



Operation management of a renewable microgrid supplying to a residential community under the effect of incentive-based demand response program

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Abstract

A micro-grid (MG) comprises different energy sources of different operational characteristics. In this paper, we present an operation management model of a MG integrated with small renewable energy resources. The MG is operating in grid-connected mode and feeding energy to a residential community. The consumers of the residential community are participating in an incentive-based demand response (DR) program. The problem is formulated for the generation scheduling of the MG sources so that the operational cost and pollutants emission from the MG could be minimized in the presence of incentive responsive loads. The problem is then solved by the mixed integer linear programming technique using CPLEX solver of the GAMS software. The simulation results are achieved by solving the problem under three different cases. For the comparison of the results, we consider two scenarios in each case; (i) without DR program, (ii) with DR program. Finally, the trade-off between two conflicting objectives has been analyzed and optimal solution is achieved and presented in the paper.

Keywords Micro-grid · Renewable energy resources · Demand response · Energy management · Pollutant emission

Introduction

The integration of renewable energy resources with the small sources having storage facility leads to the concept of micro-grid (MG) [1]. In the technical literature, the concept of MG was first presented in [2–4]. They gave a solution for the reliable integration of distributed generation (DG) units, including energy storage systems and controllable, sensitive loads. MG management methods have been explained in many papers. Desirable features of management system of MG are, output voltage and current control of various DG units, ability to balance the power, ability to implement demand side management strategies, economic dispatch of DG units and ability to work in both stand-alone and grid-connected modes of operation [5]. Proper management of MG can lead to the cost saving, lesser pollutants emission

in the environment and improvement in the reliability of the system, [6]. Due to lots of beneficial features, MG is a burning area of research among the researchers [7].

In the recent research, it is found that it is possible to reduce the electricity consumption significantly with the optimal management of the power system. For the optimal management of the system, it is required to focus on alternative energy sources. One method for this is to include DG sources in the system, specially the renewable energy resources (RER). However, the main problem in the inclusion of the RERs in the system is their uncertain power generation pattern. Hence, some strategies are required to cover the uncertainties of the RERs. One solution to this problem is to purchase more energy from the utility, but this may cause many other problems in other parts of the system, like load unbalance, higher costs, higher emission, etc. [8]. Sometimes, the system operator uses the reserve energy to manage the gap caused by the uncertainty of the RERs [9].

Another solution for this problem is the participation of the consumers in a demand response (DR) program. Modified definition of DR is presented in [10] as the change in electricity usage of end-use consumers from their normal consumption pattern, in response to the changes in the price of electricity over the time. There are different

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types of DR programs such as incentive-based programs (IBP) and price based programs (PBP). In IBPs, consumers allow the utility to control their loads during peak hours, congestion or any other emergency in the system and receive benefits in terms of incentives. In PBPs, consumers change their demand in response to price change of electricity in real time.

For the management of the MG, the researchers have focused on the two modes of MG operation; (i) stand-alone mode, (ii) grid-connected mode. Scheduling methods of the MG in stand-alone mode have been discussed in detail in [11–13]. While the research about the grid-connected mode has been included and discussed in [14–18]. In [14], the authors proposed a robust programming model for the MG scheduling. The deterministic models have been proposed and discussed in [15, 16]. In [17, 18], the authors explained the stochastic programming models of the MG scheduling. In [19], an energy management system was proposed for the management of the MG and for the uncertainties of wind and solar power sources, when they were connected to the MG. Heuristic algorithm has been used in [20] for the smart energy management of the MG. The uncertainties of photovoltaic (PV) energy source have been covered by the spinning power reserve in this paper. In [21], spinning reserve has been used to cover the shortage of wind power, while in [22] the authors used DR program for the solution of the same issue. The authors used a particle swarm optimization algorithm in [23] for the operation cost minimization under the system constraints and DR program. The authors in [24] have solved a multi-objective problem using ϵ -constraints for the management of smart distribution system connected with solar and wind power sources under the presence of DR program. The above discussed papers, did not focus on the coverage of the uncertainties caused by the wind and solar energy sources by the participation of the consumers. Along with this, in most of the papers the proposed models were complex. Hence, focus is required on the simplified models without losing the accuracy in the results.

In this paper, we present a MG energy management model. The main contribution of the paper is an easy formulation and solution of the problem in the presence of incentive responsive loads. Two objectives are formulated to minimize the operational cost and pollutants emission from the MG sources. Initially a non-linear problem is formulated and later it is converted into a linear problem with an assumption and without losing any accuracy of the result. A mixed integer linear programming (MILP) technique is applied for the solution of the converted problem. Using GAMS software, the solution is achieved in very less time as compared to the other solution tools, which is also an important factor of our paper. Use of DR program during the generation scheduling helps in the fulfillment of the gaps created by the uncertainties of the wind

turbine (WT) and PV sources, which is also an improving step toward the uncertainties management of the RERs.

The remaining paper is organized as follows: Micro-grid model is discussed in “[Problem formulation](#)” in detail. Mathematical models of different DG sources have been also included in this section. Case study and the results have been shown and discussed in “[Case studies and result analysis](#)”. Comparative analysis of different case studies has been also discussed in this section. Concluding remarks have been included in “[Conclusion](#)”.

Problem formulation

In this paper, we consider the problem of operation management of a grid-connected MG integrated with RERs. In this problem, generation of the MG is scheduled under the incentive-based demand response program to fulfill the demand of a residential community without interruption even in the presence of RERs, having intermittent characteristics. The MG, consisting of micro-turbines (MT), fuel cells (FC), battery (BA), WT, PV energy generation sources and incentive responsive loads, supplies the energy within the 24-h period. The main objective of the problem is to minimize the operating costs of the MG and the pollutant emissions from the MG without and with considering incentive responsive loads. Various equality and inequality constraints are included in the problem formulation to include the uncertainties caused by the solar and wind energy generation.

Objective function

The two objective functions of the paper, i.e., minimization of the operating cost of the MG and pollutant emission from the MG, are formulated without and with considering incentive responsive loads as follows.

