Distributed Energy Resources Scheduling with Demand Response Complex Contract

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***Abstract*—Demand response is a very flexible way to improve distributed energy resources scheduling. The innovative contribution of this paper is to include in the model complex contracts approach, which can accommodate constraints according to the particular expectations of each player. Such contracts are included in the distributed energy resources scheduling optimization to dispatch demand response according to the consumers expectations. Multi-period demand response events are considered. In this way, consumers can specify limits on the time, power, and remuneration regarding participation in demand response events, in a way that has not been considered in the literature. The state of the art treats these aspects separately or using a statistic approach, without providing consumers with options to combine their preferences regarding different aspects of their flexibility deployment. The model has been validated for 218 consumers using several scenarios and different types of distributed generation, showing that it is possible to increase demand response respecting consumers preferences.**

***Index Terms*—Complex contracts, demand response, distributed generation, virtual power player.**

I. NOMENCLATURE

Variables

$P_{DG(t,dg)}$	Active power scheduled for the distributed generation dg in period t [kW]
$P_{DR(i,t,ct)}$	Demand power shifted by the consumption cluster ct, from period i to period t [kW]
$P_{Load}{}^{NSP}{}_{(t,ct)}$	Non-supplied active power to the consumption cluster ct, in period t [kW]
$P_{Supply(t,sp)}$	Active power scheduled for the supplier sp in period t [kW]
$VPPOC$	Virtual Power Player Operation Costs [m.u.]
$X_{DG(dg)}$	Binary variable of distributed generation dg related to accept the generation in the time horizon T [kW]
$X_{DR(ct)}$	Binary variable of the consumption cluster ct to accept demand response event, in the time horizon T [kW]
$X_{Supply(sp)}$	Binary variable of supplier sp related to accept the supply in the time horizon T [kW]
$X_{DG(t,dg)}$	Binary variable of distributed generation dg related to accept the generation in period t [kW]
$X_{DR(t,i,ct)}$	Binary variable of the consumption cluster ct to accept demand response event, in period t [kW]
$X_{Supply(t,sp)}$	Binary variable of supplier sp related to accept the supply in period t [kW]

Parameters

BI	Total number of backward consumption shifting periods from each period t
BT	Total number of backward consumption shifting periods in the time horizon
$C_{DR(t,i,ct)}$	Cost of the consumption shifting to the consumption cluster ct, from period t to period i [m.u./kWh]
$C^{a}{}_{DG(t,dg)}$	Quadratic cost component of the distributed generation dg, in period t [m.u./kWh]
$C^{b}{}_{DG(t,dg)}$	Linear cost component of the distributed generation dg, in period t [m.u./kWh]
$C_{Load}{}^{NSP}{}_{(t,ct)}$	Cost of the non-supplied active power in the consumption cluster ct, in period t [m.u./kWh]
$C_{Supply(t,sp)}$	Cost of the power from supplier sp in period t [m.u./kWh]
$CRem_{DG(dg)}$	Minimum cost of each distributed generation dg in the time horizon T [m.u.]
$CRem_{DR(ct)}$	Minimum cost of each consumption cluster ct in the time horizon T [m.u.]
$CRem_{Supply(sp)}$	Minimum cost of each supplier sp in the time horizon T [m.u.]
CtN	Total number of consumption clusters
DgN	Total number of distributed generation types
FI	Total number of forward consumption shifting periods in a specific period t
FT	Total number of forward consumption shifting periods in the time horizon T
$P_{Load}{}^{Base}{}_{(t,ct)}$	Initial consumption of each consumption cluster, in period t [kW]
$P_{Load}{}^{Max}{}_{(t,ct)}$	Maximum consumption of each consumption cluster, in period t [kW]
$PMax_{DG(t,dg)}$	Maximum available capacity from the distributed generation dg in period i [kW]

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$PMax_{DR}{}^{i}{}_{(t,ct)}$	Maximum consumption shifting by the consumption cluster ct, to period i [kW]
$PMax_{DR}{}^{t}{}_{(t,ct)}$	Maximum consumption shifting by the consumption cluster ct, from period t [kW]
$PMax_{DR}{}^{t\rightarrow i}{}_{(t,i,ct)}$	Maximum consumption shifting by the consumption cluster ct, from period t to period i [kW]
$PMax_{Supply(t,sp)}$	Maximum available capacity from the supplier sp in period t [kW]
$PMin_{DG(dg)}$	Minimum contribution of each distributed generation dg in the time horizon T [kW]
$PMin_{DR(ct)}$	Minimum contribution of each consumption cluster ct in the time horizon T [kW]
$PMin_{Supply(sp)}$	Minimum contribution of each supplier sp in the time horizon T [kW]
$PMin_{DG(t,dg)}$	Minimum contribution of each distributed generation dg in period t [kW]
$PMin_{DR(t,i,ct)}$	Minimum contribution of each consumption cluster ct in period t [kW]
$PMin_{Supply(t,sp)}$	Minimum contribution of each supplier sp in period t [kW]
$PVar_{DG(dg)}$	Minimum generation variation of distributed generation dg between successive periods [kW]
$PVar_{DR(t,I,ct)}{}^{t=i}$	Minimum consumption reduction variation by the consumption cluster ct between successive periods [kW]
SpN	Total number of consumption suppliers
T	Total number of periods in the time horizon
$\alpha_{DG}{}^{Max}$	Maximum contribution of the distributed generation to the energy supply (%)
$\alpha_{DR}{}^{Max}$	Maximum total consumption reduction in each single consumption cluster (%)
$XMin_{DG(dg)}$	Minimum periods with contribution of each distributed generation dg in the time horizon T [kW]
$XMin_{DR(ct)}$	Minimum periods with contribution of each consumption cluster ct in the time horizon T [kW]
$XMin_{Supply(sp)}$	Minimum periods with contribution of each supplier sp in the time horizon T [kW]

