benefits as a motivation. Adopting this approach improves the energy consumption pattern, makes a balance between generation and consumption sides, and enhances the system efficiency [8, 9]. Obviously, DEED and demand response (DR) programs are essential programs for power system management. However, DEED and DR are related to the supply and demand sides, respectively. Consequently, by merging these two formulae of supply and demand we can approach more practical and realistic results [10]. This combination takes into account DR programs as an essentially attractive scheme for customers, based on which obtaining optimal results for both supply and demand sides will be feasible instead of these being considered separately [11]. There are few studies that consider DEED and DR jointly, and solutions for such a problem using different algorithms are compared in [12]. Ref. [13] presents a solution to the multi-objective energy management system (EMS) problem by employing the game-theory-based DR model. During power deficiency periods, the combination of EMS with DR aids the operator in confronting the imbalance between supply and demand. Nevertheless, the potential capacities of the main grid, RESs, batteries, and hourly limitation of customers for power reduction are overlooked. In [14], customers participate in the DED problem using DR and receive incentives thereof. This daily optimization and scheduling are performed for the grid-connected MG consisting of conventional and renewable energy resources without considering emissions. This optimization problem is solved by Advanced Interactive Multidimensional Modelling System (AIMMS) which should preferably be used by evolutionary algorithms for managing such complexity. The proposed energy reduction by customers is on daily basis, according to which the type of customer (the type of satisfaction for power reduction) is taken into account daily and the hourly limitation of customers for power reduction are not considered. The operator uses all the energy reduction proposed by customers, leading to more incentive payments. As a result, this approach is not practical, and the purpose of the authors of this paper is that in order to approach reality, customers need to propose their power reduction limits, based on which the type of customers is determined at each hour so as to yield a more effective and realistic cost function. Through executing the DR program (DRP), an equilibrium solution has been introduced in [15] between cost and emission reductions, where a sample hub energy system containing renewable and nonrenewable energy resources is solved by Mixed Integer Linear Programming (MILP) and the load curve is flattened. Nonetheless, by increasing the number of variables and constraints, the problem becomes more convoluted and requires much more computational time and cost. Traditional techniques are incapable of optimizing such nonlinear problems and evolutionary optimization algorithms and/or a combined method should be employed. It is worth noting that evolutionary techniques are advanced optimization designs in which parameter tuning has a considerable effect on the results. As a recently developed evolutionary technique, whale optimization algorithm (WOA) has a high potential and benefit compared to other algorithms, including its novelty, less parameter tuning, simplicity, and low computational cost. Thanks to its merits, WOA is used in this study.

Furthermore, operators highly tend to utilize RES to solve the DEED problem. Hence, it is expected that by using renewable resources and through energy management all the required energy could be supplied with the lowest cost and emission. Based on this, the zero energy balance (ZEB) fundamentals are popularly applicable which can be added to the DEED problem. The ZEB concept has been identified in the framework of its main definition based on two major types of balance, namely, the import/export balance and the load/generation balance. Due to the overlap of time intervals and different seasons, a suitable time span for calculating ZEB would be on an annual basis. But the sum of energy exchange with the main grid can be considered on a monthly, seasonal, or daily basis [16]. Net ZEB has been classified into four categories: net zero site energy, net zero source energy, net zero energy costs and net zero emissions [17]. These are briefly defined as [18]:

- Net Zero Site Energy: A site produces at least as much energy as the consumed energy during the time span, meaning that the energy balance is sought at the neighborhood of the site and the main grid's power source is neglected.

- Net Zero Source Energy: In this method, the amount of energy exported to the main grid must be equal to the energy imported during the time span, i.e., the energy balance between the power source and the consumer is examined.
- Net Zero Energy Costs: In this method, the cost of imported energy must be equal to the cost of energy exported to the main grid.
- Net Zero Energy Emissions: In this method, the amount of energy consumption from resources with emissions and pollution (non-renewable resources) is equal to the generated energy by emission-free resources (renewable resources).

In this paper, a new approach based on the proposed model in [14] is employed to efficiently include the developed DR in EMS problem. Due to the variable nature of renewable energy sources in the MGs, hourly planning intervals are more common. Therefore, the DRP is also implemented for the consumers on an hourly basis as the customers' behavioral model and the relevant cost functions have a significant impact on the optimal operation. Furthermore, limitation is considered for demand reduction of consumers, where the incurred cost of customer is developed in DRP by defining a new parameter ($\varphi_{j,t}$). Besides optimal incentive payments, compensations are paid for higher reductions when required. Also, the ZEB concept which has not been studied for MGs, is proposed in this paper as a solution. Operation of MGs with ZEB approach has a key role on the procedure of consumption reduction of nonrenewable resources, consumption optimization of renewable energies, and prevention of environmental pollution, leading to the improvement in quality of life. The paramount steps for achieving ZEB are the maximum use of DRP to reduce energy consumption and utilization of RES with low cost and minimum emissions. Furthermore, the use of EMS is among other solutions which can play a noticeable role in achieving ZEB. To this end, by combining a developed DR into the DEED, this paper proposes a ZEB-based interaction between the MG and the main grid as a solution. The sum of imported and exported energies in such an MG is considered zero. This, in addition to optimal energy management and efficiency increase, leads to economic profitability, pollution reduction, reduced purchase of power from the main grid during the peak load hours, and more efficient use of energy resources available in the MG. The ZEB approach is often more useful in cases located in a remote region or a rural site. Hence, in this paper, the proposed method is considered for grid-connected MG located in remote areas. Independence from the main grid will be the main goal of MGs in the future. The proposed model in this paper is implemented by employing the WOA for solving the DEED problem and determining the operation method of DGs, the charging/discharging of the battery, the amount of energy exchanged with the main grid, and the participation level of responsive demands and their incentives.

The rest of this paper is organized as follows: Section 2 presents the structure and model of the MG used for the DEED problem. The solution method and WOA technique are described in Section 3. Numerical results obtained from the simulation are given in Section 4 for several different scenarios. Finally, the conclusions are presented in Section 5.

2. MG Structure And Model

The MG under study includes RESs (PV and WT), battery, diesel generators and controllable loads and is connected to the main grid. Figure 1 illustrates the concept of MG with ZEB approach.