Operating cost minimization

The operating cost of the MG consists of the cost functions of all energy generation sources considered in the MG, cost of energy exchange with the main grid and cost of DR participation. Cost functions of sources include fuel cost of the sources, maintenance cost and their start-up and shut-down cost. The operating cost function is formulated as:

$$\min C = \sum_{t=1}^{24} \{C_{DG}(t) + C_S(t) + C_{GRID}(t) + C_{DR}(t)\}, \quad (1)$$

$$C_{DG}(t) = \sum_{x=1}^X P_{DGx}(t) \times OC_{DGx}(t), \quad (2)$$

$$C_S(t) = \sum_{y=1}^Y P_{S_y}(t) \times OC_{S_y}(t), \tag{3}$$

$$C_{GRID}(t) = P_{GRID}(t) \times RT_{GRID}(t), \tag{4}$$

$$C_{DR}(t) = P_{DR}(t) \times RT_{DR}(t), \tag{5}$$

where C is the operating cost function which is to be minimized, $P_{DG_x}(t)$ and $P_{S_y}(t)$ are the active power output of x th DG and y th energy storage unit at time t , respectively. $P_{GRID}(t)$ and $P_{DR}(t)$ are the active power exchange with the grid and the power for participation in the DR program at time t , respectively. $OC_{DG_x}(t)$ and $OC_{S_y}(t)$ are the operating costs of the DG and energy storage unit at time t , respectively. $RT_{GRID}(t)$ is the rate for the power exchange with the grid at time t . $RT_{DR}(t)$ is the rate for participation in the DR program.

Pollutant emission minimization

The pollutant emission function of the MG consists of the emission functions of all conventional energy generation sources considered in the MG and emission function of the main grid. The mathematical model of the emission function is given as:

$$\min E = \sum_{t=1}^{24} \left\{ \sum_{x=1}^X P_{DG_x}(t) \times EM_{DG_x}(t) + \sum_{y=1}^Y P_{S_y}(t) \times EM_{S_y}(t) + P_{GRID}(t) \times EM_{GRID}(t) \right\}, \tag{6}$$

where $EM_{DG_x}(t)$, $EM_{S_y}(t)$ and $EM_{GRID}(t)$ are the quantity of pollutants emission in kg/MWh from the DG, energy storage unit and grid at time t , respectively. We consider CO₂ (carbon dioxide), SO₂ (sulfur dioxide) and NO₂ (nitrogen dioxide) pollutants in this paper.

Constraints

The constraints associated with the problem are as follows.

Active power generation limit

$$P_{DG_x(mm)}(t) \leq P_{DG_x}(t) \leq P_{DG_x(mx)}(t), \tag{7}$$

$$P_{S_y(mm)}(t) \leq P_{S_y}(t) \leq P_{S_y(mx)}(t), \tag{8}$$

$$P_{GRID(mm)}(t) \leq P_{GRID}(t) \leq P_{GRID(mx)}(t), \tag{9}$$

where $P_{DG_x(mm)}(t)$, $P_{S_y(mm)}(t)$ and $P_{GRID(mm)}(t)$ are the minimum real power of x th DG, y th energy storage unit and the grid at time t , respectively. $P_{DG_x(mx)}(t)$, $P_{S_y(mx)}(t)$ and

$P_{GRID(mx)}(t)$ are the maximum level of the real power of the units.

Load balance

$$\sum_{x=1}^X P_{DG_x}(t) + \sum_{y=1}^Y P_{S_y}(t) + P_{GRID}(t) = P_D(t) - P_{DR}(t), \tag{10}$$

where $P_D(t)$ is the demand level of the residential community at time t .

Battery limits

$$SOC_y(t) = SOC_y(t-1) + \eta_{ch_y} \times m_{ch_y} \times P_{ch_y}(t) - \frac{1}{\eta_{dis_y}} \times m_{dis_y} \times P_{dis_y}(t), \tag{11}$$

$$SOC_y(t) \leq SOC_y^{mx}, \tag{12}$$

$$SOC_y(t) \geq SOC_y^{mn}, \tag{13}$$

$$m_{ch_y} + m_{dis_y} \leq 1. \tag{14}$$

The above battery limits have been taken from [25], where $SOC_y(t)$ and $SOC_y(t-1)$ are the state of charge of y th storage device at current and previous hour, respectively. $P_{ch_y}(t)$ and

$P_{dis_y}(t)$ are the charging and discharging rate during a defined interval Δt . Equation (12) and (13) represent the maximum and minimum charging limits of the storage device at hour t . m_{ch_y} and m_{dis_y} are the binary variables and Eq. (14) indicates that charging and discharging of the storage device cannot take place simultaneously. η_{ch_y} and η_{dis_y} are charging and discharging efficiencies of the storage device.

Demand response modeling

In this paper, a residential community is considered as the participant of the incentive-based DR program. The behavior of residential consumer is modeled as follows.

$$\text{cost}(n, t) = p(n, t) \times \text{price}(n, t), \tag{15}$$

$$p(n, t) \leq p_t^{mx}, \tag{16}$$

$$P_{DR}(t) = \sum_{n \in N} p(n, t), \tag{17}$$

where $n=1, 2, \dots, N$ represent the number of residential consumers in the residential community. $p(n, t)$ and $\text{price}(n, t)$ are the planned reduction in the load and the incentive payment

due to load reduction by the n th consumer at time t , respectively. $cost(n, t)$ is the total cost for the DR participation of the n th consumer at time t . p_t^{max} is the maximum load reduction proposed by the consumer at time t . Equation (17) indicates the total load reduction of the residential community at time t .

Proposed solution

Objective functions of the paper are shown by Eqs. (1) and (6). The objectives shown by the equations are linear. The linear function does not create a complexity during the solution. Both the equality and inequality type constraints have been shown by Eqs. (7–10). Due to the linearity of the objective functions with the constraints having both integer and non-integer values, the problem is solvable using MILP techniques. For the solution of MILP problem, we use CPLEX solver of GAMS software. For the solution of MILP problem, CPLEX uses a branch and cut algorithm which solves a series of linear programming and sub-problems. Branch and cut algorithm is a very successful method for solving a variety of integer programming problems, and it provides a guarantee of optimality. This method is an exact algorithm consisting of a combination of a cutting plane method and a branch-and-bound algorithm. It takes less than a few seconds to obtain the solution on 64-bit, intel core-i7, 3.40 GHz personal computer.

Table 1 Power generation limits of installed DG sources

S. no.	Source type	Min. power (kW)	Max. power (kW)
1	MT	6	30
2	FC	3	30
3	Battery	−30	30
4	WT	0	25
5	PV	0	15
6	Utility	−30	30

Table 2 Operating costs and emission values of the DG sources

S. no.	Source type	Operating cost (₹ct/kWh)	SO ₂ (kg/MWh)	NO ₂ (kg/MWh)	CO ₂ (kg/MWh)
1	MT	3.3	0.0036	0.1	720
2	FC	5.41	0.003	0.0075	460
3	Battery	0.38	0.0002	0.001	10
4	WT	0.44	0	0	0
5	PV	0.37	0	0	0
6	Utility	–	0.5	2.1	950

Case studies and result analysis

A grid-connected micro-grid consisting of multiple generation sources, like MT, FC, BA, WT and PV, is considered for the case study. Maximum and minimum power generation limits of the energy sources are shown in Table 1 [26]. Operating costs of different DGs, amount of pollutants emission from the system are shown in Table 2 [26, 27].