Indexes

ct	Consumption cluster index
dg	Distributed generation type
i	Consumption shifted period index
sp	Electricity supplier
t	Consumption shifting period index
$t0$	Beginning of the scheduling horizon

II. INTRODUCTION

DEMAND response Demand Response (DR) enables the participation of consumers in the operation of the electric grid by reducing their consumption through load curtailment strategies or shifting their consumption to a different period [1-2]. The use of DR can promote several benefits to the electric power system, such as preventing critical operating situations [3] or improving the efficiency of electricity markets [4]. DR programs also have a significant relationship with the successful implementation of smart grids [5,6]. Such programs can be categorized into incentive-based or in price-based [7], whether consumers are paid according to the actual energy consumption reduction or benefiting with lower prices of electricity in real-time, respectively. Small consumers can be aggregated by Virtual Power Player (VPP) [8]. A VPP is also able to manage a distribution network [9].

The main objective and innovative contribution of the present paper is to establish complex contracts between a VPP and consumers participating in DR programs, as well as distributed generators. With these contracts, the expectations of each player are agreed and the VPP will have consumers response closer to the expected. The consumer knows that he will be called only in the conditions that he has established. As it will be discussed in section 2, the related literature use treats these aspects separately regarding energy, power, time, and remuneration, limiting the options of consumers. as it implies a set of constraints conflicting, complex contracts method is selected and applied.

The implemented complex contracts are included in the distributed energy resources scheduling optimization in order to dispatch demand response according to the consumers expectations. Typically, the VPP establishes a contract, let's say a regular contract with consumers for the payment of each actual kWh reduction, and with DG for payment of each kWh generation. Complex contracts are like regular ones but including the complexity of other topics like financial targets, support capabilities, and delivery schedules. Whereas a regular contract might have one or several agreements, a complex contract have many interdependent agreements to be accomplished [10].

After this introduction, Section 2 discusses the related work and contributions, and Section 3 and explains the proposed methodology. Section 4 is devoted to the optimization problem. Section 5 brings the case study and the results. Conclusions are given in Section 6.

III. RELATED WORKS AND CONTRIBUTIONS

The present paper is related with the study made in [11], which focused on DR by reducing and shifting the consumption, and on DG resources. Other studies show the advantages of managing load by reducing and shifting consumption [12,13], as well as in scenarios where a renewable-based generation has a relevant penetration, with the known difficult predictability [14]. In the present paper, the implemented case study and scenarios deal with periods occurring wind unavailability. The work in [15] presents a methodology to accommodate the uncertainty of DR in both the load reduction and the recovery periods. The impact on the management of renewables-based distributed generation is discussed. In the present paper, it is proposed to establish contracts between aggregator and consumers in order to have a more accurate and larger DR activation, respecting consumers expectations.

In [16], the authors address the scheduling of demand in the day-ahead, maximizing the usage of renewables-based generation. A distributed optimization algorithm is used in a case-study with residential, non-residential, and industrial loads. In the present paper, the optimization is made in a centralized way, by the VPP, for several consumption clusters.

In [17], a Virtual Power Plant performs a fuzzy optimization of the resources in day ahead and in real-time. While the bidding strategies are optimized, the profits of the VPP are maximized and the dependency of conventional generators is reduced. In the present paper, costs are minimized in order to give more focus to the DR activation, instead of aiming VPP profit maximization. With the proposed complex contracts, it is avoided to ask consumers to make bids that can be difficult to them.

Wind curtailment is treated in [18]. Energy storage was introduced in order to allow a more flexible management of resources avoiding wind curtailment. In the present paper, wind unavailability is studied, avoiding wind curtailment and the need of using costly storage solutions.

The work in [19] analyze the mutual effects of DR and market prices while the remuneration of renewables and the incentives for DR, as well as the value of lost load are accounted. In [20], a meta-analysis is performed in order to maximize the implementation of DR programs in urban areas considering the increase of renewables. In [19] and [20], market approaches for DR integration are used, based on bids and DR playing in the market. In the present paper, the authors are driven to the definition of contracts that respect the consumers and DG owners' preferences.