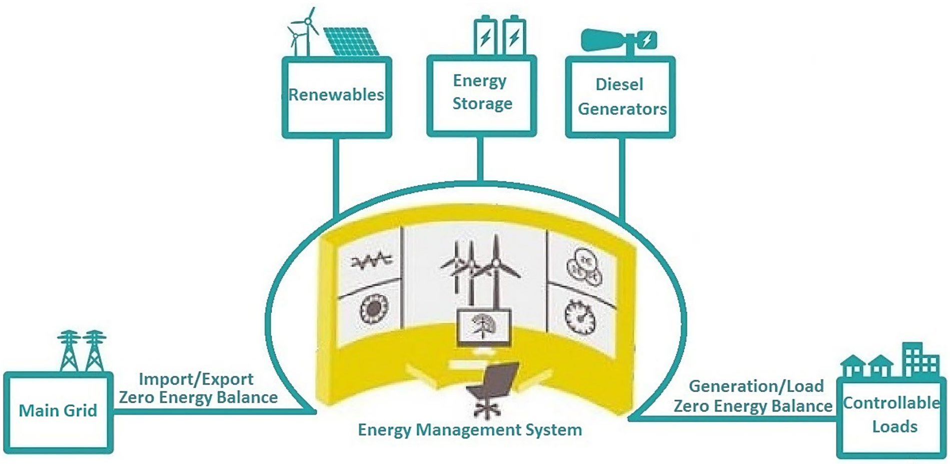

Figure 1. Components of the ZEB-based main grid-connected MG

Each component of the considered system is separately modeled based on their specific features and related constraints. In the following, to implement the mathematical model, the cost function of the energy management problem within a time span T is defined.

2.1. Photovoltaic Model

Output of PV arrays is fully dependent on solar radiation. The mathematical representation of the hourly generated power by the PV is expressed as [14, 19]:

$$p_{pv,t} = \eta_{pv}\, a_{pv}\, i_{pv,t} \tag{1}$$

2.2. Wind Turbine Model

The hourly power output of a WT is highly dependent on wind speed. The mathematical expression for transforming hourly wind speed to electrical power is written as [21, 22, 23]:

$$p_{wind,t} = 0.5\, \eta_{wind}\, \rho_{air}\, c_p\, a\, v_{hub,t}{}^3 \quad (2)$$

2.3. Diesel Generator Model

Power generation cost of the DG, in the form of a quadratic function, is represented by [23, 24]:

$$cf_{i,t} = a_i\left(p_{i,t}\right)^2 + b_i p_{i,t} \quad (3)$$

Emission reduction using the DG is also expressed as a quadratic function as [22]:

$$ce_{i,t} = \alpha_i\left(p_{i,t}\right)^2 + \beta_i p_{i,t} \quad (4)$$

2.4. Utility Model

The potential capacity of the main grid is of importance for the MGO, where the MG sells/purchases its excess/deficit energy to/from the main grid according to the prices and internal generation level. Utility's power at each hour is given in (5):

$$p_{utility,t} = \sum_{t=1}^{T}\left(p_{import,t} b_t{}^u - p_{export,t}\left(1 - b_t{}^u\right)\right) \quad (5)$$

The MG can purchase/sell power from/to the main grid at each hour. Negative and positive value exchanges respectively mean selling/purchasing power to/from the main grid (or purchasing/selling power to/from the MG). The cost of power exchange between the MG and the main grid is represented as:

$$ct_t = \begin{cases} \sum_{t=1}^{T}\left(\lambda_{export,t}\, p_{utility,t}\right) & :\ p_{utility,t} < 0 \\ 0 & :\ p_{utility,t} = 0 \\ \sum_{t=1}^{T}\left(\lambda_{import,t}\, p_{utility,t}\right) & :\ p_{utility,t} > 0 \end{cases} \quad (6)$$

Ultimately, positive and negative values of ct_t describe the imposed cost and achieved revenue for the MGO, respectively.

2.5. Battery Model

In addition to reducing emissions caused by fossil fuel consumption, batteries store energy at non-peak periods and discharge at peak periods. In this paper, a more realistic operation of the battery is modelled with regard to its self-charging factor. As a result, battery charging/discharging is scheduled in such a way that leads to more reduction in the overall cost. Battery power at hour *t* is given by:

$$p_{batt,t} = \sum_{t=1}^{T}\left(p_{dis,t}\, b_t{}^{batt} - p_{ch,t}\left(1 - b_t{}^{batt}\right)\right) \quad (7)$$

where positive and negative values of $p_{batt,t}$ mean that the battery is discharging and charging, respectively. The operation cost (depreciation cost) of the battery at hour t is:

$$cb_t = \sum_{t=1}^{T}\sigma\left(p_{dis,t}\, b_t{}^{batt} - p_{ch,t}\left(1 - b_t{}^{batt}\right)\right) \quad (8)$$

2.6. Developed Demand Response Model

In this paper, an extended model of DR for a grid-connected MG is presented considering the customers' cost functions and the respective incentive payments. The benefit function of the customers (bc_j) is given as (9), which is the difference between the revenue and costs of customers. $rc_{j,t}$ is the amount of money received by customers as an incentive and is applied in the form of discount or consumption credit on their bills. The imposed costs on customers ($cc_{j,t}$) represents their dissatisfaction due to power reduction.

$$bc_{j,t} = rc_{j,t} - cc_{j,t} \quad (9)$$

If $bc_j \geq 0$, it is reasonable for customers to participate in the DRP. Based on this, the minimum benefit of the participating customers is guaranteed.

To calculate the dissatisfaction cost of power reduction for customers, a quadratic function is used, as given in (10):

$$cc_{j,t} = k_{1,j} pc_{j,t}{}^{pro\,2} + k_{2,j} pc_{j,t}{}^{pro} - k_{2,j} pc_{j,t}{}^{pro}\theta_{j,t} \quad (10)$$

Where both coefficients, $k_{1,j}, k_{2,j}$, are positive and can be estimated using the historical data [24]. The customers may be demanding higher than their required level in order to be able to afford curtailments for a given hour. The value of θ can be between 0 and 1 and shows the satisfaction level of customers for power reduction. As implied by (11), the value of φ is between 0 and 1, showing the satisfaction level of customers for power consumption. In other words, less satisfaction for power consumption is equal to more satisfaction for power reduction. It is assumed that a linear bilateral relationship is available between $\theta_{j,t}$ and $\varphi_{j,t}$.

$$\varphi_{j,t} = 1 - \theta_{j,t} \quad (11)$$

By substituting (11) in (10), we have:

$$cc_{j,t} = k_{1,j} pc_{j,t}{}^{pro\,2} + \varphi_{j,t} k_{2,j} pc_{j,t}{}^{pro} \quad (12)$$

The least willing customer for energy consumption or the most willing customer for energy reduction ($\varphi_{j,t} = 0$) is seeking the highest marginal benefit or lowest marginal costs. Conversely, the most willing customer for energy consumption or the least willing customer for energy reduction ($\varphi_{j,t} = 1$) is looking for the lowest marginal benefit or highest marginal cost.

