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Improving the benefits of demand response participation in facilities with distributed energy resources

Carlos Roldán-Blay*, Guillermo Escrivá-Escrivá, Carlos Roldán-Porta

Institute for Energy Engineering, Universitat Politècnica de València, Camino de Vera, s/n, edificio 8E, escalera F, 5^a planta, 46022 Valencia, Spain

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ABSTRACT

Demand response has proven to be a distributed energy resource of great potential over the last decades for electrical systems operation. However, small or medium size facilities generally have a very limited ability to participate in demand response programs. When a facility includes several generation resources, energy storage systems, or even demand flexibility, the decision-making becomes considerably harder because of the amount of variables to be considered. This paper presents a method to facilitate end users' decision-making in demand response participation. The method consists of an algorithm that uses demand and generation forecasts and costs of the available resources. Depending on the energy to be reduced in a program, the algorithm obtains the optimal schedule and facilitates decision making, helping end users to decide when and how to participate. With this method, end users' capability to participate in these programs is clearly increased. In addition, the method is contrasted by simulations based on real programs developed at the Campus de Vera of the Universitat Politècnica de València. The simulations carried out show that the developed method allows end users to take advantage of the potential of their facilities to provide demand response services and obtain the maximum possible benefit.

1. Introduction

Demand response (DR) is a distributed energy resource (DER) with a great potential to improve the electrical systems operation [1]. In addition, it is a good complement to other improvements that are currently being implemented in electricity systems, such as the installation of smart meters [2]. However, DR resources have always been untapped or at least underused [3]. Some studies developed in several countries try to facilitate DR participation by focusing on the development of policies to support DR, as reviewed in Ref. [4]. Some others propose DR protocols in order to standardise the stages of offering, requesting, participating, verifying, and so on [5]. However, with the integration of renewable energy sources (RESs) and energy storage systems (ESSs) the scenario has changed. Thus, new tools to facilitate end user's participation in demand response programs (DRPs) have to be developed, especially in facilities with a significant percentage of energy provided by DERs, as proved in Ref. [6].

The complexity of energy management in these facilities is increasing due to the integration of new renewable energy resources. Some methods to optimise renewable energy systems management are reviewed in Ref. [7]. However, the potential for participation in DR is significantly increased in facilities with DERs and especially with ESSs [8], since they have higher flexibility. Some studies develop methods to optimise the available resources including DR. For example, in Ref. [9] a method is proposed to improve the overall system efficiency using receding horizon optimisation and demand-responsive schemes. Other studies developed during the last years are focused on the optimisation of DR from the perspective of the market [10]. Some other studies perform DR optimisation methods focused on the different agents in the electricity system [11]. In Ref. [12], a new hierarchical optimisation framework for the optimal operation of multiple microgrids is presented. This method optimises the operation of microgrids considering DR. Similarly, in Ref. [13], a method is proposed to optimise multiple microgrids with critical energy peak pricing DRPs. These works do not focus on end users decision-making to participate in DRPs, but they offer optimal management of the system. In Ref. [14], an interesting study is developed to prove that with end users' participation in DRPs, operational costs

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* Corresponding author.
E-mail address: carrolbl@die.upv.es (C. Roldán-Blay).

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Nomenclature

Acronyms

CPI	Ciutat Politècnica de la Innovació
DER	distributed energy resource
DEROP	distributed energy resources optimisation (name of an energy resources management optimisation algorithm)
DR	demand response
DROP	demand response optimisation (name of proposed algorithm)
DRP	demand response program
ESS	energy storage system
LabDER	Laboratory of Distributed Energy Resources (at the UPV)
PV	photovoltaic
RES	renewable energy source
UPV	Universitat Politècnica de València

Superscripts

(i)	iteration in the DEROP algorithm. From (0) to (f)

Subscripts

j	time index in the simulation period. From 0 to $N-1$
k	energy resource index. From 1 to n
g	energy resource corresponding to the grid

Parameters, variables, and functions

T	duration of the simulation period
N	number of intervals in which the simulation period is divided
n	number of energy resources in the energy hub (generation and storage resources)
τ	simulation step size, length of each simulation interval
t_j	instant in which the jth simulation interval ends $(j>0)$
d_j	total power demand at instant t_j
$(d_j)_b$	demand to be supplied with DEROP$_b$ during the time interval $[t_j, t_{j+1}]$
p_{jk}	power provided by resource k during the time interval $[t_j, t_{j+1}]$
p_{jg}	power provided by the grid during the time interval $[t_j, t_{j+1}]$
$(p_{j,g})_{\text{máx}}$	maximum allowed power to be supplied by the grid during the DRP
$p_{j,flex}$	flexible power available to be curtailed
$p_{j,DRP}$	requested power curtailment in the DRP
q_{jk}	associated cost of resource k during the time interval $[t_j, t_{j+1}]$
Q_j	total cost of generated power during the time interval $[t_j, t_{j+1}]$
C_1	total energy cost without participation in the DRP
C'_1	total energy cost without participation in the DRP, without using any DERs management optimisation algorithm
C_2	total energy cost with participation in the DRP
C'_2	total energy cost with participation in the DRP, without using any DERs management optimisation algorithm
C_a	total energy cost with participation in the DRP without using flexibility
C_b	total energy cost with participation in the DRP using flexibility
t_{DRP}	time interval during which the DRP takes place
P_R	premium offered by the energy trader in exchange for the requested power curtailment
C_f	total cost of the flexible power curtailed to fulfil the DRP