With deeper concerns in regulation aspects, the work in [21] concluded that the main barriers of DR are related to consumer engagement and DR automation. In [22], a model is proposed so the fluctuations of spot prices are efficiently managed considering the short-term price elasticity of the consumers. Finally, the work in [23] focuses on the fair remuneration of DR, allocating price variations in real-time to different consumers according to their actual contribution for the high or low prices.

Focusing on the most recent literature on the VPP field, the work in [24] proposes a method to coordinate the operation of a VPP and voltage regulation to improve the static voltage stability in a distribution network. In [25], a demand response participation degree is established in order to improve the operation of energy storage provided by both battery storage and pumped storage in a microgrid. Incentives are paid for DR in [26], maximizing benefits for energy retailers. A certain price is paid to consumers according to the actual consumption reduction. The risk assessment for microgrid aggregation considering DR and renewables is presented in [27], where DR modeling is addressed by a certain amount of DR achieved and respective payment, considering a random uncertainty on the consumers response. Introducing DR in the distributed generation planning, the work in [28] addresses the integration of prosumers in the activities of an aggregator interacting with consumers, prosumers, and the DSO. The consumers and prosumers are integrated as resources that are paid for the actual quantity provided.

Finally, regarding the DR, DG, and suppliers modeling of contracts, in the most recent related literature, in [29] and [30], the uncertainty of PV and DR is modeled using a stochastic framework for several scenarios generated by Monte Carlo method. In [29] the focus is given to PV and DR, while in [30] the focus is given to retailers. Still on statistical simulations, in [31], the consumers react to prices in real-time to define the optimal consumption, price, and production, aiming to maximize the social welfare. In a distribution network reliability perspective, in [32] several scenarios are tested for the positive impacts of DR and electric vehicles, where these resources are prioritized. For last, in [33], numerical studies are given to show the advantages of shiftable and interruptible loads, where the available amount is modeled as maximum capacity. Furthermore, time interval and number of interruptions are modeled. The work in [10] deals with the definition of complex contracts. The energy field is not the main one in [10]; so, the authors in the present paper propose to adapt it to the VPP resource scheduling, focusing on DR programs participation by consumers.

The works referred deal with DR and address the way that DR can contribute to the efficient management of renewables-based generation, namely in the scope of electricity markets, some of them addressing the uncertainty of consumers response, the fairness of DR remuneration, and the barriers for DR fostering. Such works are made in the scope of retailers or aggregators, most of the times aiming to maximize their profit, dealing with DR modeling by different approaches which don't involve directly the consumers or generation owners.

The above-mentioned literature addresses the consumer, DR, DG, and suppliers using statistic and stochastic approaches to model their behavior and the respective impact on the network operation and planning. However, these models disregard adequate modeling of consumers and DG preferences, not directly considering contractual settings able to represent the bounds of consumers and DG preferences in what regards total minimum total and conditions to participate in DR events.

The most innovative contribution of this paper is to include in the model complex contracts approach, which can accommodate constraints according to the particular expectations of each player. These contracts are included in the distributed energy resources scheduling optimization by a VPP, to dispatch demand response according to the consumers expectations. So, the consumers can specify limits on the time, power, and remuneration regarding participation in demand response events. Such approach has not been considered in the literature as the state of the art treats these aspects separately or using a statistic approach, without providing consumers with options to combine their preferences regarding different aspects of their flexibility deployment. The proposed model includes:

- complex contracts which consider constraints regarding the minimum and maximum use time of each resource, and minimum incentive payments established for each type of resource
- use of the complex contracts in the scope of DG and DR contracts with VPP
- optimization of the distributed energy resources by the VPP, minimizing the operation costs, and considering the complex contracts
- validation with a comprehensive set of scenarios considering periods of wind unavailability, and the shifting of consumption to other periods.

IV. PROPOSED CONTRACT MODEL

This paper develops a model that can be used by a VPP to schedule the DR and DG resources and, thus, to manage them according to the availability and the operation costs minimization. Complex contracts are established with consumers and producers, respectively for DR and for DG, as well as with suppliers for energy acquisition, taking into account the expectations of each player. Those contracts include constraints for use time of each resource; minimum payment established for each type of resource; and the supply and/or use of DR resources in the time horizon. Constraints representing complex contracts between the VPP and resources are listed in Table I.

TABLE I
CONSUMPTION AND SUPPLY MODEL PARAMETERS VALUES

Complex contract	Equations
Amount of power – this parameter regards a defined minimum amount of power that producers, suppliers and consumers will, respectively, generate, provide and consume.	(2) – (10)
Incentive – the VPP can also contract the minimum incentive to be granted to each resource. This means that the VPP has contracted that such resource must receive a minimum certain amount of payment.	(11) – (13)
Ramping – the change in the schedule of two consecutive periods respects a maximum limit so the consumer or producer doesn't need to provide a huge response in a short amount of time.	(14) – (15)
Time – this parameter regards the minimum number of periods that are established for the scheduling. If a resource is scheduled, it must be scheduled by the VPP for the minimum number of periods defined.	(16) – (18)