The benefit function of the MGO with the maximization objective is written as [14]:

$$Max\ \mathrm{bo} = \sum_{t=1}^{T}\sum_{j=1}^{J}\left(\lambda_{j,t} pc_{j,t}{}^{pro} - rc_{j,t}\right) \quad (13)$$

Where $\lambda_{j,t}$ is the cost of not supplying power to a specific customer, which can also be referred to as the rate of power exchange at a specific bus. Under specific conditions, transmitting electricity to remote areas and supplying some loads by the MGO requires an exorbitant cost. This high cost is defined as the "value of power interruptibility" and the MGO can easily calculate it using optimal power flow (OPF) [23]. The first term in (13) points to the MGO's revenue, as a function of the MGO's not delivering "pc" kW of power to a specific customer on the grid. The second term in (13) is the MGO's cost, paid as an incentive for the reduced "pc" kW power to the customer.

2.6.1. Calculation of $\varphi_{j,t}$

Parameter $\varphi_{j,t}$ adopts a value in the range of 0 and 1, and its value will be studied on an hourly basis in this paper in relation to the power reduction proposed by customers ($pc_{j,t}{}^{pro}$). Consequently, more reasonable results are obtained and it is effective on the customer costs and their received incentives. According to the definition of objectives, maximizing the MGO benefit is taken into account. In such a case, $bc_{j,t}$ must be minimum, meaning that the customers are satisfied, with the minimum benefits, to help the system remain stable. It does not imply that customers do not receive any incentives. Rather, they receive it proportional to their dissatisfaction caused by power reduction:

$$bc_{j,t} = 0 \quad \rightarrow \quad rc_{j,t} = cc_{j,t} \tag{14}$$

Therefore, the benefit function of the MGO under the contract of the DR is as follows:

$$\text{bo} = \sum_{t=1}^{T}\sum_{j=1}^{J}\left(\lambda_{j,t}pc_{j,t}{}^{pro} - cc_{j,t}\right) \tag{15}$$

The value of $\varphi_{j,t}$ is obtained on an hourly basis by the MGO considering the proposed $pc_{j,t}{}^{pro}$ by the participating customers in the DR, and $\lambda_{j,t}$ also helps it. Since the MGO tends to achieve its maximum benefit, we have:

$$\frac{\partial \text{bo}}{\partial pc_{j,t}{}^{pro}} = \lambda_{j,t} - 2k_{1,j}pc_{j,t}{}^{pro} - \varphi_{j,t}k_{2,j} = 0 \tag{16}$$

Then, $\varphi_{j,t}$ is found as:

$$\varphi_{j,t} = \frac{\lambda_{j,t} - 2k_{1,j}pc_{j,t}{}^{pro}}{k_{2,j}} \tag{17}$$

where $\varphi_{j,t}$ is the type of customer in a normalized form and represents the satisfaction level of customers for power consumption (or dissatisfaction level of customers for power reduction) on an hourly basis.

2.6.2. Mandatory Power Reduction

In some systems, the amount of demand is greater than the generation level; hence, the power balance is not met and the crucial role of DRP is highlighted in these cases. According to DRP and $pc_{j,t}{}^{pro}$, it is possible that in some hours the power balance is again not met, in which case a contract is signed between the MGO and the customers for further power reduction. Based on this, in some hours, the MGO is ready to compensate manifold damage for power reduction so as to persuade customers to reduce their power consumption beyond $pc_{j,t}{}^{pro}$, especially at peak load periods. This is so-called mandatory power reduction ($pc_{j,t}{}^{mand}$) in this paper. This is beneficial for both the MGO and the customers. This damage is taken into account only if $pc_{j,t}{}^{opt}$ is greater than $pc_{j,t}{}^{pro}$. In this method, in order to receive more incentive during the peak load period, the customers reduce power greater than $pc_{j,t}{}^{pro}$ and consistently shift their consumption to low-load periods. Power reduction greater than $pc_{j,t}{}^{pro}$ is represented as follows:

$$pc_{j,t}{}^{mand} = \begin{cases} \sum_{j=1}^{J}\sum_{t=1}^{T}\left(pc_{j,t}{}^{opt} - pc_{j,t}{}^{pro}\right) : if\ \left(pc_{j,t}{}^{opt} > pc_{j,t}{}^{pro}\right) \\ 0 \qquad : if\ \left(pc_{j,t}{}^{opt} \leq pc_{j,t}{}^{pro}\right) \end{cases} \tag{18}$$

In this paper, the paid incentive to customers as compensation for the mandatory power reduction, which is greater than $pc_{j,t}{}^{pro}$, is given as:

$$ccm_{j,t} = \begin{cases} \mu\ cc_{j,t}\left(pc_{j,t}{}^{mand}\right) : if\ \left(pc_{j,t}{}^{opt} > pc_{j,t}{}^{pro}\right) \\ 0 \qquad : if\ \left(pc_{j,t}{}^{opt} \leq pc_{j,t}{}^{pro}\right) \end{cases} \tag{19}$$

where, μ denotes the coefficient of incentive payment due to mandatory power reduction. The sum of imposed costs to the customers includes costs of dissatisfaction due to power reduction as well as damage and loss as a result of mandatory power reduction. The received incentive by customers is then rewritten as follows:

$$rc_{j,t} = cc_{j,t} + ccm_{j,t} \tag{20}$$

2.7. Integration of MG Generation Model with DR Model and Emissions

The objective function for optimal operation of the grid-connected MG is comprised of three main parts, namely the operation costs of MG units (f_1), the benefit of the MGO caused by DR ($-f_2$), and emission-related costs (f_3). Modeling of each of these objective functions was described in the previous sections. In optimization problems, weighting is very effective in investigating different modes of operation and showing how increasing the priority of an objective helps reach the desired results. In the present study, the MOOP is simplified to a SOOP using weighted sum method. Since the improvement in each of the mentioned objectives affects other objectives, it is essential to find a compromise between these objectives. In economic-environmental operation, costs and emission are taken into account, where the final objective function is obtained by minimizing Eq. (24):