and emissions may be significantly reduced. Some works analyse the problem of DR optimisation from the perspective of energy planning, like [15], in which the Portuguese electric system is studied. This kind of studies usually propose methods to model long-term evolution of energy demands and find an optimised solution from a technical and economic point of view, as presented in Ref. [16]. These studies are related to energy planning and systems sizing. Related to these works, [17] analyses the optimisation of appliances schedule to decrease system sizes and costs thanks to DR participation. Another example of a study that proposes using DR to optimise component size in microgrids and reduce the number of batteries and other elements is presented in Ref. [18]. [17,18] are more focused on end users participation, but they do not study how to facilitate their decision-making in DRPs. In Ref. [19] a very interesting study is presented to optimise smart residential buildings management to participate in collaborative DR actions. Although this work is more related to the planning stage than to the operation stage, it shows several interesting contributions by analysing the necessary technology that is currently available. A comprehensive review of methods to optimise sizing and planning of renewable energy systems considering DR actions is presented in Ref. [20].

The issue analysed in the present work is related to the short-term optimisation (one day ahead) of existing facilities that have renewable resources, ESSs and flexibility to participate in DR. In Ref. [21], this problem is studied for industrial customers including different provision methods, but the goal is to analyse prices volatility and the benefits for the system and the market of DR participation. Similarly, [22] solves the problem to facilitate the system operator the task of prioritising different DRPs for running in a microgrid. A very similar problem to the one studied in this paper is studied in Ref. [23], but it focuses on minimising the operational cost of a microgrid, instead of maximising the benefits of DR for the customer. The goal of these works is to minimise operational costs, but they do not provide a method to qualify end users and facilitate their decision-making in DR participation.

Previous studies have not focused on facilitating decision-making to increase end user's participation in DRPs. Indeed, in these facilities, the decision-making process to participate in DR is more complex. End users need to decide when to participate, how much energy to offer for reductions and the premium to accept or decline participation in DRPs. Furthermore, in complex facilities with DERs and especially if there are ESSs available, end users need to decide how to schedule their resources to participate with the maximum benefits during the whole period. These are the aspects that have not been addressed and need to be studied to increase the benefits of DR resources.

This article explains a method to facilitate decision-making when participating in DRPs. The proposed method consists of an algorithm that uses energy demand and generation forecasts in a facility with several resources. Using these data, the algorithm obtains the optimal schedule of the available resources to participate in a DRP in which the energy to be reduced and the premium are known. Some of the main features that justify the relevance and interest of this method are:

1) It is a simple, easy to implement and fast method to help in DRP participation.
2) The method is flexible, because it supports as many energy resources as needed, including sources, ESSs, demand flexibility, grid supply and others.
3) The method studies the maximum benefit that can be obtained and helps the user to decide if participating in the DRP or not and which resources to use.

The method is tested on a university campus that has previously participated in DRPs. Based on real data from DRPs and RESs installed in this campus, DRPs are simulated including several DERs in the facility. The simulations carried out show that the method facilitates the participation in DRPs and simplifies the decision-making. Moreover, the method maximises the benefit obtained through DR.

The paper is organised as follows. Section 2 describes the proposed method. The facilities in which DRPs are simulated are described in Section 3. Section 4 shows the simulated scenarios and the results of the simulations carried out. These results are discussed in section 5. Finally, the main conclusions of this work are drawn in section 6.

2. Materials and methods

The proposed method is shown in Fig. 1. The method is explained below.

Using data from the real DRPs in which the UPV participated, a method has been developed to facilitate the decision-making and the optimal management of the resources of a facility to participate in DRPs and obtain the maximum possible benefit. This method has been called DROP (Demand Response Optimisation) algorithm. It is an algorithm based on DEROP (an algorithm explained in Ref. [24], which allows optimising the use of DERs in a facility). The proposed method and the conditions of the scenarios that have been simulated are described below. Actually, in the case studies developed here, DEROP algorithm is used to calculate the optimal schedule to apply the proposed method, but other optimisation methods would also be suitable to apply DROP.

In a facility that has flexible demand (with an associated cost C_f), several generation resources, ESSs and grid supply, the participation in a DRP could be significantly complicated. First, grid demand (the power curve supplied by the electricity grid) will depend on RESs and the use of ESSs. In other studies, some methods are described to minimise the cost of energy when these types of resources are available in a facility. For this work, DEROP algorithm, presented in Ref. [24], is taken as a basis.