It is considered that a battery of 150 kWh capacity is connected in the system, which charges when there is sufficient economic energy available from other power sources and discharges during opposite scenario. The charging and discharging efficiency of the battery is 95%. Minimum and maximum amount of the energy storage in the battery is 10% and 100% of battery capacity, respectively. The power outputs of considered renewable energy sources are predicted for day ahead use by an expert system and are shown in Table 3.

It is assumed that the micro-grid supplies the energy to a residential community having a total demand of 1684 kWh on a particular day. The hourly demand of the residential community is shown in Fig. 1 [26]. Real time market price is taken from [28] and is shown in Fig. 2.

Table 3 Forecast value of renewable energy sources of the MG

Hour	PV (kW)	WT (kW)	Hour	PV (kW)	WT (kW)
1	0	2.4	13	23.5615	7.6
2	0	2.4	14	22.33025	5.6
3	0	2.4	15	20.07325	9.6
4	0	0.2	16	15.21975	8.6
5	0	1.4	17	11.6505	5.6
6	0	3.4	18	4.878	2.4
7	3.02075	2.4	19	0	4.6
8	8.02225	1.4	20	0	3.4
9	13.67525	3.4	21	0	4.6
10	17.70025	5.6	22	0	4.6
11	21.57475	6.6	23	0	0.4
12	22.724	5.6	24	0	2.4

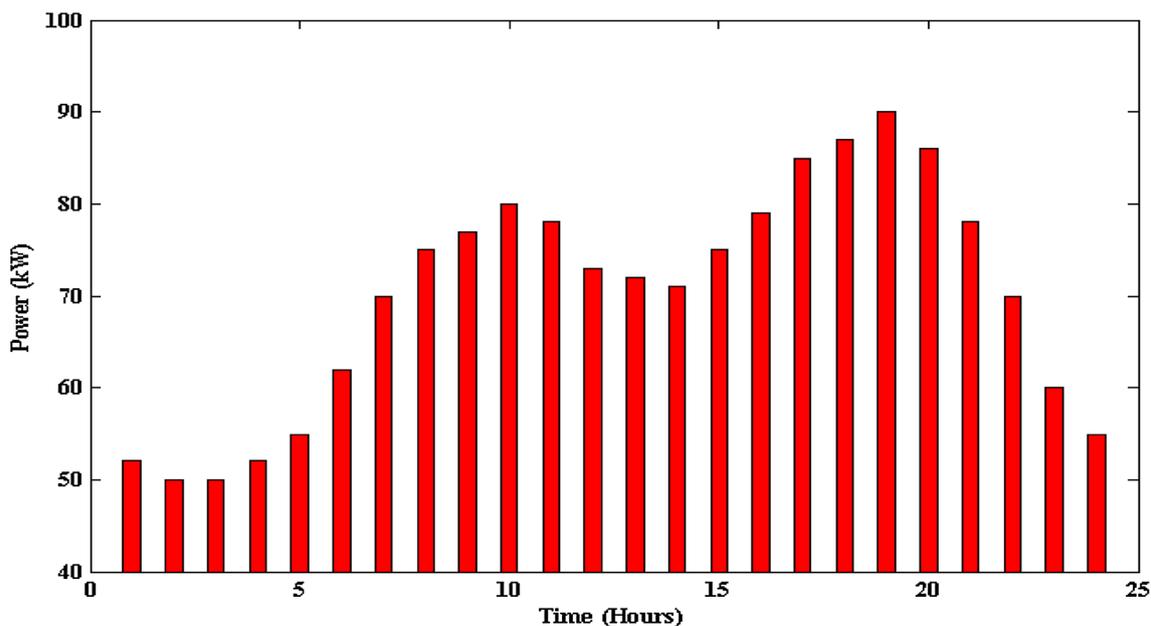


Fig. 1 Hourly load demand of the residential community

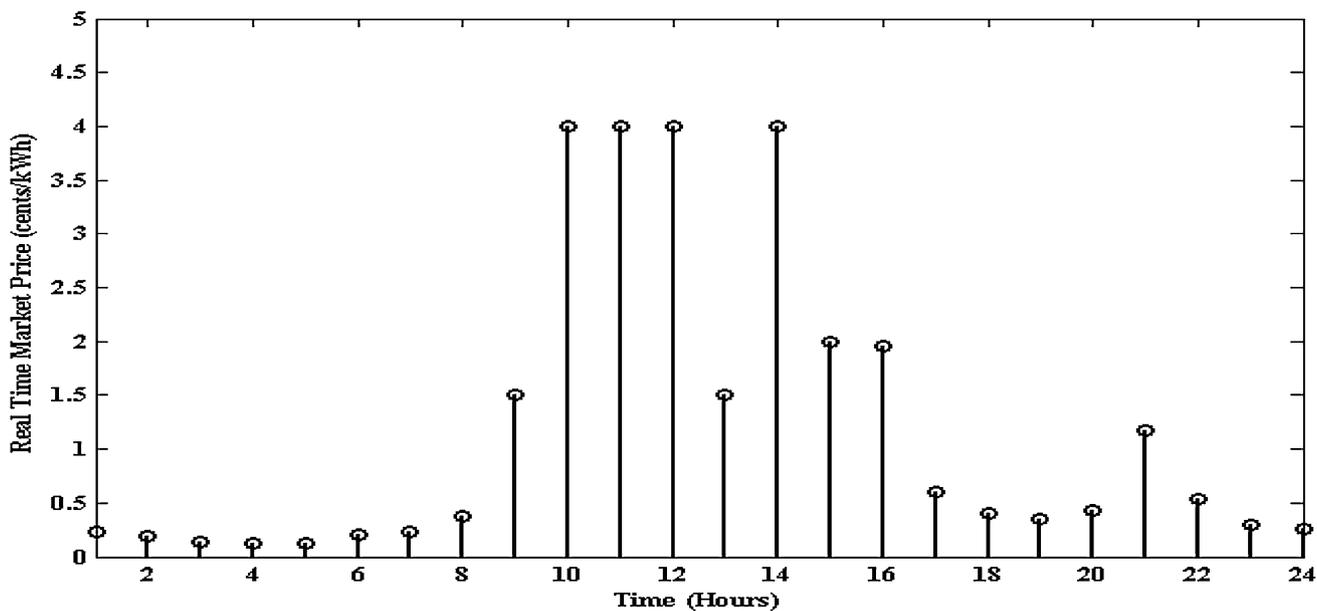


Fig. 2 Real time market price

Further, it is assumed that 40% of the total consumers are participating in the DR program. Prices for the participation in the incentive-based DR program are shown in Table 4. In this paper, it is assumed that the consumers participate in a DR program in which the demand response value is 33% of the total available load for the demand response.