$$f_1 = \sum_{t=1}^{T}\left(\sum_{i=1}^{I} cf_{i,t} + ct_t + cb_t\right) \tag{21}$$

$$f_2 = \sum_{t=1}^{T}\sum_{j=1}^{J}\left(rc_{j,t} - \lambda_{j,t}pc_{j,t}{}^{opt}\right) \tag{22}$$

$$f_3 = \sum_{t=1}^{T}\sum_{i=1}^{I} ce_{i,t} \tag{23}$$

It has to be noted that both f_1 and f_2 are based on ($); however, given the importance of MGO benefit as an objective function for the authors in this paper, it has been represented by a separate weighting factor.

$$min\ cost = w_1\,(f_1) + w_2(f_2) + w_3(f_3) \tag{24}$$

As in (25), weight are assigned based on the importance of their respective objective function and are normalized so that their sum is equal to 1.

$$w_1 + w_2 + w_3 = 1 \tag{25}$$

2.8. Constraints

Different constraints, such as operation constraints, have to be observed during the whole operation. Technical constraints can be denoted using the following mathematical equations:

PV power limit:

$$0 \leq p_{pv,t} \leq p_{pv}{}^{max} \quad (26)$$

WT power limit:

$$0 \leq p_{wind,t} \leq p_{wind}{}^{max} \quad (27)$$

DGs generated power limit:

$$p^{min} \leq p_{i,t} \leq p_i{}^{max} \quad (28)$$

The ramp rate limit for DGs: This constraint determines the maximum increase or decrease in the generated power by DGs from one hour to the next.

$$-dr_i \leq (p_{i,t+1} - p_{i,t}) \leq ur_i \quad (29)$$

The utility constraint: This refers to the transmission line constraint for power exchange between the MG and the main grid.

$$-p_{utility}{}^{min} \leq p_{utility,t} \leq p_{utility}{}^{max} \quad (30)$$

Load/Generation ZEB constraint: At each time interval, the summation of generated power by renewable and non-renewable energy resources plus the energy exchange with the main grid and the battery has to be equal to the consumption level; otherwise, customers will apply power reduction policy.

$$\sum_{i=1}^{I} p_{i,t} + p_{wind,t} + p_{pv,t} + p_{utility,t} + p_{batt,t} = p_{demand,t} - \sum_{j=1}^{J} pc_{j,t}{}^{opt} \quad (31)$$

The amount of optimal power reduction ($pc_{j,t}{}^{opt}$) is obtained from the sum of $pc_{j,t}{}^{norm}$ and $pc_{j,t}{}^{mand}$:

$$\sum_{j=1}^{J} pc_{j,t}{}^{opt} = \sum_{j=1}^{J} (pc_{j,t}{}^{norm} + pc_{j,t}{}^{mand}) \quad (32)$$

Import/Export ZEB constraint: This constraint is defined as the difference between the exported and imported energy at a specific time span [16].

$$p_{utility,t} = p_{import,t} - p_{export,t} \leq 0 \quad (33)$$

The constraint of energy stored in the battery: The amount of energy stored in the battery should not be less than a predetermined limit. State of charge (SOC) of the battery at any time is given by [28, 29, 30]:

Charge:

$$soc_{t+1} = soc_t \,.\, (1 - \xi \,.\, \Delta t) + \frac{\eta_{ch} \times p_{ch,t}\, b_t{}^{batt}}{c_{batt}} \quad (34)$$

Discharge:

$$soc_{t+1} = soc_t \,.\, (1 - \xi \,.\, \Delta t) - \frac{p_{dis,t}\,(1 - b_t{}^{batt})}{c_{batt} \times \eta_{dis}} \quad (35)$$

Where c_{bat} is the battery's capacity that depends on the technology used.

Battery energy status limit:

$$soc^{min} \leq soc_t \leq soc^{max} \quad (36)$$

The constraint of charging/discharging power of the battery: At each time interval, the battery can be charged or discharged up to a predetermined level.

$$p_{batt}{}^{min} \leq p_{batt,t} \leq p_{batt}{}^{max} \quad (37)$$

If:

$p_{batt,t} > 0$, the battery is discharging;

$p_{batt,t} < 0$, the battery is charging;

$p_{batt,t} = 0$, the battery is inactive.

$$\sum_{t=1}^{T} [rc_{j,t} - (cc_{j,t} + ccm_{j,t})] \geq 0 \quad (38)$$

Eq. (38) shows "Individual rationality constraint", which ensures that the daily payment to every customer is equal to or greater than the daily incurred cost of customers. Thus, the more power reduction is realized, the more received incentive by customers will be.

With regard to the daily budget of the MGO, the range of payment to customers is given by (39) which states that the daily payment to customers has to be less than the daily budget of the MGO [14].

$$\sum_{t=1}^{T} \sum_{j=1}^{J} rc_{j,t} \leq ob \quad (39)$$

3. Proposed Whale Optimization Algorithm (WOA)

WOA is a meta-heuristic optimization algorithm inspired by nature that imitates the hunting technique of humpback whale and acts using a special hunting mechanism known as the bubble-net method. In this method of feeding, whales encircle the prey inside shrinking bubbles by creating spiral bubbles (in the form of the number 9). First, they explore the vicinity of the prey (global optimum point) and then the nearest place to the prey (local optimum point). Once the best position is specified, the whale's position is updated with respect to that. Therefore, whales (the initial population) are divided into two groups. One group is responsible for seeking the prey (exploration phase), and the other group makes an effort to hunt the prey (exploitation phase). Based on this, vector $\vec{b}$ is defined as follows [26]:

$$\vec{b} = 2\vec{r}.\vec{c} - \vec{r} \quad (40)$$

$\vec{c}$ is a random vector in the range of [0, 1] and allows reaching any position inside the search space. The fluctuation range of $\vec{b}$ is reduced by the value of *r*, in which case WOA is initialized by a set of random solutions. In other words, $\vec{b}$ is a random value between [-*r*, *r*], where *r* is decreased from 2 down to 0 during the iteration period. At each iteration, the search agents update their positions through the decrease in b and according to the exploration mechanism (if $|b| \geq 1$) and/or exploitation mechanism (if $|b| < 1$).