Several resources are managed by VPP, as shown in Fig.1, respecting the complex contracts. For each constraint, the VPP should consider the number of participants in each type of resource. The cluster of the maximum index for consumption is given by CtN; the number of suppliers is given by SpN; and the number of DG resources is given by DgN. Generically each one of the types is represented by ct for the consumption cluster, dg for the DG unit, and sp for the supplier. For the DR use in period t, there are two types of DR: reduction and shift. A reduction, partly consists of effective reduction that will not be done in any other period; however, there is some amount of consumption that is reduced during a period that will be shifted to the period immediately before t0 and immediately after T. The shift of consumption between periods influences the final consumption after the scheduling performed by the VPP, i.e., if a period receives more power than the one reduced or shifted to other periods, its final consumption can be higher than the initial. The innovation of the work in the present paper consists in considering complex contracts in this scheduling.

V. OPTIMIZING THE SCHEDULING OF DEMAND RESPONSE RESOURCES INCLUDING COMPLEX CONTRACTS

In this section, the objective function and the resource availability constraints are presented in sub-section A, and the constraints concerning the complex contracts are presented in sub-section B. The formulation of the optimization problem aims at determining the optimal scheduling of demand response resources, considering complex contracts for the periods of the scheduling horizon (from t0 to T). This approach allows to reduce the consumption and to shift the consumption from several specified ct consumption clusters bounded by CtN. The shifting of consumption in each period i is comprised between t-BI and t+FI. The optimization problem considers the formulation presented in [11], adding new constraints regarding complex contracts.

A. Objective function and resource availability

The objective of the optimization problem is to minimize the operating costs for each resource in each period t, as in Eq. (1). Several constraints are implemented, such as: the energy balance; the amount energy that can be moved in each period i between the backward shifting limit BI and the forward shifting limit FT; the maximum limit of the consumption that can be shifted from period t to period I; the maximum limit for the total consumption that can be shifted from the specific period t to all the shifted periods I; the maximum amount of consumption shifting that can be done between periods; and the maximum capacity of each supplier sp and distributed generation dg for each period t. These constraints were already presented in [11] and are implemented in the present paper.

B. Complex contracts

Other equations, namely the ones concerning complex contracts, and are listed/explained below. The first set of constraints (eq. (2) to (4)) regards the minimum amount that each type of resource should participate with, between t0-BT and T+FT.

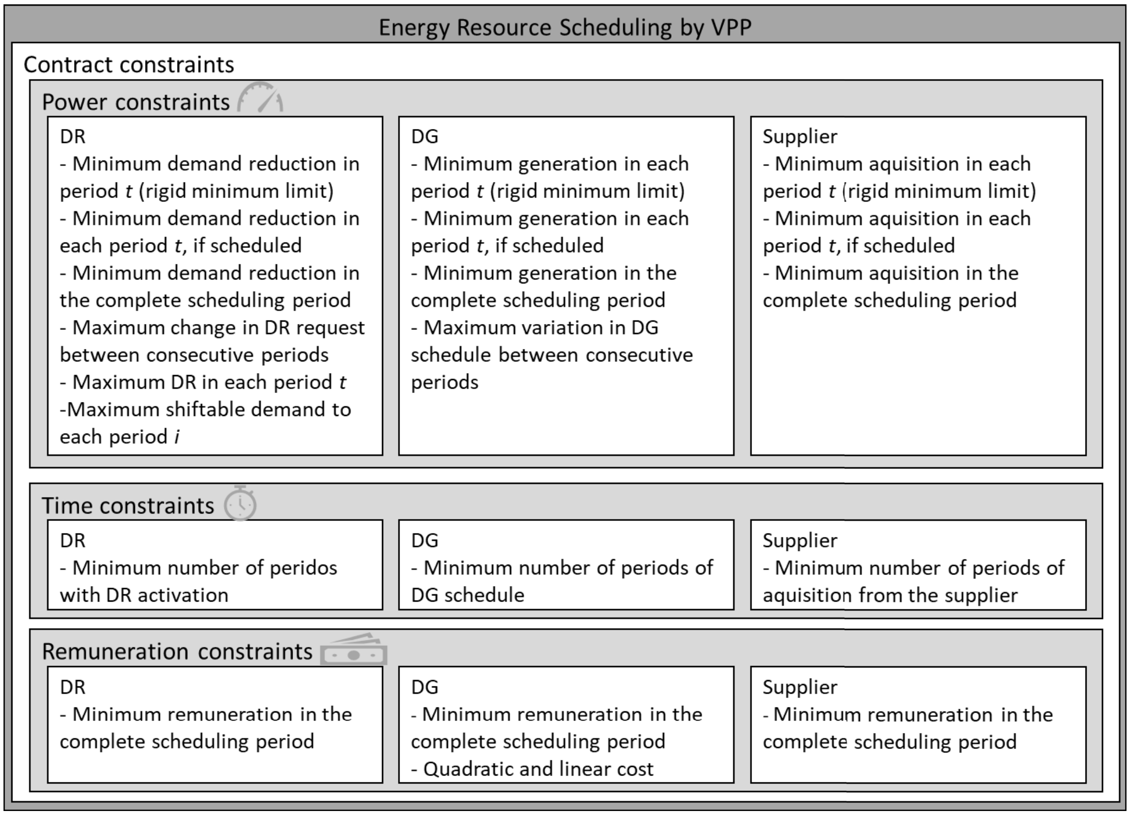

Fig. 1. Complex contracts definition.