Table 4 Incentive rates for different DR values

The demand response value	33% of available load for demand response	66% of available load for demand response	100% of available load for demand response
Incentive rate (€ct/kWh)	1.5	2.5	3.5

For the case study, following two cases have been considered and each case is analyzed without and with considering the DR program.

1. MG operation management with all the normal constraints
2. MG operation management by considering infinite power exchange with the grid.

Minimization of operating cost in case-1, without and with DR program

In this case, the operating cost of the MG is minimized by scheduling the MG generation units under their normal constraints. The results of generation scheduling of the units are shown in Table 5, Fig. 3 and Table 6, Fig. 4, without and with the responsive loads, respectively. The results shown in Table 5 and Fig. 3 are related to the case without considering the DR program. The results indicate that the utility power is purchased during low market price hours, while the MG power is sold to the utility during high price hours.

Table 6 and Fig. 4 show the results related to the case with considering the DR program. Under the

incentive-based DR program, few demand of the consumer reduces and in response, they receive the incentives. It can be clearly seen from the results that due to reduction in the load demand under the DR program, the use of MT and grid power during high price hours reduces significantly because of their high cost. The generation of MT power reduces more because it has higher energy generation cost. Along with this, the scheduled generation pattern of other sources can be also seen in the table. Finally, the operating cost of the MG is 3074.38 €ct and 2634.98 €ct without and with the DR program, respectively, which shows a very significant reduction in the operating cost and verifies the effectiveness of the proposed approach.

Figure 5 shows the impact of the DR program on the load demand of the consumers. The peaks on the demand curve without the DR program are reduced to some lower value.

Further, this case is analyzed with an assumption that the power shifting is allowed. Due to this assumption consumers load demand reduce at some hour and shift to some other hour. Hence, the total demand remains constant with and without the DR program. With this assumption, the

Table 5 Power scheduling without DR in case-1 (for minimum operation cost)

Hour	MT (kW)	FC (kW)	BA (kW)	PV (kW)	WT (kW)	GRID (kW)	Total demand (kW)
1	6	3	10.6	0	2.4	30	52
2	30	3	-15.4	0	2.4	30	50
3	30	3	-15.4	0	2.4	30	50
4	30	3	-11.2	0	0.2	30	52
5	30	3	-9.4	0	1.4	30	55
6	30	3	-4.4	0	3.4	30	62
7	30	3	1.57925	3.02075	2.4	30	70
8	30	3	2.57775	8.02225	1.4	30	75
9	30	3	-3.07525	13.67525	3.4	30	77
10	30	3	30	17.70025	5.6	-6.30025	80
11	30	3	-3.89875	21.57475	6.6	20.724	78
12	30	3	30	22.724	5.6	-18.324	73
13	30	3	-22.1615	23.5615	7.6	30	72
14	30	3	30	22.33025	5.6	-19.9303	71
15	30	3	-17.6733	20.07325	9.6	30	75
16	30	3	-7.81975	15.21975	8.6	30	79
17	30	3	4.7495	11.6505	5.6	30	85
18	30	3	16.722	4.878	2.4	30	87
19	30	3	22.4	0	4.6	30	90
20	30	3	19.6	0	3.4	30	86
21	30	3	10.4	0	4.6	30	78
22	30	3	2.4	0	4.6	30	70
23	28.6	3	0	0	0.4	30	62
24	19.6	3	0	0	2.4	30	55



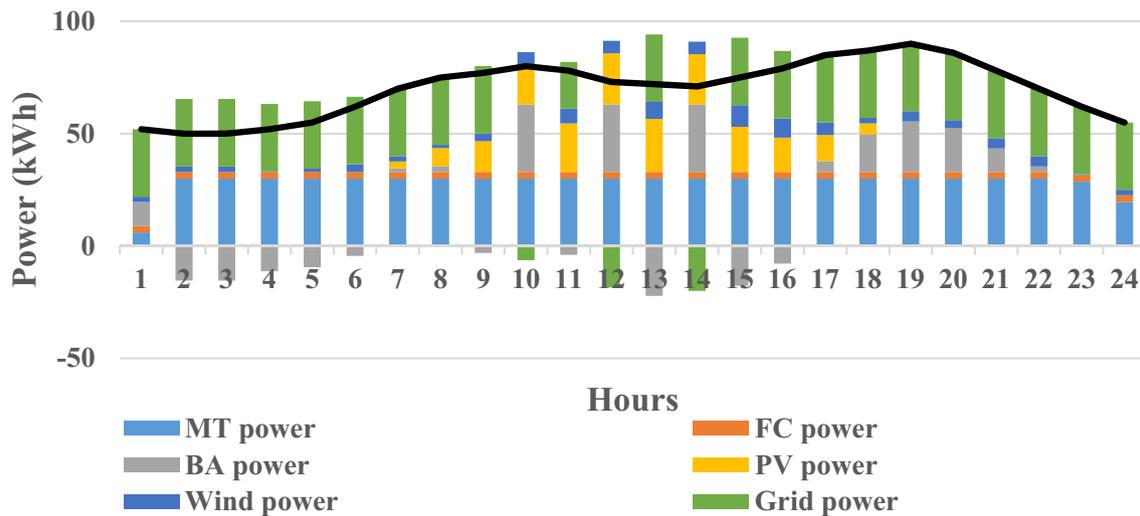


Fig. 3 Power scheduling without DR in case-1 (for minimum operation cost)

Table 6 Power scheduling with DR in case-1 (for minimum operation cost)

Hour	MT (kW)	FC (kW)	BA (kW)	PV (kW)	WT (kW)	GRID (kW)	Total demand (kW)
1	6	3	10.6	0	2.4	23.136	45.136
2	13.692	3	-5.692	0	2.4	30	43.4
3	30	3	-22	0	2.4	30	43.4
4	30	3	-18.064	0	0.2	30	45.136
5	30	3	-16.66	0	1.4	30	47.74
6	30	3	-12.584	0	3.4	30	53.816
7	15.017	3	7.32225	3.02075	2.4	30	60.76
8	30	3	-7.32225	8.02225	1.4	30	65.1
9	16.76075	3	0	13.67525	3.4	30	66.836
10	30	3	30	17.70025	5.6	-16.8603	69.44
11	30	3	30	21.57475	6.6	-23.4708	67.704
12	30	3	30	22.724	5.6	-27.96	63.364
13	6	3	-7.6655	23.5615	7.6	30	62.496
14	30	3	30	22.33025	5.6	-29.3023	61.628
15	30	3	-27.5733	20.07325	9.6	30	65.1
16	30	3	-18.2478	15.21975	8.6	30	68.572
17	30	3	-6.4705	11.6505	5.6	30	73.78
18	30	3	5.238	4.878	2.4	30	75.516
19	10.52	3	30	0	4.6	30	78.12
20	8.248	3	30	0	3.4	30	74.648
21	20.385	3	9.719	0	4.6	30	67.704
22	30	3	-6.84	0	4.6	30	60.76
23	13.576	3	6.84	0	0.4	30	53.816
24	12.34	3	0	0	2.4	30	47.74

operating cost of the MG increases to a value 3059.83 €. The load demand curve with the above assumption is shown in Fig. 6.