3.1. Optimal Search for Prey (Exploration Phase)

In the exploration phase, whales search the prey location (the best solution) randomly and update their positions according to the positions of other whales. The mathematical model of this phase is described as:

$$\vec{p}(k+1) = \overrightarrow{p_r}(k) - \vec{b}.\vec{m} \quad (41)$$

$$\vec{m} = |\vec{v}.\overrightarrow{p_r(k)} - \overrightarrow{p(k)}| \quad (42)$$

$$\vec{v} = 2.\vec{c} \quad (43)$$

Where $\overrightarrow{p_r(k)}$ is the position vector randomly chosen among the current population (a random whale). $\overrightarrow{p(k)}$ denotes the position vector of a candidate solution (a random individual whale) based on which the positions are updated. Therefore, by selecting different values for vectors $\vec{b}$ and $\vec{v}$, different points at the neighborhood of the best solution can be chosen.

3.2. Optimal Encirclement of Prey (Exploitation Phase)

For $|b| < 1$ at each step, the prey-encircling process is formed, and it is assumed that the whale has found the vicinity of the prey. To model prey encircling, it is considered that there is a probability of 50% between the shrinking encircling mechanism or bubble-net attacking mechanism (to mitigate the spiral movement of the whale), which is used for updating the positions of whales during the optimization process. It is worth mentioning that δ is a random value between [0, 1]. Depending on the value of δ, WOA is able to act between either spiral encircling mechanism (if $\delta \geq 0.5$) or shrinking encircling mechanism (if $\delta < 0.5$). Using vector $\vec{s}$, the distance between the positions of whale and prey is calculated, and then a spiral equation is established between these positions. $\overrightarrow{p^*}(k)$ is the position of the best solution and if there is a better solution, $\overrightarrow{p^*}(k)$ has to be updated at each iteration. By decreasing $\vec{b}$, the search agents move towards the best solution (prey). Assuming that currently the best solution is the target prey or near to the optimum, whales update their positions with respect to the prey at every moment. As a result, the position of the whale is updated at each iteration using the following equation:

$$\vec{p}(k+1) = \begin{cases} \vec{s}.e^{df}.cos(2\pi f) + \overrightarrow{p^*}(k) & : if\ \delta \geq 0.5 \\ \overrightarrow{p^*}(k) - \vec{b}.\vec{m} & : if\ \delta < 0.5 \end{cases} \quad (44)$$

$$\vec{m} = \left|\vec{v}.\overrightarrow{p^*}(k) - \vec{p}(k)\right| \quad (45)$$

where d is a constant value to define the form of the logarithmic movement and f is a random number chosen between -1 and 1. Adjusting the values of vectors $\vec{b}$ and $\vec{v}$ we can obtain different locations around the best agent. It should be noted that the same concept can be generalized to a search space with N dimensions, and search agents inside the hypercube will move around the best solution obtained so far [26].

4. Simulation Results

The performance of DEED-WOA in the form of an optimal scheduling is investigated in this paper for different scenarios. The optimization model is 24-hour scheduling horizon that determines the following variables: optimal power reduction by customers, optimal incentive payment to customers, optimal power generation of DGs, optimal charging/discharging of the battery, and optimal exchanged power between the main grid and the MG.

Assumptions of the proposed method are as follows:

- Remote customers of the MG are capable of reducing their load and only their electrical loads are investigated.
- Definition of balance is used both for import/export and load/generation in a 24-hour time span.
- Renewable generators are always operating at their maximum possible power, as allowed by the weather conditions and based on their generation forecast beforehand. Moreover, their operation costs are considered zero.
- All units operate with a unity power factor. As such, only the active power is studied.
- DGs are always connected to the circuit, their startup costs are not considered, and their maintenance costs are included in the power generation cost function. Furthermore, DGs are controllable and can rapidly supply the output power at any hour upon request.
- DGs emission of MG has been investigated and main grid emission is not considered.
- Output cost function coefficients of participating customers ($k_{1,j}$, $k_{2,j}$) and the daily budget are known to the MGO.
- Power reduction limitation is bid by customers on an hourly basis and the resultant received incentive represents a real benefit in the DRP.

In this paper, the grid-connected MG is investigated using the developed model of DR and the ZEB approach. It includes 3 DG units, 1 WT unit, 1 PV unit, 1 battery unit, and 3 rural consumers in remote regions. Since electricity transmission to remote areas is usually expensive and demands exorbitant cost, DGs are used in small and average scales to supply the required power of such areas. Data of the three DGs (fuel cost coefficients, emission coefficients, output power limits, ramp rate limit) have been taken from [14].

The hourly values of power interruptibility ($\lambda_{j,t}$) for the three customers is shown in Figure 2 [14]. To obtain the hourly values of $\lambda_{j,t}$, Locational Marginal Prices (LMP) from the Pennsylvania-New Jersey-Maryland (PJM) Market are used [27].

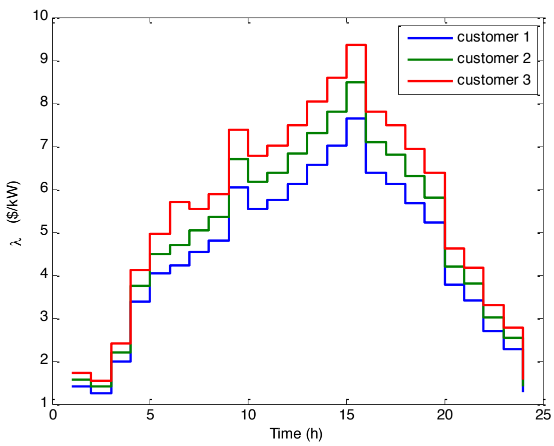

Figure 2. Hourly values of power interruptibility.

The total load demand of an MG per day is assumed 865.14 kWh and the peak load at 15:00 is 42.1 kW [14]. The maximum values for $\lambda_{j,t}$ and $p_{demand,t}$ happen at hour 15:00. The maximum output power of WT and PV units are assumed 11 kW and 15 kW, respectively [20]. Maximum transferrable power between the main grid and the MG is assumed 4 kW. The required parameters for battery application are provided in Table 1.