With these constraints, the VPP is able to comply with scheduling the minimum amount of power agreed with each resource for each period. Eq. (2) regards the minimum amount that each distributed generation dg should generate in each period t. Eq. (3) concerns the minimum amount provided by each supplier sp. Eq. (4) corresponds to the minimum reduced consumption of each ct in each period t, and the demand shifted to each period t from other periods i.

The constraints presented in eq. (5) to (7) regards the minimum amount for each of the three types of resources (DG, Suppliers, and Clusters). With these constraints, the VPP is able to comply with scheduling the minimum amount of power agreed with each resource for each period, in the case that those are scheduled, i.e. if the resource is scheduled in a certain period, then the minimum amount of power should be respected. So, in eq. (5) is defined the minimum that each dg resource must generate in the total period between t0-BT and T+FT. Eq. (6) defines the minimum amount that must be provided by each supplier sp during the entire period (between t0-BT and T+FT). Regarding the clusters, eq. (7) ensures that the reduced consumption globally of each cluster ct has a given minimum amount for the period between t0-BT and T+FT. It considers the reduced consumption in each period t, and the demand that is shifted from each period t to i for the period BI to FI. The number of DG resources is given by DgN, the number of suppliers is given by SpN, and the maximum of consumption clusters is CtN. Parameters XDG, XSupply, and XDR determine whether the respective resources are activated by the VPP.

Eq. (8) to (10) ensure that the participation of each resource for the period t0-BT and T+FT complies a minimum amount. In these constraints, the total amount provided by each resource in the complete scheduling period is kept above the minimum. In this way, eq. (8) regards each distributed generation dg resource, and eq. (9) and (10) are related to each supplier sp and each cluster ct, respectively. It should be noted that for clusters, it is considered the consumption in each period t and consumption that is shifted from period t to i.

The minimum incentives (remuneration) for each resource is defined in eq. (11) to (13). This means that, for the period between t0-BT to T+FT, each resource must be remunerated by a minimum amount, according to the agreement with the VPP, as established in complex contracts. Eq. (11) regards the dg, in order to ensure the established minimum incentive payment. Eq. (12) and (13) regard each supplier sp, and each cluster ct, respectively.

The following set of constraints (eq. (14) to (15)) make possible to ensure stability in distributed generation dg and cluster ct between t0-BT and T+FT. In this way, eq. (14) defines that the variation of generation in generation distributed dg between two successive periods should be limited, i.e., when the VPP schedules a certain value of production for a period t-1, in the period t the generation is limited regarding the level relative increase between periods. A decrease is also accommodated by the same constraint. Eq. (15) limits the participation of each ct cluster between two successive periods, considering only the DR event of consumption reduction. These limits are defined in the complex contracts established between the VPP and the resources.

The last set of constraints (eq. (16) to (18)) allow the VPP to schedule the dg resources and cluster ct, during a minimum of periods. The parameters (XMin) limits the minimum of periods t operation in time horizon between t-BI and t+FI, respectively. Eq. (16) is devoted to dg resources, while eq. (17) is devoted to suppliers. Finally, eq. (18) regards consumption clusters. In these equations, as defined in complex contracts, each resource will be scheduled for a certain minimum number of periods, as agreed with the VPP.

In summary, while the objective function and the resource availability constraints implemented in the proposed optimization model have been implemented in previous works regarding DG and DR, equations (2)-(18) bring innovative contribution for the consumers participating in DR events in order to have your participation actually respecting their expectations. This makes possible to the VPP to have a more accurate response of the consumers to the demand response events, as well as DG owners providing generation as scheduled.

$$Minimize\ VPPOC = \sum_{to-BT\le t}^{t\le T+FT}\left[\begin{array}{l}\sum_{sp=1}^{SpN} P_{Supply(t,sp)}\times C_{Supply(t,sp)}\\ +\sum_{dg=1}^{DgN}\left(\begin{array}{l}P^2_{DG(t,dg)}\times C^a_{DG(t,dg)}\\ +P_{DG(t,dg)}\times C^b_{DG(t,dg)}\end{array}\right)+\\ \sum_{t-BI\le i}^{i\le t+FI}\sum_{ct=1}^{CtN}\left(\begin{array}{l}P_{DR(t,i,ct)}\times C_{DR(t,i,ct)}\\ +P^{NSP}_{Load(t,ct)}\times C^{NSP}_{Load(t,ct)}\end{array}\right)\end{array}\right] \qquad (1)$$

$$P_{DG(t,dg)} \ge PMin_{DG(t,dg)}; \forall to-BT \le t \le T+FT; \forall 1 \le dg \le DgN \qquad (2)$$