Let us suppose that in these conditions the participation in a DRP was requested, asking to reduce a certain amount of energy consumed from the grid during a certain time period. During this DRP, energy flows could be managed in several ways. On the one

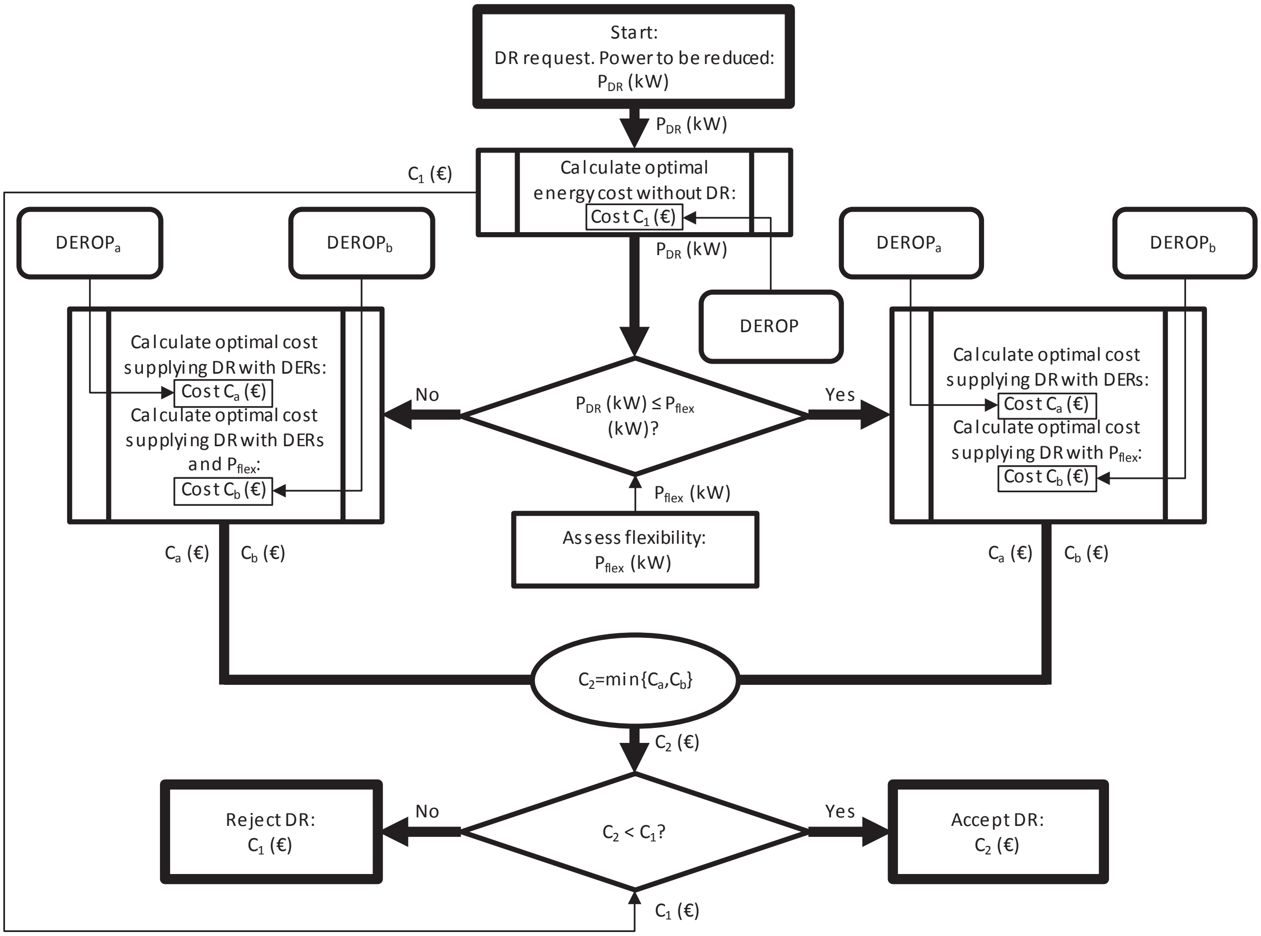

Fig. 1. Flow diagram of DROP algorithm to optimise DR actions in facilities with DERs.

hand, some load could be disconnected taking into account the cost assigned to this reduction. On the other hand, the energy stored in the ESSs could be used. Moreover, extra energy could be stored in the ESSs to be used during the DRP, changing the initial schedule calculated to optimise the management of resources before the DR action was requested. All these possibilities make it easier for this facility to participate in the DRP. However, when participating, the energy manager must decide how to comply with the DRP conditions. To carry out this decision-making the authors propose DROP algorithm, which is explained below.

First, the minimum energy cost assuming the facility does not participate in the DRP (C_1) must be calculated. To compute this calculation, DEROP algorithm may be used in order to guarantee that C_1 is the optimal cost for this facility. This cost corresponds to the optimal energy management of the available resources, so the demand curve supplied by the grid is optimal and it is taken as a starting point for the rest of the method. As explained in Ref. [24], this cost may be obtained with equation (1) after achieving the optimal energy management:

$$C_1 = \int_0^T Q_j \cdot dt \approx \sum_{j=0}^{N-1}\left(\sum_{k=1}^{n} p_{jk}\cdot q_{jk}\cdot\tau\right) = \sum_{j=0}^{N-1} C_j \tag{1}$$

where T is the length of the simulation period (24 h in this case), Q_j is the total cost of generated power for the time interval $[t_j, t_{j+1}]$, N is the number of intervals of duration τ in which the simulation period is divided (for example 96 intervals of 15 min each), p_{jk} is the average power provided by resource k in a set of n available resources, with an associated cost q_{jk}.

Second, the minimum energy cost with participation in the DRP (C_2) must be calculated. On the one hand, it is necessary to calculate this cost by participating without making use of the flexibility and using the energy stored in the ESSs (C_a). This means that the power curtailment in the grid supply curve during the DRP is executed using energy stored in the ESSs. To calculate C_a, equation (2) should be used:

$$C_a = \sum_{j=0}^{N-1}\left(\sum_{k=1}^{n} p_{jk}\cdot q_{jk}\cdot\tau\right) - P_R \tag{2}$$

where P_R is the premium offered by the energy trader in exchange for the requested power curtailment.