Table 1. Internal Parameter values of battery

Parameters	value
η_{ch} , η_{dis}	95%
DOD	66%
soc^0	30%
soc^{min}	30%
soc^{max}	100%
ξ (kWh/month)	5%
c_{batt} (kWh)	4
σ ($/kWh)	0.004

To calculate the incentive paid to customers due to ${pc_{j,t}}^{mand}$, the value of μ is determined based on a contract between customers and the MGO, and is set at μ = 2 in this study. In other words, to reduce the mandatory power above ${pc_{j,t}}^{pro}$, the amount of incentive is doubled. The microgrid operator's daily budget (ob) is $500 and output cost function coefficients of customers ($k_{1,j}$, $k_{2,j}$) are given in [14].

The MGO receives the hourly power reduction bid of customers (${pc_{j,t}}^{pro}$) according to Figure 3 and employs it to determine the type of customers ($\varphi_{j,t}$) based on Table 2. It has to be noted that (${pc_{j,t}}^{pro}$), as per Figure 3, has been selected based on simplicity and customers' comfort and independent of the time-of-use- (TOU-) based DR.

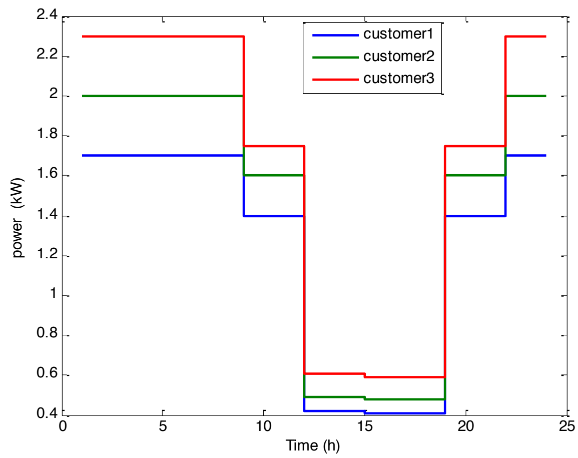

Figure 3. Bid amount of power curtailment for different customers.

Referring to Figure 2, the maximum and minimum values of $\lambda_{j,t}$ occur at 15:00 and 2:00, respectively. On the other hand, based on Figure 3, the maximum and minimum values of ${pc_{j,t}}^{pro}$ appear between 22:00-8:00 and 15:00-18:00, respectively. As indicated by (17), when ${pc_{j,t}}^{pro}$ is at its maximum and $\lambda_{j,t}$ is at its minimum, $\varphi_{j,t}$ will have its minimum value and vice versa. According to Table 2, the maximum and minimum values of $\varphi_{j,t}$ occur for Customer 1 at 15:00 and Customer 3 at 2:00, respectively.

Table 2. Proposed $\varphi_{j,t}$ values for customer types from 0 to 1.

t	$\varphi_{j,t}$ j=1	j=2	j=3
1	0.2697	0.1943	0.0117
2	0.2576	0.1832	0.0000
3	0.3157	0.2355	0.0572
4	0.4287	0.3375	0.1683
5	0.4828	0.3859	0.2216
6	0.4974	0.399	0.2703
7	0.5216	0.4212	0.2599
8	0.5442	0.4415	0.282
9	0.6950	0.6108	0.5229
10	0.6554	0.5755	0.4839
11	0.6716	0.5899	0.4995
12	0.8773	0.8079	0.7954
13	0.9128	0.8392	0.8298
14	0.9491	0.8719	0.8656
15	1.0000	0.9177	0.9156
16	0.8983	0.8262	0.8155
17	0.8765	0.8066	0.7941
18	0.8401	0.7739	0.7584
19	0.6296	0.5520	0.4586
20	0.5133	0.4474	0.3442
21	0.4842	0.4212	0.3156
22	0.3738	0.2885	0.1150
23	0.3391	0.2571	0.0806
24	0.2584	0.1845	0.0013

To show how the priority of an objective affects itself and other objectives, and to establish a single-objective function, the weighting method is used in the MOOP to represent features of different operation scenarios. It is worth noting that the MGO often considers equal priorities for all three objective functions. This is known as the base scenario (Scenario 4). Thereby, studying the influence of different weights in MOOP is of paramount importance for sensitivity analysis and observing the impacts.

Once the optimization problem, the objective function, constraints and input parameters are determined, optimal management in different scenarios is sought using WOA. Optimization results obtained from different scenarios with the import/export ZEB approach are given in Table 3. It is incumbent on us to note that as using φ_j or $\varphi_{j,t}$ does only affect the second term of the objective function (dependent on the DRP development), only the second terms of the objective functions are compared.

Table 3. Results of DEED-WOA with the import/export ZEB approach

Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Weights: w_1, w_2, w_3	0, 1, 0	0.5, 0.5, 0	0, 0.5, 0.5	1/3, 1/3, 1/3	0, 0, 1	1, 0, 0	0.5, 0, 0.5
Fuel Cost ($)	257.92	257.7	229.41	229.02	228.98	228.98	228.98
Customer Incentive ($)	213.58	226.30	360.88	363.49	377.06	389.45	389.45
Mandatory Curtailment (kWh)	9.72	11.39	12.43	12.51	12.53	12.38	12.38

Normal Curtailment (kWh)		72.76	72.45	101.46	101.83	103.00	104.40	104.40
Diesel Generation (kWh)		436.83	436.60	405.56	405.10	405.06	405.06	405.06
Import/Export Balance (kWh)		0	0	0	0	0	0	0
f_1 ($)		179.57	179.35	151.07	150.68	150.62	150.61	150.61
f_2 ($)	with φ_j	-180.55	-173.33	-133.89	-132.59	-117.05	-106.24	-106.24
	with $\varphi_{j,t}$	-180.53	-176.27	-146.95	-145.82	-131.66	-121.37	-121.37
	%decrease	--	1.66%	8.88%	9.07%	11.09%	12.47%	12.47%
Total operation Cost ($): $(f_1 + f)$		-0.96	3.07	4.12	4.85	18.96	29.23	29.23
f_3 (lb)		706.66	705.82	596.19	594.76	594.62	594.62	594.62

Scenario 1 is used for assessing the highest benefit of the MGO (minimization of the cost caused by the DRP) and costs related to generation units and emissions are neglected. In this scenario, since the power reduction by customers is low, the paid incentive is minimal, the optimal capacity of DGs are disregarded and their obtained generated capacity is greater than those of other scenarios. In scenarios 2 and 3, minimization of emissions and operation costs of generation units are neglected, respectively. Scenario 4 is used for optimizing the MG performance with the simultaneous objectives of reducing power generation costs and emissions and maximizing the benefit for MGO. In this scenario, objective functions are reasonably and fairly jointed together resulting in the best practical performance. Scenario 5, neglecting the operation costs of power generation and the benefit of the MGO, tries to reduce emissions. In scenarios 6 and 7, the lowest cost is related to the generation of distributed energy resources and the lowest benefit is associated with the MGO, meaning that in these scenarios maximizing the benefit of the MGO (caused by DRP) and optimal incentive policy are disregarded and the highest incentive is paid to customers, resulting in the increase in costs.