$$P_{Supply(t,sp)} \ge PMin_{Supply(t,sp)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le sp \le SpN \qquad (3)$$

$$P_{DR(t,i,ct)} \ge PMin_{DR(t,i,ct)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le ct \le CtN \qquad (4)$$

$$P_{DG(t,dg)} \ge PMin_{DG(t,dg)} \times X_{DG(t,dg)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le dg \le DgN;\ \forall X_{DG(t,dg)} \in \{0,1\} \qquad (5)$$

$$P_{Supply(t,sp)} \ge PMin_{Supply(t,sp)} \times X_{Supply(t,sp)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le sp \le SpN;\ \forall X_{Supply(t,sp)} \in \{0,1\} \qquad (6)$$

$$P_{DR(t,i,ct)} \ge PMin_{DR(t,i,ct)} \times X_{DR(t,i,ct)}; \forall to-BT \le t \le T+FT; \forall 1 \le ct \le CtN;\ \forall X_{DR(t,ct)} \in \{0,1\} \qquad (7)$$

$$\sum_{to-BT\le t}^{t\le T+FT} P_{DG(t,dg)} \ge PMin_{DG(dg)}; \forall to-BT \le t \le T+FT; \forall 1 \le dg \le DgN \qquad (8)$$

$$\sum_{to-BT\le t}^{t\le T+FT} P_{Supply(t,sp)} \ge PMin_{Supply(sp)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le sp \le SpN \qquad (9)$$

$$\sum_{to-BT\le t}^{t\le T+FT}\sum_{t-BI\le i}^{i\le t+FI} P_{DR(t,i,ct)} \ge PMin_{DR(ct)}; \forall to-BT \le t \le T+FT;\ \forall BI \le i \le FI;\ \forall 1 \le ct \le CtN \qquad (10)$$

$$\sum_{to-BT\le t}^{t\le T+FT}\left(P^2_{DG(t,dg)} \times C^a_{DG(t,dg)} + P_{DG(t,dg)} \times C^b_{DG(t,dg)}\right) \ge CRem_{DG(dg)}; \forall to-BT \le t \le T+FT; \forall 1 \le dg \le DgN \qquad (11)$$

$$\sum_{to-BT\le t}^{t\le T+FT}\left(P_{Supply(t,sp)} \times C_{Supply(t,sp)}\right) \ge CRem_{Supply(sp)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le sp \le SpN \qquad (12)$$

$$\sum_{t-BI\le i}^{i\le t+FI}\left(P_{DR(t,i,ct)} \times C_{DR(t,i,ct)}\right) \ge CRem_{DR(ct)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le ct \le CtN \qquad (13)$$

$$\left|P_{DG(t,dg)} - P_{DG(t-1,dg)}\right| \le PVar_{DG(dg)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le dg \le DgN \qquad (14)$$

$$\sum_{t-BI\le i}^{i\le t+FI}\left(P_{DR(t,i,ct)} - P_{DR(t-1,i,ct)}\right) \le PVar^{t=i}_{DR(t,i,ct)}; \forall to-BT \le t \le T+FT;\ \forall BI \le i \le FI;\ \forall 1 \le ct \le CtN \qquad (15)$$

$$\sum_{to-BT\le t}^{t\le T+FT} X_{DG(t,dg)} \ge XMin_{DG(dg)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le dg \le DgN;\ \forall X_{DG(t,dg)} \in \{0,1\} \qquad (16)$$

$$\sum_{to-BT\le t}^{t\le T+FT} X_{Supply(t,sp)} \ge XMin_{Supply(sp)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le sp \le SpN;\ \forall X_{Supply(t,sp)} \in \{0,1\} \qquad (17)$$

$$\sum_{t-BI\le i}^{i\le t+FI} X_{DR(t,i,ct)} \ge XMin_{DR(ct)}; \forall to-BT \le t \le T+FT;\ \forall 1 \le ct \le CtN;\ \forall X_{DR(t,ct)} \in \{0,1\} \qquad (18)$$

The implemented optimization problem is a mixed-integer nonlinear model. The case study here presented include 91 849 variables. The proposed model was implemented in TOMLAB® environment and the solutions have been obtained using CPLEX solver.

VI. CASE STUDY AND RESULTS

In this section are presented the assumptions that are considered in the case study and the results are presented and discussed. The scheduling performed by the VPP concerns one day, which is divided into 96 periods of 15 minutes. Four types of DG resources (thermal, PV, hydro, and wind), whose profiles are presented in Fig. 2, corresponding to a real situation of Portuguese power system operation. Suppliers are a regular supplier and an additional supplier, providing for all periods 4100 kW and 3000 kW, respectively. As it can be seen in Fig. 2, Hydro based DG is of a small amount. In fact, in the role of the VPP operation, small size resources should be aggregated in order to make them competitive. One can find small hydro power plants starting from 15 kW rated power, or even less [24]. Fig. 3 shows the consumption pattern for the 96 periods. The 218 consumers are grouped in 5 consumption clusters, according to their characteristics [13]. On the consumption side, in addition to considering the consumption in each period, it is also defined the maximum capacity consumption reduction and consumption shift, as well as respective remuneration (incentive payment), when DR events occur. In this case study are considered two DR events (DR1 and DR2), as it can be seen in Fig. 3.