In Fig. 6, it can be noticed that some demand during high market price time shifts towards low market price time but the peaks on the demand curve do not reduce.

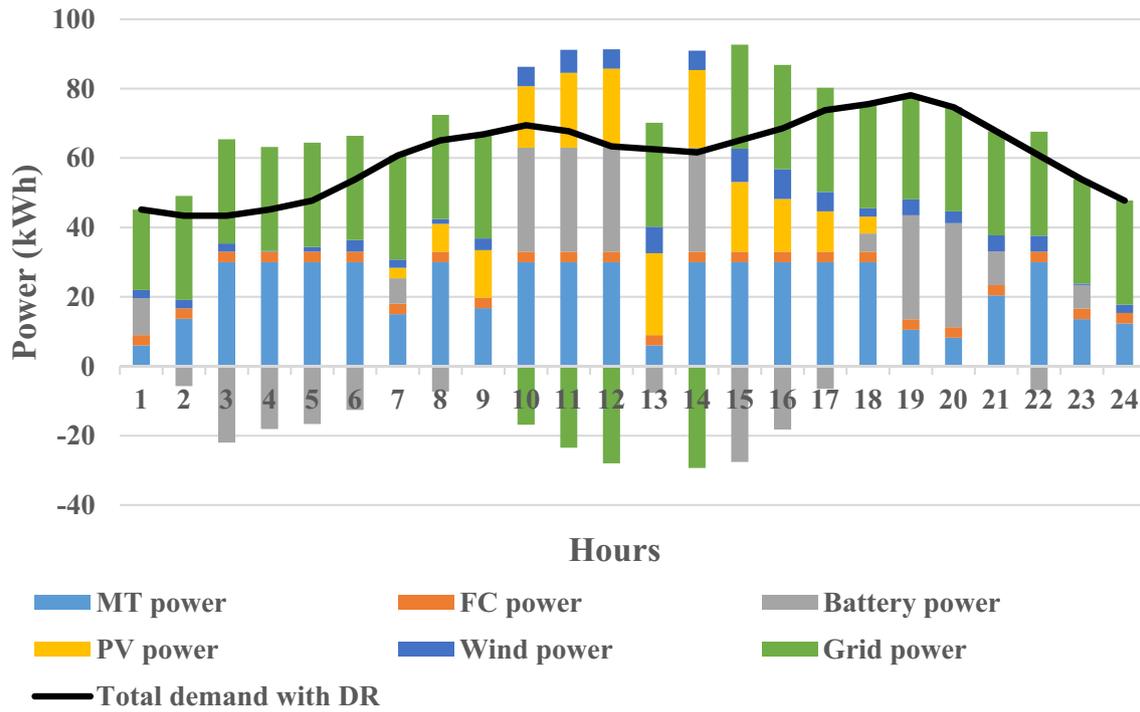


Fig. 4 Power scheduling with DR in case-1 (for minimum operation cost)