In order to observe the simulation performance, it is assumed that the MGO considers equal priorities for all three objective functions. Among the defined scenarios regarding the interaction between the objectives, the following values are found as the optimal solution for scenario 4 (the base scenario): operation cost = $150.6838, benefit of the MGO = $145.8294, and emissions = 594.76619 (lb). In comparison to the respective worst case scenarios, co-optimization results for objectives in this scenario show 16% reduction in operation cost, 20% increase in the benefit of the MGO, and 15.4% reduction in emissions. Table 4 lists optimization results of different scenarios without the import/export ZEB approach sorted for the sake of simplicity and easier comparison of sensitivity analysis.

Table 4. Results of DEED-WOA without the import/export ZEB approach

Scenario		Scenario 2	Scenario 6	Scenario 7	Scenario 4	Scenario 1	Scenario 3	Scenario 5
Weights: w_1, w_2, w_3		0.5, 0.5, 0	1, 0, 0	0.5, 0, 0.5	1/3, 1/3, 1/3	0, 1, 0	0, 0.5, 0.5	0, 0, 1
Fuel Cost ($)		259.81	252.19	238.35	232.27	218.69	164.82	159.25
Customer Incentive ($)		473.62	499.99	492.48	460.01	226.06	309.05	381.69
Mandatory Curtailment (kWh)		36.49	40.82	32.78	34.73	11.46	8.96	10.55
Normally Curtailment (kWh)		82.09	85.45	94.02	87.65	67.79	95.98	104.40
Diesel generation (kWh)		438.98	430.23	413.65	403.53	387.56	318.51	310.89
Import/Export Balance (kWh)		-38.38	-37.32	-20.02	-6.73	52.36	96.00	96.00
f_1 ($)		52.70	66.92	110.07	208.11	478.65	641.43	635.82
f_2 ($)	with φ_j	-23.59	-1.98	-53.00	-93.13	-149.24	-135.91	-92.09
	with $\varphi_{j,t}$	-39.56	-33.34	-71.91	-100.61	-149.64	-153.74	-110.53
	%decrease	40.37%	94.04%	26.29%	7.43%	0.27%	11.59%	16.68%
Total Operation Cost ($): $(f_1 + f_2)$		13.13	33.58	38.16	107.49	329.00	487.68	525.28
f_3 (lb)		713.64	685.92	636.16	622.44	572.26	387.92	370.40

As observed in Table 4, energy exchange with the main grid is limitless and import/export ZEB is not implemented. In scenarios 1, 3, and 5, in which $w_1 = 0$, the optimal energy exchange with the main grid is discarded; hence, a greater amount of energy is purchased from the main grid. Therefore, generation by DGs is decreased, obviously resulting in reduced fuel costs and emissions. As mentioned before, it is assumed that in scenario 4 the MGO considers equal priorities for the given three objectives, i.e. reduction of operation costs, maximizing the benefit of the MGO, and reducing emissions.

Based on Table 3, 4, with the policy of import/export ZEB, operation costs of units, the benefit of the MGO, and emissions respectively experience 27.6% reduction, 44.9% increase, and

4.4% reduction compared to those of the approach without import/export ZEB (in scenario 4). Based on the comparison of the given results, it is witnessed that applying import/export ZEB results in better performance. Results of scenario 4 (the base scenario) after carrying out the optimization process with the import/export ZEB approach are provided in the following figures.

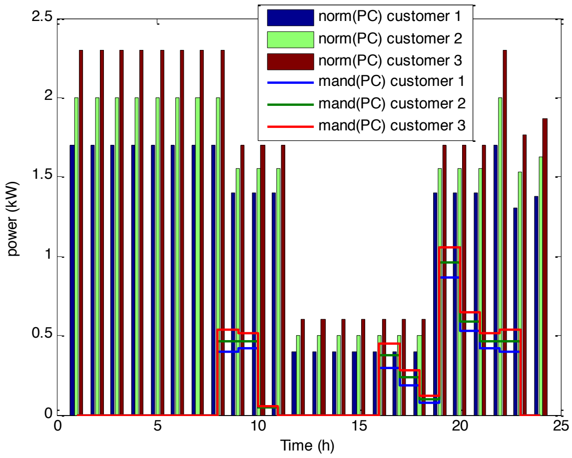

Figure 4. Amounts of optimum power curtailment by customers (sum of normal and mandatory power curtailments).

Figure 4 represents the values of $pc_{j,t}{}^{norm}$ and $pc_{j,t}{}^{mand}$, the sum of which shows the optimal power reduction by customers ($pc_{j,t}{}^{opt}$). The maximum value of $pc_{j,t}{}^{mand}$ is associated with hours 19:00 and 20:00 when the demand is high and PV is not accessible. During periods when $pc_{j,t}{}^{mand}$ is applied, first, the customers apply power reduction as much as $pc_{j,t}{}^{pro}$. However, the balance cannot be maintained and this is when the positive role of $pc_{j,t}{}^{mand}$ becomes clear. It is essential to note that the role of $pc_{j,t}{}^{mand}$ is not merely to maintain balance between supply and demand, but it also helps in further reduction of costs and emissions.

As Customer 3 has proposed greater power reduction at all hours compared to other customers, $\varphi_{3,t}$ and $\theta_{3,t}$ have become smaller and greater, respectively, than those of other customers for all hours. According to this fact, the capacity of Customer 3 in the developed DRP has been fully utilized and it receives the greatest incentive in comparison to other customers.