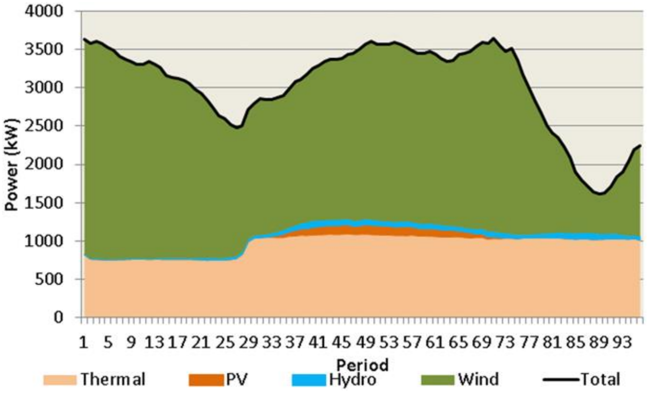

Fig. 2 Distributed generation profiles.

The 96 periods constituting the case study are divided as is shown in Fig. 2. Thus, it follows that the resource scheduling period is comprised between the periods 49 and 84, which corresponds to 10 hours. Moreover, it is considered the backward and forward horizon that include 3 hours each, between the periods 36 and 37 and between the periods 85 and 96, respectively. The minimum notification period is of 8 hours (32 periods). The details for each consumption cluster are shown in Table 2. The same values have been assumed for both the parameters PMaxDRt(t,ct) and PMaxDRi(t,ct), for each consumption cluster. The base consumption PLoadBase(t,ct) has been defined for each consumption cluster ct as a percentage of the total base consumption presented in Fig. 3.The final maximum consumption in each cluster, in each period t, has been defined as 120% of the respective base consumption. In what concerns the distributed generation and the suppliers, Table III presents the value of each parameter, regarding four types of DG, a regular amount of power and an additional amount of power, available at distinct prices.Table IV identifies the association of each constraint to each type of resource. As shown in Table II, not all resource types are restricted by the same constraint. According to the description in Section 4, “(2)” refers to the first constraint implemented in the present paper.

The same applies to all the constraints referred in Table III. The percentages for the first set of constraints (2)-(4) refer to the minimum amount that each resource must provide, in each period t. For example, "Wind" must comply with 50% of its maximum capacity, in each period t. Regarding sets of constraints (5)-(7) and (8)-(10), the percentage refers to the total capacity of each resource has to the global period T. For example, for the set of constraints (5)-(7), the "Regular Supplier" is defined that during the overall period T, this resource should provide the system at least 40% of its total capacity. For the set of constraints (11)-(13), the percentage values refer to the minimum remuneration of each resource, in global period T.

TABLE II

CONSUMPTION AND SUPPLY MODEL PARAMETERS VALUES

Parameter	**Consumption cluster**				
	ct1	**ct2**	**ct3**	**ct4**	**ct5**
$PMax_{DR^{t}(t,ct)}$ [kW]	444.3	292.1	584.7	559.6	315.0
$PMax_{DR^{i}(t,ct)}$ [kW]	444.3	292.1	584.7	559.6	315.0
Base consumption (%)	32.32	20.97	16.23	21.24	9.23
Remuneration [m.u./kW]	According to Table 2				
$C_{Load}{}^{NSP}{}_{(t,ct)}$ [m.u. / kW]	8				
$P_{Load}{}^{Max}{}_{(t,ct)}$ [kW]	120 % of the base consumption				
$\alpha_{DR}{}^{Max}$ (%)	80				

The corresponding percentages to the restrictions (14)-(15) indicate the variation that each of the associated resources can have between two successive periods t, i.e., for example, the resource of distributed generation dg "Thermal" between two consecutive periods t only can vary their generation (increase/decrease) by 30% compared to the nominal of its generation for each t.

TABLE III
SUPPLIER AND DG MODEL PARAMETERS

Resource	**Cost parameters**		**Capacity**	$\alpha_{DG}{}^{Max}$
	Quadratic	Linear	[kW]	(%)
Regular supplier	-	0.07	According to Fig. 2	60
Additional supplier	-	0.18		
Thermal	0.0034	0.12		
PV	0.0045	0.02		
Hydro	0.0072	0.06		
Wind	0.0021	0.04		

TABLE IV
ASSIGNMENT CONSTRAINTS OF EACH RESOURCE (DISTRIBUTED GENERATION DG, SUPPLY SP, CLUSTER CT)