On the other hand, the minimum energy cost participating in the DRP and using flexibility (C_b) must be calculated. This situation involves optimising the management of resources to meet demand and comply with the DRP conditions, having an extra cost due to the flexibility used to meet the requested power reduction. To compute C_b, equation (3) should be used:

$$C_b = \sum_{j=0}^{N-1}\left(\sum_{k=1}^{n} p_{jk}\cdot q_{jk}\cdot\tau\right) + C_f - P_R \tag{3}$$

Where C_f is the total cost of the flexible power reduced to fulfil the DRP. Note that in the calculation of C_b, the extra costs due to the use of flexibility (C_f) must be included.

The minimum of these two costs will be the optimal cost with participation (C_2), as shown in equation (4).

$$C_2 = \min\{C_a, C_b\} \tag{4}$$

If the optimal cost with participation is lower than the optimal cost without participation ($C_2 < C_1$), then the DRP must be accepted. Otherwise (if $C_2 > C_1$), the DRP must be rejected.

To calculate the cost C_a, an algorithm called DEROP_a is used. This algorithm is a modification of DEROP. In this version, the first stage (maximising the use of RESs) remains unchanged. In the second stage (optimising of the use of ESSs and grid power supply) an additional constraint is added to prevent the power contributed by the network from exceeding the maximum power allowed during the hours of the DRP. The storage of energy surplus in the ESSs guarantees the effective utilization of all the available renewable energy, as stated in Ref. [25]. As shown in Ref. [26], hybrid renewable systems are suitable for non-connected zones thanks to these strategies. Moreover, ESSs allow a greater potential to participate in the DRP, as this work shows below. This extra condition is imposed every time an iteration of the second stage is executed. Therefore, to accept a new iteration, constraints (5) and (6) must be simultaneously fulfilled.

$$C^{(i+1)} < C^{(i)} \tag{5}$$

$$p_{j,g} \le \left(p_{j,g}\right)_{\text{máx}}, \forall j : \left[t_j, t_{j+1}\right] \subset t_{DRP} \tag{6}$$

where $C^{(i)}$ is the total energy cost in iteration i, $p_{j,g}$ is the average power provided by grid during the time interval $[t_j, t_{j+1}]$, $(p_{j,g})_{\text{máx}}$ is the maximum allowed average power to be supplied by the grid during the DRP to meet its conditions and t_{DRP} is the time interval during which the DRP takes place.

With the additional condition (6), the algorithm optimises the energy resources management ensuring that the grid will not provide higher average power than the maximum allowed in the DRP. Occasionally, it may happen that for this purpose the algorithm needs to store more energy in the ESSs than the optimal amount without the constraint (6). This will be automatically detected and executed by DEROP_a.

To calculate C_b, an algorithm called DEROP_b will be used. This algorithm is a modification of DEROP_a. This algorithm assumes the flexibility is implemented since the beginning of the optimisation process. That is, DEROP_b assumes that the demand curve to satisfy is the expected demand curve minus the flexibility curve needed to fulfil the DRP. Consequently, the demand curve to be satisfied will correspond to equation (7):

$$\left(d_j\right)_b = d_j - \min\left(p_{j,flex}, p_{j,DRP}\right), \forall j : \left[t_j, t_{j+1}\right] \subset t_{DRP} \tag{7}$$

Where $(d_j)_b$ is the demand to be supplied with DEROP_b during the time interval $[t_j, t_{j+1}]$, d_j is the forecasted demand, $p_{j,flex}$ is the flexible power available to be reduced y $p_{j,DRP}$ is the requested power curtailment in the DRP.

Note that if $P_{j,flex} < P_{j,DRP}$, the rest of the power curtailment during the time interval $[t_j, t_{j+1}]$ is provided by the ESSs. The opposite situation is not considered (that is, using all the energy stored in the ESSs and providing the rest of power through flexible demand) due to the high cost of this ESSs usage.

With the constraint of equation (7), the algorithm continues optimising the energy resources management by decreasing the total cost of grid energy supply, preventing the grid from supplying more power than the limit set in the DRP. However, since it uses the available power curtailments through flexible demand, the amount of energy to store in the ESSs is lower than in the previous scenario. This allows this facility to participate in a DRP even if the requested power reduction is higher than the flexibility available in its end uses. In this case, DROP algorithm would automatically calculate the optimal resources management and it would check if the DRP is profitable.

3. Facilities description

To show some simulations with the proposed algorithm, a real case of DR participation at the Campus de Vera of the Universitat Politècnica de València has been analysed. From these simulations, some important conclusions are drawn.

The Campus de Vera of the Universitat Politècnica de València (UPV) has around 90 buildings with classrooms, laboratories, offices, and so on. The annual energy consumption of the campus is around 50 GWh and its peak power is around 16 MW in summer and 10 MW in winter. One of the facilities included in this campus is the Ciutat Politècnica de la Innovació (CPI), in which many activities related to research and development are carried out. These facilities represent approximately between 15% and 20% of the total consumption of this campus.