Figure 5 illustrates the optimal amount of generation by each RES and DG, charging/discharging power of the battery, power reduction by customers and power exchanges with the main grid. As the operation costs for WT and PV units are considered zero, their maximum output powers are utilized.

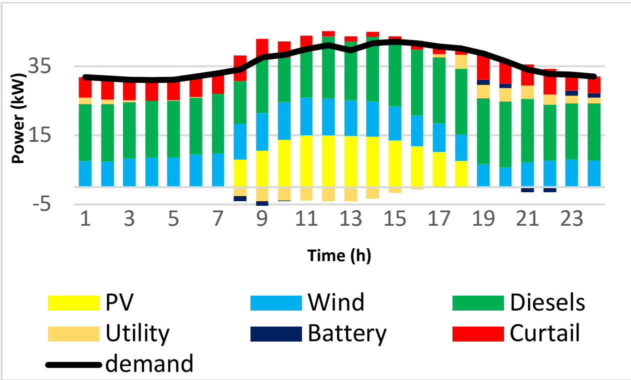

Figure 5. Results of optimal operation and scheduling with the import/export ZEB approach (Scenario 4).

According to Figure 5, all resources are maintained within their acceptable range of power generation. PV and WT do not impose any fuel cost and emission. Therefore, when used, they sensibly lower the overall cost and emissions. At the lowest and highest cases, WT delivers delivers 15.7% and 30.3% of the demand, respectively, and provides a valuable help to other units to reduce costs and emissions. Power generation by the PV from 19:00 to 7:00 of the next day is zero because solar radiation is unavailable. PV generation during 8:00 to 18:00 is coincident with the peak load which aids in considerable reduction of costs and emissions at those hours. Since PV and WT generation is high at hours 8:00 and 9:00 and considerable power reduction is made by customers, the battery is suitably charged so as to be able to provide acceptable discharging performance in case of emergency. Regarding the fact that power reduction by customers is low during hours 8:00 to 16:00, the excess produced power is sold to the main grid. As seen, since PV and WT have a minor role in power generation, the main grid plays a key role and compensates for the power deficiency. Nonetheless, with gradual growth in PV and WT generation, DGs reduce their output generation to lower the costs. The highest power reduction in the DG occurs when PV is connected to the grid. In this case, given the power reduction by customers, the generated power is in excess and is first used for battery charging and then sold to the main grid. The battery can store the excess energy during the low-demand hours and deliver it to the MG at hours when there is energy deficit. The role of all units, especially PV unit, is significant as its produced energy is sold to the main grid when PV is reconnected to the circuit and is also used to charge the battery at 8:00 and 9:00 so as to assist with the supply of the load at the next hours. The best performance of the battery occurs at 19:00 and 20:00 when the PV is disconnected and WT is at its lowest generation level. In this case, discharging the battery and purchasing energy from the main grid assists to meet the demand. In this study, in addition to minimizing operation costs, the amount of battery charging/discharging was also controlled so as to prevent degradation of battery's lifespan caused by abrupt charging/discharging which, in turn, may impose extra costs on the system.

Table 5. Customer energy curtailments (Scenario 4)

Energy Curtailed (kWh)	With import/export ZEB (kWh)			Without import/export ZEB (kWh)		
	${PC_{j,t}}^{norm}$	${PC_{j,t}}^{mand}$	${PC_{j,t}}^{opt}$	${PC_{j,t}}^{norm}$	${PC_{j,t}}^{mand}$	${PC_{j,t}}^{opt}$
Customer 1	29.1733	3.6457	32.819	25.8884	9.7915	35.6799
Customer 2	33.9452	4.1722	38.1174	29.8572	13.3403	43.1975
Customer 3	38.7170	4.6988	43.4185	31.9047	11.6060	43.5107
Total Energy Curtailed	101.8355	12.5167	114.3549	87.6503	34.7378	122.3881
%Reduction	11.77%	1.44%	13.21%	10.13%	4.01%	14.14%

Referring to Table 5, power reductions in cases with and without import/export ZEB are 13.21% and 14.14% of the total demand, respectively. In the case without import/export ZEB, due to selling energy to the main grid, customers procure greater power reduction and receive more incentive, which causes the benefit of the MGO to drop 31%. Based on this fact, the strain on other units of the MG increases, and operation costs and emissions increase by 38% and 4.6%, respectively. The result is that the approach without import/export ZEB is used as a solution when it is intended to increase the consumers' participation in energy exchange with the main grid. However, this leads to increased costs and emissions and therefore, the other approach, i.e. with import/export ZEB is preferred.

5. Conclusion

In this paper, optimal performance of a grid-connected MG in different scenarios was investigated. Also, by combining a developed DR inside the dynamic economic emission dispatch algorithm (DEED), the interaction between the MG and the main grid based on ZEB was proposed as a solution and, thereby, two approaches, namely with and without import/export ZEB, were evaluated. The use of ZEB provides many advantages including optimal energy management, increased efficiency, economic benefits, reduced emission, reduced power purchase from the main grid during peak load hours, and more efficient use of energy resources available in the MG. Analysis of optimal power allocation for different units shows that reducing the generated power by units with high emission in most hours of a day is essential for minimizing the emissions. The stored energy in the battery can contribute to minimizing the costs and emissions through being discharged during peak load hours especially when the penetration level of RES is low. The presence of RESs leads to reduced operation costs, reduces the dependency on fossil fuels and DGs, and assists in the execution of ZEB. Based on the limits sets by the offered power reductions by customers, customer types are determined and their cost function for receiving realistic incentive is developed in the DRP. In scenario 4, based on simultaneous optimization of objectives, the participation level of each of MG resource and the status of energy storage show remarkable reductions in operation costs and emissions. The proposed EMS is able to implement ZEB in the MG. The study of Scenario 4 under the approach without import/export ZEB showed that this approach can be considered as a solution when increased participation level of consumers is of interest; nevertheless, the approach with import/export ZEB provides lower cost and emission and therefore is the preferred approach. In general, by considering the ZEB approach, either with or without import/export, operation costs for all scenarios have decreased; however, the amount of emission depends on the type of balance, so that if balance is positive/negative, the amount of emission of the MG decreases/increases. The accuracy of the suggested method for solving optimal energy management problems in MGs as well as for optimizing other problems in power systems with the import/export ZEB approach are verified.

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