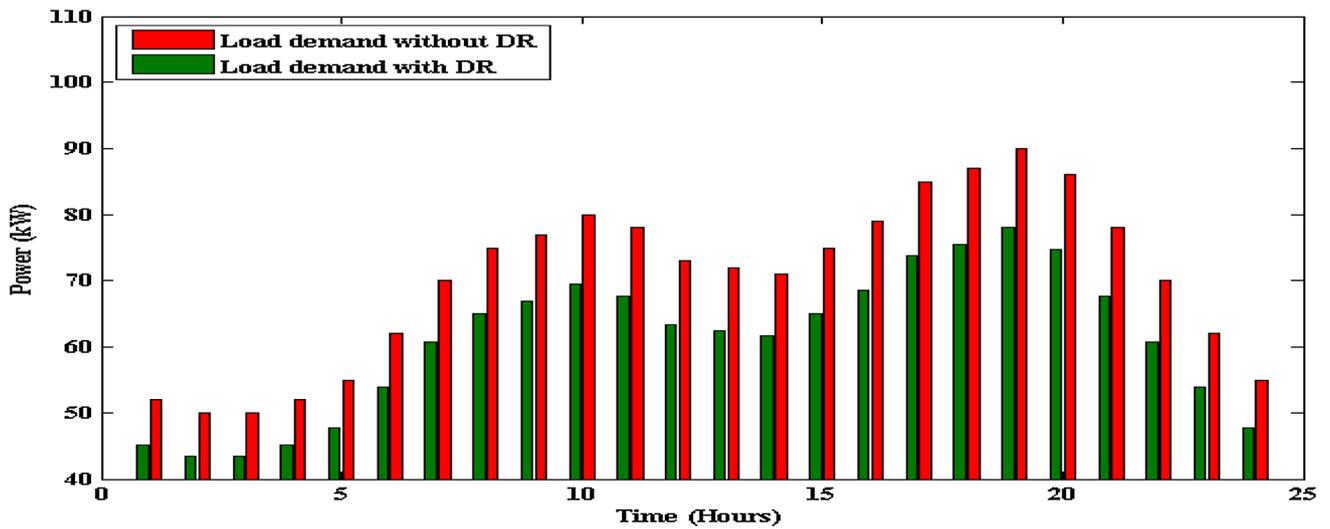


Fig. 5 Load demand of the residential community with and without DR

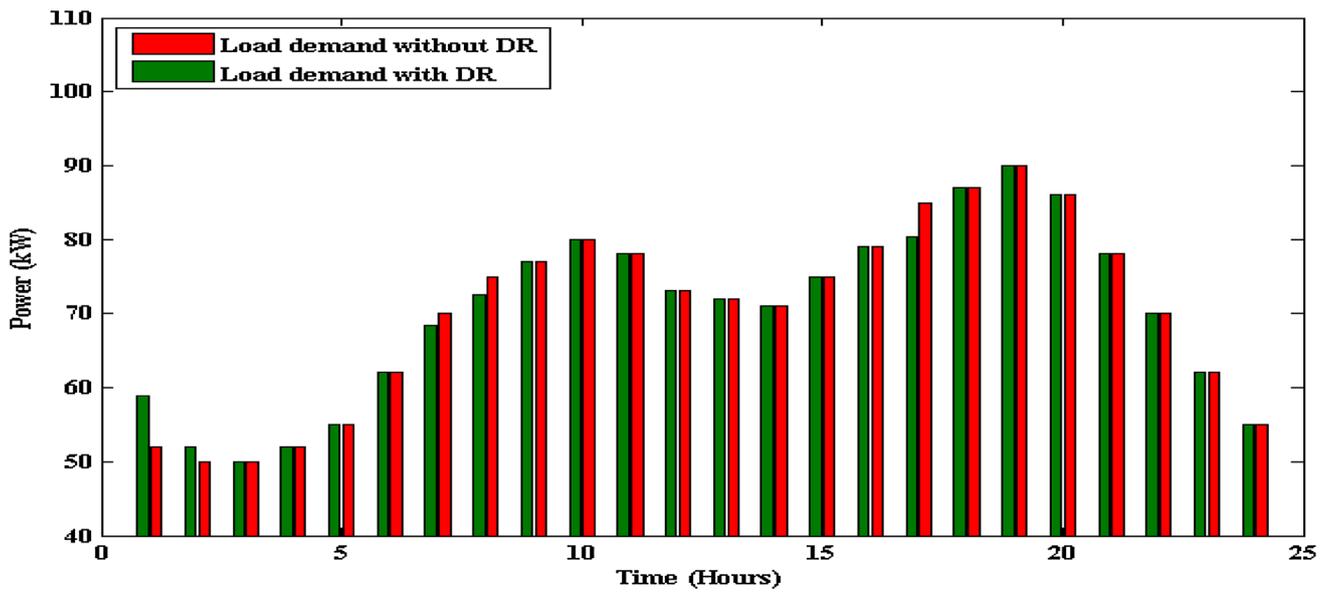


Fig. 6 Load demand of the residential community with and without DR, with the assumption of load shifting

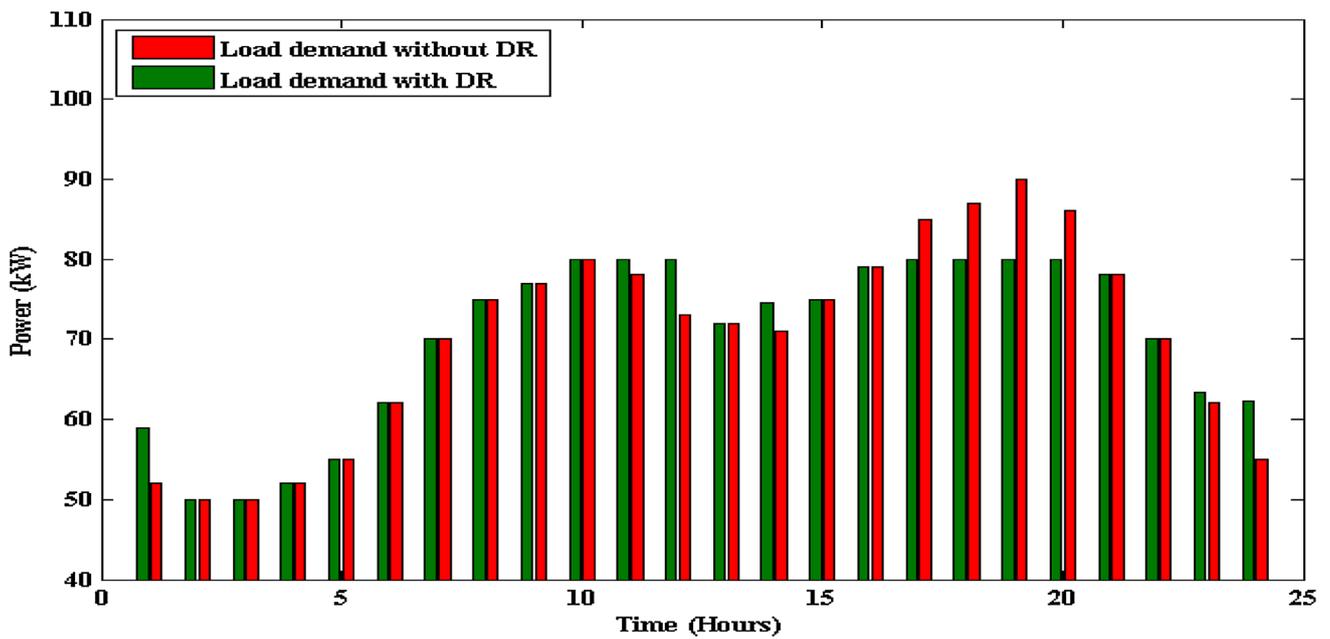


Fig. 7 Load demand of the residential community with and without DR, with the assumption of load shifting and upper limit on per hour energy consumption

Table 7 Power scheduling without DR in case-2 (for minimum operation cost)

Hour	MT (kW)	FC (kW)	BA (kW)	PV (kW)	WT (kW)	GRID (kW)	Total demand (kW)
1	6	3	-30	0	0	73	52
2	6	3	15	0	0	26	50
3	6	3	-30	0	0	71	50
4	6	3	-30	0	0	73	52
5	6	3	-30	0	0	76	55
6	6	3	0	0	0	53	62
7	6	3	0	0	0	61	70
8	6	3	0	0	1.4	64.6	75
9	6	3	0	13.67525	3.4	50.92475	77
10	30	3	30	17.70025	5.6	-6.30025	80
11	30	3	30	21.57475	6.6	-13.1748	78
12	30	3	30	22.724	5.6	-18.324	73
13	6	3	-30	23.5615	7.6	61.8385	72
14	30	3	30	22.33025	5.6	-19.9303	71
15	6	3	30	20.07325	9.6	6.32675	75
16	6	3	15	15.21975	8.6	31.18025	79
17	6	3	0	11.6505	5.6	58.7495	85
18	6	3	-30	0	2.4	105.6	87
19	6	3	-30	0	0	111	90
20	6	3	0	0	3.4	73.6	86
21	6	3	30	0	4.6	34.4	78
22	6	3	30	0	4.6	26.4	70
23	6	3	-30	0	0	83	62
24	6	3	-30	0	0	76	55

This problem can be solved by putting an upper limit on the per hour energy consumption under the DR program. This upper limit on the energy consumption further increases the operating cost of the MG to the value 3085.47 €ct. The demand curve with the upper limit on energy consumption is shown in Fig. 7.

Minimization of operating cost in case-2, without and with DR program

In this case, it is assumed that the MG can exchange infinite power with the utility and other constraints remain as they were in case-1. The results shown in Table 7 are related to the case without considering the DR program. The results

show that only utility power is purchased to fulfill the load demand during the hours where the real time market price is lower than the price of generation of other sources. The MG power is sold to the utility during the hours, when the real time market price is high so that the operating cost of the MG could be minimized.