In these facilities, a pilot project was carried out to assess the potential of UPV to participate in DR. The purpose of this project was to propose, execute and verify DRPs at the facilities of the UPV. Fig. 2 shows an example of participation in one of these DRPs developed at the facilities of the CPI.

In this DRP, a DR request was made asking to reduce 500 kW from 5:00 p.m. to 6:00 p.m. The fulfilment of the requested curtailment was verified at the end of the day. The premium offered by the electricity trader in exchange for fulfilling the DRP was € 0.05 per reduced kWh (up to 500 kWh). The economic balance of this DRP shows a benefit of € 25 due to the premium, since the requested reduction was completely fulfilled. The energy trader was a private company that offered a DR action. Then the consumer modified the expected demand and the accomplishment was verified later for the settlement.

In this case, to satisfy the 500 kW curtailment, several chillers and fan coils were alternatively shut down to avoid comfort losses. All the time, the internal temperature of each room was controlled. It was automatically scheduled by the energy management system implemented in most of the buildings in this campus, called DERD system [27]. DERD sent an order through a PLC to the local control system of the building to switch on and off the different controllable loads.

Although this kind of DRPs in this pilot project produced small benefits, there are additional benefits related to these actions. For example, energy demand reductions can create structural savings, avoiding the need to change or add new equipment and decreasing the number of faults.

In a general case, the flexible power of a certain facility may have an associated cost (cost of products that are not produced, cost of the extra needs derived from energy that is not consumed, and so on). Through energy audits carried out in several buildings of the UPV, the maximum demand flexibility of the CPI has been estimated in several end uses, both in summer and in winter. To assess the real potential of a complex building like the CPI to change energy consumption in a specific end use, a system approach must be used, as explained in Ref. [28]. The costs of using this flexibility to fulfil the aforementioned DRP are shown in Fig. 3. The figure has two y-axis: the primary for energy (columns) and the secondary for energy costs (marks). This figure shows that in each hour of the day the maximum flexible power to be disconnected is associated with a cost that has been obtained through energy analyses. During 1 h, there may be several offers of power curtailment with different associated costs, corresponding to different end uses (hot water, air conditioning, lighting, etc.). The cost is estimated by analysing the response of the users and the affected processes. When the power curtailments are executed, users have to start with the end uses that have the lowest cost, similarly to the matching up of the energy market.

Demand flexibility can be increased by redesigning energy systems, as other studies suggest [29]. In this case, the reduction of flexible power would be executed by reducing the available 37.4 kWh of lighting consumption (with an estimated cost of € 2.99), 215.6 kWh of domestic hot water consumption (whose cost is € 21.56) and the remaining 247 kWh of the consumption of air conditioning (that would have an estimated cost of € 39.52). Therefore, assuming that the reduced power in the DRP was flexible power from these end uses, the cost of this power curtailment is € 64.07. The cost of the forecasted energy for the day of the DRP was € 4125.53. The cost of energy consumption after performing the power curtailment is € 4051.35 (without the mentioned flexibility costs). Finally, the total benefit of this DRP taking into account the premium and the extra cost of the implemented flexibility is € 35.11.

In other studies, consumption forecast methods have been developed with enough accuracy to use these forecasts as a baseline for the verification of DRPs. For example, [30] shows an energy forecast method using artificial neural networks. In Ref. [31], this method is improved using a time temperature curve model to forecast hourly temperature.

In the UPV, there are several RESs, such as several photovoltaic (PV) power plants, a wind generator, batteries, a gasifier, and so on. In LabDER (laboratory of distributed energy resources), studies of the operation, the integration and the management of all these resources are developed [32]. Thanks to this laboratory, real

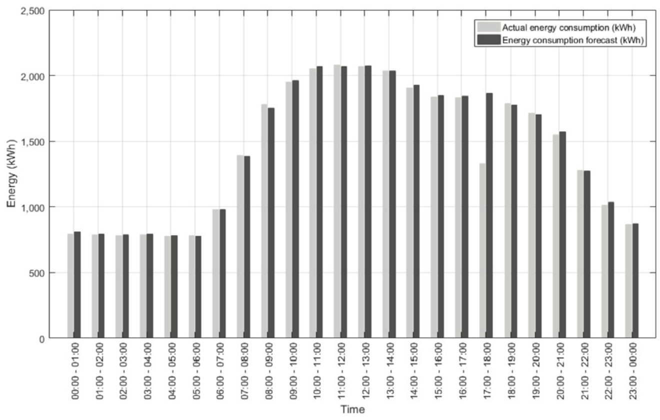

Fig. 2. Real DRP executed at the CPI facilities (curtailment of 500 kW from 5:00 p.m. to 6:00 p.m.).

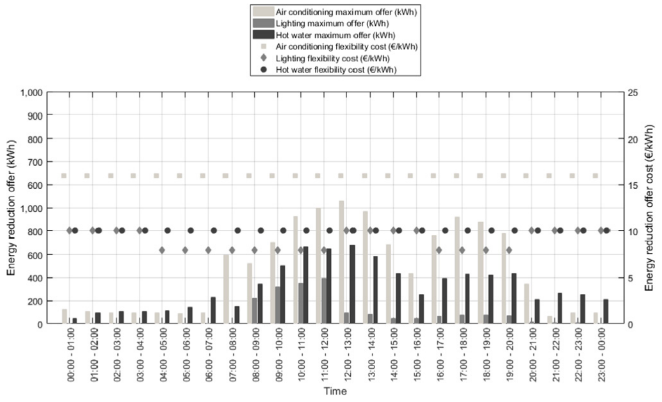

Fig. 3. Offers of maximum flexible demand curtailment in the CPI facilities during the most favourable day and its associated costs (for the day of the DRP, these values are used to evaluate the results).

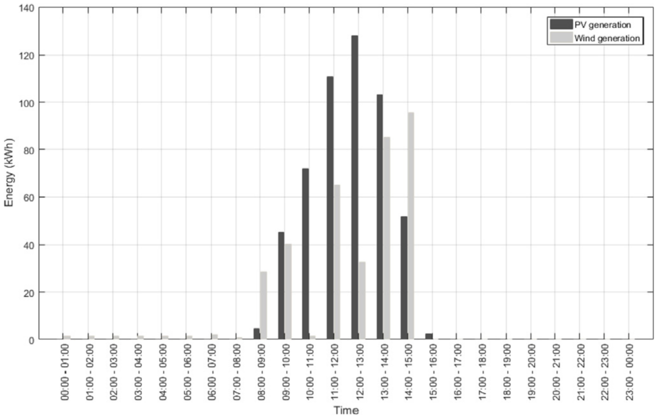

Fig. 4. Generation curves obtained from real measurements in LabDER, used to simulate the optimal management during the proposed DRP.

measurements of energy generated every 15 min by these RESs over a long time have been stored in a database.

4. Simulation of scenarios

Based on LabDER measurements, CPI consumption with the RESs described below is going to be simulated:

- A 175 kW PV farm.
- A 100 kW wind generator.
- Batteries with 8 devices of 48 V and 5000 Ah (approximately 250 kWh in each device).

By scaling the data measured in the LabDER facilities, the generation curves for the date of the DRP described above are obtained. These curves are shown in Fig. 4. If the CPI had these facilities, its participation in this DRP could be more complex than it was in the aforementioned project. The described method will be applied to this facility and the participation in the DRP will be simulated with the purpose of maximising the benefit.

Applying DEROP to the day of the DRP described above, the optimal demand curve from the grid would be like the one shown in Fig. 5 (optimised grid supply). The differences with the curve presented in Fig. 2 are due to the estimated generation that RESs (PV and wind) would have and to the energy exchanges with the ESSs and the grid to minimise the energy cost. After applying DROP, the optimal schedule is shown as participation proposal.

With these demand and generation curves and the proposed ESSs, the described DRP will be simulated and the application of DROP algorithm will be explained.

With the procedure described above, in the case of the proposed DRP, the cost of each of the situations described for the facility to be simulated is going to be calculated. In the case of not participating (if the DRP is rejected), the minimum cost of energy for the whole day would be $C_1 =$ € 3797.87, corresponding to the cost of the optimal demand shown in Fig. 5. In the case of participating by providing energy from the ESSs, the optimal energy supply cost would be € 3814.01 and the premium would be $P_R =$ € 25, so the total energy cost would be $C_a =$ € 3789.04. In the case of participating by means of flexible power, a premium of $P_R =$ € 25 would be again obtained and the extra cost of the reduced flexible power would be $C_f =$ € 64.07. Since the optimal energy supply cost for these conditions is € 3723.89, the final cost would be $C_b =$ € 3762.96. The costs and benefits obtained in each scenario are summarised in Table 1. Applying the flow chart of Fig. 1 the DRP should be accepted and fulfilled by means of flexible power curtailments. The total benefit obtained thanks to this participation compared to not participating would be € 34.91 (0.92%).

If the demand was not optimised with DEROP, the optimal energy cost would be $C'_1 =$ € 4004.62 (including a basic management of DERs). If, under these conditions, the facility participated in the DRP through flexibility, the energy supply cost would be € 3930.44. In this case, taking into account the premium of $P_R =$ € 25 and the extra cost of the reduced flexible power $C_f =$ € 64.07, the DRP benefit is € 35.11, with a total cost of $C'_2 =$ € 3969.51. In contrast, optimising the management of the simulated available resources with DROP algorithm, the DRP would provide a benefit of € 34.91 (lower than € 35.11), as shown in Table 1, but the final cost would be $C_b =$ € 3762.96, 5.2% less than C'_2. That is, if no DERs management optimisation algorithm is used (such as DEROP) when participating in DR, greater benefits are obtained from participation (€ 35.11). However, these benefits represent lower percentages, since they start from a significantly higher energy cost. Therefore, it is necessary to optimise DERs management in any scenario to