The results related to the case with considering the DR program are shown in Table 8. From the results of Tables 7 and 8, it can be said that the MG consumes/sells more energy from/to the utility during low/high price hours under the effect of DR program. The generation patterns of the other sources of the MG can be seen in the table. The operating cost of the MG in this case is 1630.48 €ct and 1521.18 €ct without and with the DR program, respectively.

Table 8 Power scheduling with DR in case-2 (for minimum operation cost)

Hour	MT (kW)	FC (kW)	BA (kW)	PV (kW)	WT (kW)	GRID (kW)	Total demand (kW)
1	6	3	-30	0	0	73	52
2	6	3	15	0	0	26	50
3	6	3	-30	0	0	71	50
4	6	3	-30	0	0	73	52
5	6	3	-30	0	0	76	55
6	6	3	0	0	0	53	62
7	6	3	0	0	0	61	70
8	6	3	0	0	1.4	64.6	75
9	6	3	0	13.67525	3.4	50.92475	77
10	30	3	30	17.70025	5.6	-16.8603	69.44
11	30	3	30	21.57475	6.6	-23.4708	67.704
12	30	3	30	22.724	5.6	-27.96	63.364
13	6	3	-30	23.5615	7.6	61.8385	72
14	30	3	30	22.33025	5.6	-29.3023	61.628
15	6	3	30	20.07325	9.6	-3.57325	65.1
16	6	3	15	15.21975	8.6	20.75225	68.572
17	6	3	0	11.6505	5.6	58.7495	85
18	6	3	-30	0	2.4	105.6	87
19	6	3	-30	0	0	111	90
20	6	3	0	0	3.4	73.6	86
21	6	3	30	0	4.6	34.4	78
22	6	3	30	0	4.6	26.4	70
23	6	3	-30	0	0	83	62
24	6	3	-30	0	0	76	55

Minimization of pollutants emission in case-1, without and with DR program

Now the case-1 is considered again, but with the other objective function, which minimizes the emission of the pollutants from the utility and the MG energy sources under normal constraints. Tables 9 and 10 show the scheduled power generation of the MG sources to meet the load demand, without and with DR program, respectively.

The results shown in the tables indicate that the MG does not purchase energy from the utility in this case, because the emission of pollutants is highest from the utility. On the other hand, the renewable energy sources of the MG continue to generate their maximum energy, because they do not emit any pollutant in the environment during their operation. The pollutant emission in this case is 731.99 kg without DR program and 521.84 kg with the DR program. It can be seen in Tables 9 and 10 that the DR program helps in covering the uncertainties related to the PV and WT sources of the MG. Further, the case study to analyze the pollutants emission in case-3 is not done because the renewable energy sources of the MG are scheduled to generate their maximum

energy and the utility purchase energy from the grid. Hence, it does not create a significant difference from the results of case-1. Therefore, there is no need to include the case study of remaining case.

Simultaneous minimization of operating cost and pollutants emission in case-1, without and with DR program

In this case, the results of the two conflicting objective functions, i.e., operating cost and pollutants emission are presented, when they are solved simultaneously, without and with the DR program. There is a trade-off involved in between the two objective functions. This can be seen in Figs. 8 and 9, in which the two conflicting objective functions have been solved together without and with DR program, respectively, and plotted with respect to a base factor having the values in the range of [0, 1]. During each solution, the base factor value is complementary for the objective functions. Due to the trade-off, if the operator wants that the operational cost of the MG should be the lowest, then the emission level from the generation source will be very



Table 9 Power scheduling without DR in case-1 (for minimum emission)

Hour	MT (kW)	FC (kW)	BA (kW)	PV (kW)	WT (kW)	GRID (kW)	Total demand (kW)
1	19.6	30	30	0	2.4	-30	52
2	30	30	16	0	2.4	-28.4	50
3	30	30	-30	0	2.4	17.6	50
4	30	30	21.8	0	0.2	-30	52
5	30	30	23.6	0	1.4	-30	55
6	30	30	28.6	0	3.4	-30	62
7	30	30	-25.4208	3.02075	2.4	30	70
8	30	30	-24.4223	8.02225	1.4	30	75
9	30	30	29.92475	13.67525	3.4	-30	77
10	30	30	-14.583	17.70025	5.6	11.28275	80
11	30	30	19.82525	21.57475	6.6	-30	78
12	30	30	14.676	22.724	5.6	-30	73
13	30	30	-30	23.5615	7.6	10.8385	72
14	30	30	-30	22.33025	5.6	13.06975	71
15	30	30	-30	20.07325	9.6	15.32675	75
16	30	30	25.18025	15.21975	8.6	-30	79
17	30	30	-20.3023	11.6505	5.6	28.05175	85
18	30	30	-10.278	4.878	2.4	30	87
19	30	30	30	0	4.6	-4.6	90
20	30	30	30	0	3.4	-7.4	86
21	30	30	30	0	4.6	-16.6	78
22	30	30	-24.6	0	4.6	30	70
23	30	30	30	0	0.4	-28.4	62
24	30	30	0	0	2.4	-7.4	55

high. On the other hand, if the scheduler reduces the emission to the minimum level then system has to compromise with the high operational cost. Hence, the scheduler finds an optimum solution of the problem, without and with the DR program. The optimum solution for the operational cost and the pollutants emission level is shown in Table 11. It is clear from the results that the value of operating cost and pollutant emission decreases by generation scheduling under the DR program.

Conclusion

In this paper, a MG operation management system has been proposed, in which the energy generation of the MG sources and the utility has been scheduled under the DR program. The participation of the consumers in incentive-based DR program helped in covering the operational limitations of battery source and uncertainties caused by the PV and WT sources. To better analyze the system, two objective

functions have been modeled and solved by considering two different cases. Each case has been analyzed with and without the DR program. The objective functions were modeled to minimize the operating cost and the pollutants emission from the MG sources. The minimum value of each objective function has been calculated by solving the formulated MILP problem by the CPLEX solver of GAMS software. The formulated objective functions for the considered system were linear. Hence, the proposed solution approach is simple for the management of a micro-grid integrated with the renewable energy sources under the responsive loads. Finally, the trade-off between the objective functions has been analyzed without and with the DR program and satisfactory results have been achieved. Use of offered price packages for the DR and real time market price during the generation scheduling is also an important aspect of the paper. In future, this work can be extended by considering different pricing scheme and other demand response programs in the system.