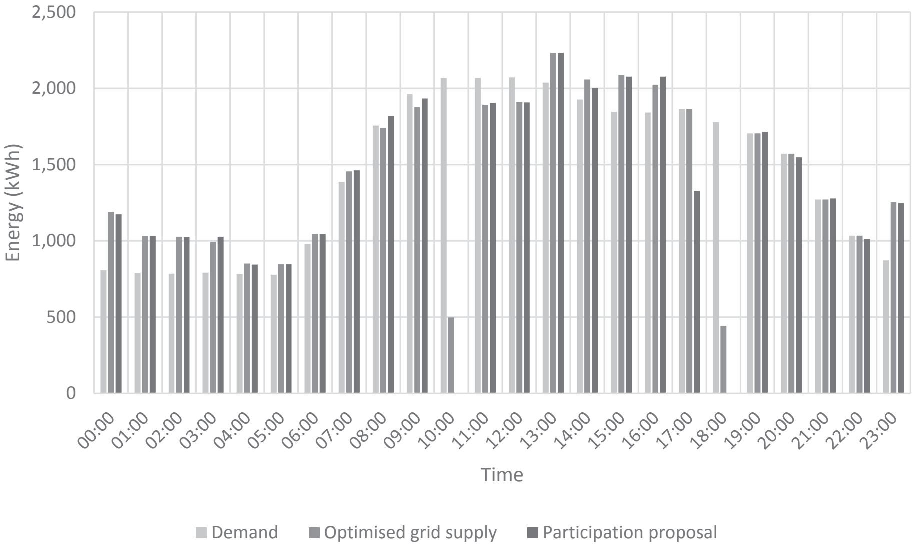

Fig. 5. Electricity supply from the grid during the day of the DRP optimised with DEROP, demand to meet and optimised participation proposal using DROP.

Table 1
Costs and benefits of each simulated scenario.

Scenario	1 (no participation)	2a (participation without flexibility)	2b (participation with flexibility)
Prima (€)	0	25	25
Energy saved (kWh)	0	500	500
Optimal energy demand cost (€)	3797.87	3814.01	3723.89
Cost of flexibility (€)	0	0	64.07
Total cost (€)	3797.87	3789.04	3762.96
Net benefit of DRP (€)	0	8.83	34.91
Benefit of DRP in percentage (%)	0	0.23	0.92

evaluate the minimum cost achievable in each situation.

The described procedure demonstrates that the optimal management of the available resources and the use of DROP algorithm (developed to facilitate decision-making when a facility that has DERs participates in DRPs) minimise the energy cost. Moreover, this algorithm achieves an optimal use of the available resources in the most favourable situation (whether participating in the DRP or not participating). This allows greater benefits than if the facility participates in DRPs using only one resource (either flexibility or ESSs). For example, in this case study, comparing scenarios 2a and 2b, using all the resources (flexibility and DERs, scenario 2b) allows this facility to obtain a benefit 4 times greater than using only ESSs. In other cases, the situation could be the opposite one (obtaining greater benefits with ESSs than with flexibility).

However, this is not the only advantage of using DROP in decision-making. The same DRP has been simulated with the conditions of all the working days of a whole year (consumption forecasts, demand flexibility, and so on). If this DRP was offered every working day of a year, this facility could only participate in approximately 26.58% of the days without using DROP algorithm. This is because flexible power is often insufficient to obtain an economic benefit, either due to lower consumption or due to events that force the demand to remain unchanged. Note that the flexibility shown in Fig. 3 is the maximum value that the facility can offer during the most favourable days with its current design. In this situation, the annual economic savings obtained through participation in this DRP would be around € 2264.43. Conversely, simulations of DROP algorithm carried out in Matlab prove that, thanks to the optimised management of DERs and flexibility, this user could participate in almost all DRPs. With DROP, this facility could participate in 86.85% of the working days of a whole year and the annual economic savings would be around 11,610.42 €. This benefit is 5 times greater than the annual benefit obtained without using DROP, with a 60.27% higher participation, thanks to the optimal management of the available resources. The comparison of both scenarios demonstrates that this method enables users to participate in DRPs, especially in facilities where the impact of DERs on the energy cost is significant.

Fig. 6 shows the monthly benefit obtained without applying the method and applying it, throughout the year.

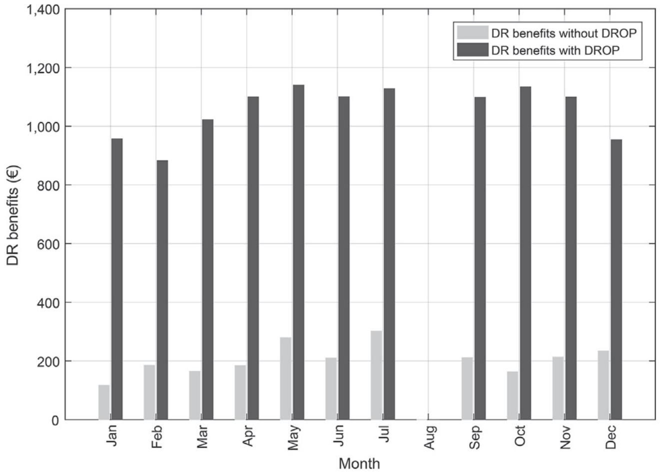

Fig. 6. Comparison of the benefit obtained by simulating the same DRP during a whole year with DROP algorithm and without DROP algorithm.

5. Results and discussion

The first set of simulated scenarios shows that participation in the DRP without using flexibility produces a benefit of 0.23% of the optimal energy cost for the whole day, as indicated in Table 1. On the other hand, participation in the same DRP using flexibility provides a benefit 4 times greater. In addition, the proposed method, based on DEROP algorithm to optimise the energy resources management, allows a 5.2% benefit compared to a scenario with participation in the DRP but without using any algorithm to optimise DERs management.

From this set of scenarios, a sensitivity analysis has been carried out. The benefit obtained (in percentage) with optimal participation versus not participating has been studied, always using the optimal management with DEROP according to the power curtailment requested and the premium offered. The results of this sensitivity analysis are shown in Fig. 7. The purpose of this analysis is to check the possible benefits in different situations of amount of energy reduced and premium, as these magnitudes would be uncertain and depending on the amount of actors willing to participate in a real case.

As shown in Fig. 7, the method provides benefits in a wide range of options. Many of the combinations studied would be unfeasible without using DROP algorithm, since the maximum flexible power is limited (710.6 kWh in the most favourable conditions). Furthermore, the flexible power has sometimes a high cost (0.16 €/kWh for air conditioning). However, thanks to the proposed method, maintaining a premium of 0.05 €/kWh, this facility can accept a DRP consisting of a curtailment of 800 kW from 5:00 p.m. to 6:00 p.m. and obtain a benefit of 0.2% compared to the optimal energy cost without participation. This is possible due to the optimal management of flexible power and ESSs. As a result of this study, it is observed that there is an optimum power to be reduced depending on the offered premium, which provides the maximum benefit for the studied facility. In addition, there is a maximum power to be reduced for each premium, above which the DRP must be rejected.

To complete this study, the initial DRP has been simulated assuming that the offer was made over a whole year.

As shown in Fig. 6, DRPs are accepted many times thanks to DROP algorithm, producing significantly greater benefits than if DROP was not used. In fact, if the algorithm is not used, a DRP can only be accepted on those days in which a curtailment of 500 kWh can be offered without a too high cost. That is, only DRPs that can be

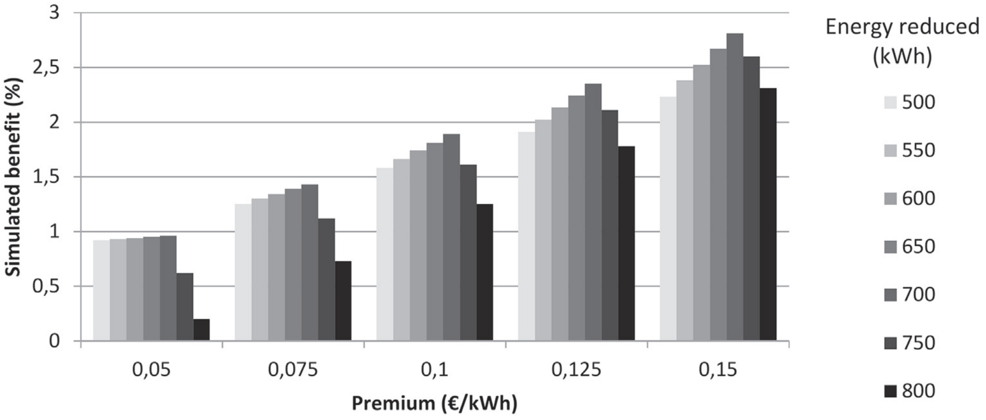

Fig. 7. Sensitivity analysis of the simulated benefit (in percentage) of the proposed method.

fulfilled through flexible power and that produce net benefits are accepted. For the simulation of a whole year, a benefit of € 2264.43 has been obtained if the DROP algorithm is not used. In contrast, if the proposed algorithm is used, the benefit obtained in a whole year is 5 times higher, with a percentage of DRPs accepted a 60.27% higher.

6. Conclusions

This paper presents DROP (Demand Response Optimisation) algorithm, a method to facilitate optimal decision-making when participating in DRPs in facilities that have RESs, ESSs, grid supply and flexibility.

The method is simple, fast and easy to be implemented. Not only does the proposed method facilitate decision-making, but it also maximises the achievable benefit when participating in DRPs. This benefit is improved because the algorithm makes optimal use of the available resources (RESs, ESSs, grid supply and flexibility) in the most profitable scenario. Therefore, the user is enabled to participate in DRPs. The main contribution of this method is that the facility's energy manager knows if this facility should participate in a DRP and when to use each resource, especially ESSs.

The method has been simulated with real data of generation facilities (scaled to compute the simulations) from LabDER and real consumption curves of the CPI at the Campus of Vera of the UPV. It has been proven that, in this facility, the use of DROP algorithm allows a benefit of 0.92% of the optimal energy cost without participating. In addition, this benefit is 5.2% of the optimal energy cost participating in the DRP without any algorithm to optimise the management of DERs. Furthermore, simulating the same DRP for a whole year, the method allows participation to be profitable 86.85% of the days, whereas if only flexible power could be used to fulfil the requested power curtailment, the DRP would be profitable 26.58% of the days. This produces an annual benefit 5 times greater than the DR benefit without using the method. The absolute values of this study are not relevant as this is a case study developed from a pilot project and there are several factors that could improve some aspects of these experiences. For example, the flexibility of a facility can be improved by means of a redesign of the energy system. Also, the premium and the benefits depend on the amount of facilities willing to participate in DRPs. This is why a sensitivity analysis has also been carried out to show that the proposed method allows benefits in a wide range of scenarios.

In addition to all the above, the described method increases the potential of facilities with DERs to participate in DRPs, by significantly increasing the benefit they can obtain from them and the power that these facilities can offer. Using this algorithm, a DRP consisting of a curtailment of P kW may be simulated varying P between P_{min} and P_{max} to calculate the maximum power to be offered in DR. This also allows the facility to assess the optimal power to be offered that produces the maximum benefit in the DRP. Therefore, DROP algorithm is a decision-making tool as well as a method to optimise the management of DERs to participate in DR.

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