Table 10 Power scheduling with DR in case-1 (for minimum emission)

Hour	MT (kW)	FC (kW)	BA (kW)	PV (kW)	WT (kW)	GRID (kW)	Total demand (kW)
1	12.736	30	30	0	2.4	-30	45.136
2	30	30	11	0	2.4	-30	43.4
3	30	30	11	0	2.4	-30	43.4
4	30	30	14.936	0	0.2	-30	45.136
5	30	30	-30	0	1.4	16.34	47.74
6	30	30	20.416	0	3.4	-30	53.816
7	30	30	-30	3.02075	2.4	25.33925	60.76
8	30	30	-27.7818	8.02225	1.4	23.4595	65.1
9	30	30	19.76075	13.67525	3.4	-30	66.836
10	30	30	16.13975	17.70025	5.6	-30	69.44
11	30	30	9.52925	21.57475	6.6	-30	67.704
12	30	30	-30	22.724	5.6	5.04	63.364
13	30	30	-30	23.5615	7.6	1.3345	62.496
14	30	30	-30	22.33025	5.6	3.69775	61.628
15	30	30	0	20.07325	9.6	-24.5733	65.1
16	30	30	14.0725	15.21975	8.6	-29.3203	68.572
17	30	30	26.5295	11.6505	5.6	-30	73.78
18	30	30	-21.762	4.878	2.4	30	75.516
19	30	30	30	0	4.6	-16.48	78.12
20	30	30	30	0	3.4	-18.752	74.648
21	30	30	30	0	4.6	-26.896	67.704
22	30	30	26.16	0	4.6	-30	60.76
23	30	30	-15.34	0	0.4	8.756	53.816
24	30	30	15.34	0	2.4	-30	47.74

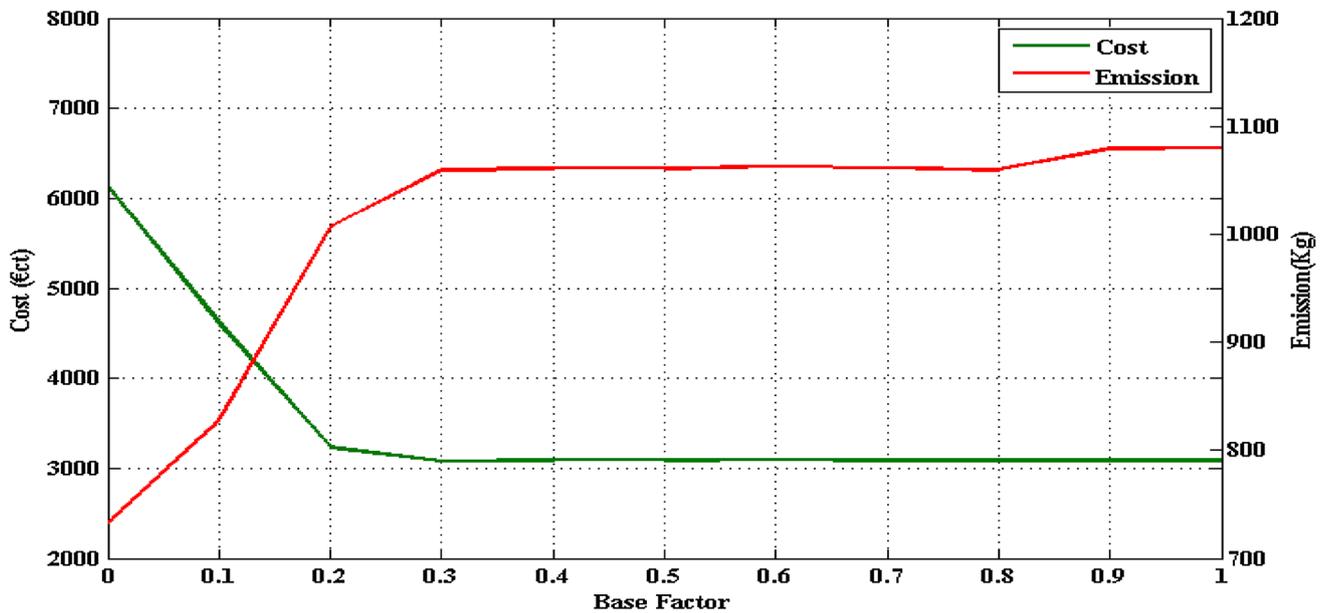


Fig. 8 Variation in operation cost and emission value without the DR program

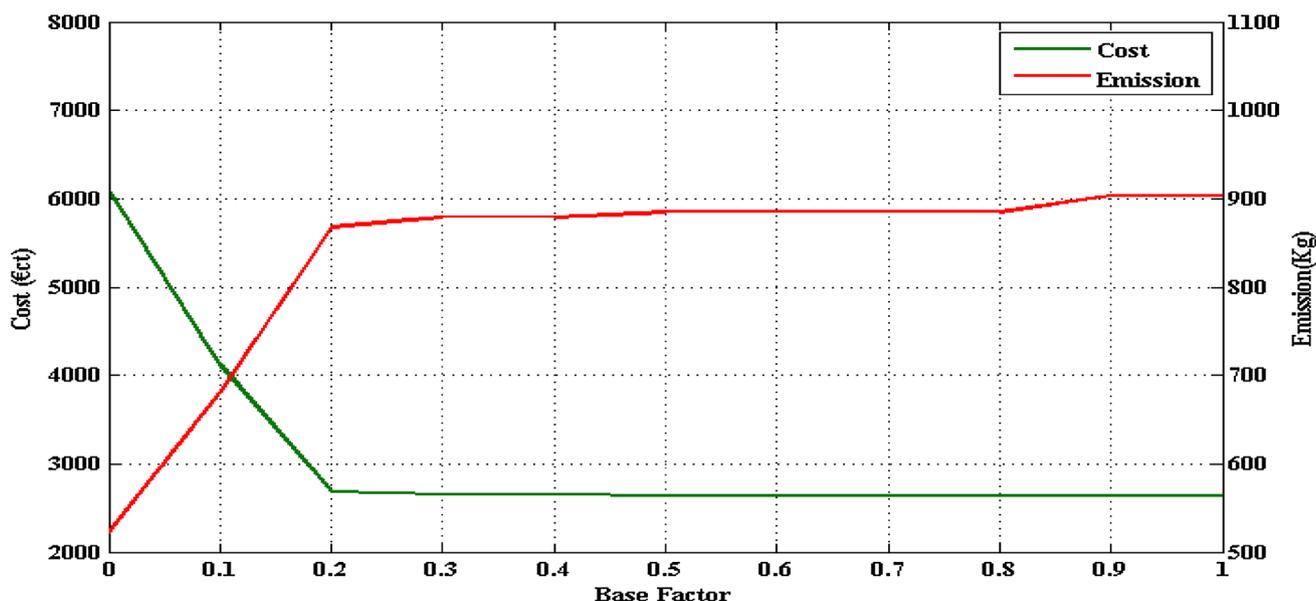


Fig. 9 Variation in operation cost and emission value with the DR program

Table 11 Optimal values of operating cost and emission without and with the DR program

	Without DR	With DR
Operation cost (€ct)	3087.28	2637.89
Emission (kg)	1060.41	884.82

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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