Resource	Assignment constraints					
	(2)-(4)	(5)-(7)	(8)-(10)	(11)-(13)	(14)-(15)	(16)-(18)
Thermal	-	-	-	-	30 %	30 periods
PV	-	-	50 %	50 %	-	-
Hydro	-	-	-	-	-	-
Wind	50 %	-	-	-	-	30 periods
Regular Supplier	25 %	40 %	-	30 %	-	40 periods
Additional Supplier	-	-	20 %	10 %	-	10 periods
ct1	-	-	-	-	40 %	-
ct2	-	-	-	-	40 %	-
ct3	-	-	20 %	-	40 %	11 periods
ct4	-	20 %	-	10 %	40 %	-
ct5	10 %	20 %	-	10 %	40 %	-

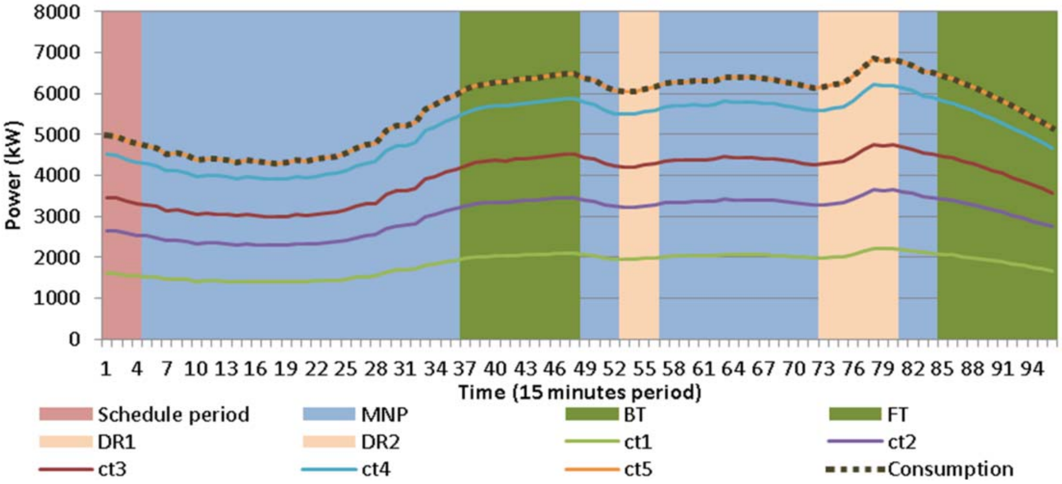

Fig. 3 Consumption profiles

The last set of constraints are allocated the minimum number of periods that each resource must participate, for example, the resource of distributed generation "Thermal" must participate in 30 periods, being that the global period T has 60 periods. For the remaining resources is similar, but for the resource of cluster "ct3", the global period T that can participate are 44 periods, therefore, in this set of constraints is imposed that this resource participates in 25% in the total time, corresponds at 11 periods defined. This case study is implemented in three different scenarios – ScenA, ScenB, and ScenC. In both the ScenA and ScenB, only is considered for the case study the constraints identified in [11].

The ScenC considers the constraints presented in this paper, corresponding to the complex contracts (Table 4), as well as the constraints identified in [11]. In the ScenA, these unavailabilities of wind are only compensated by distributed generation and supplier resources, whereas in both cases of other scenarios, ScenB and ScenC, the unavailabilities of wind are compensated by use of all resources, as is identified in Table V. For all scenarios, it is assumed wind unavailability in two periods, relative to baseline wind power generation shown in Fig. 2, influencing both DR events (DR1 and DR2), referred to in Fig. 3. In the first unavailability, in period 50, considering total unavailability of 2329 kW, and in the second unavailability, in period 70, there is a partial unavailability of 80%, which results in a total of 1967 kW of power decrease.

As previously mentioned, three distinct scenarios have been implemented.

TABLE V
CONSTRAINTS CONSIDERED IN EACH SCENARIO

Scenario	***Constraints in [10]***		***Complex Contracts with DR and DG***
	DR	DG	
A	-	X	-
B	X	X	-
C	X	X	X

A. Resources schedule in scenario ScenA

Fig. 4 show the scheduling performed by the VPP considering that occurs in two distinct periods a wind unavailability, specifically in periods 50 and 70. As can be seen, for the periods 50 and 70 there is total and partial wind unavailability, respectively, which causes the need to compensate for this lack of wind power. It is necessary that the VPP schedules a more considerable amount from other sources, especially use the additional and regular supplier, and thermal generation.

The additional supplier only participates in scheduling resources for the 50 and 70 periods, where there is wind unavailability. In this case study, the periods where occurs wind unavailability allow to check interesting aspects, in particular, the vulnerability of DG resources, which continue to be unstable due to the characteristic of the unpredictability of natural resources. Thus, it is crucial that the VPP establish contracts with external suppliers.

B. Resources schedule in scenario ScenB

Fig. 5 shows a similar situation to the one presented in sub-section 5.1. However, the VPP in this scenario can consider using DR scheduling of resources. Therefore, considering likewise the two periods of wind unavailability, the schedule made by the VPP do not need to use an additional supplier to compensate for the lack of wind. In this case, the use of DR allows to remain the balance of the electric power system, not using an additional supplier, yet it was necessary to have an increase in participation by the regular supplier and thermal generation in periods 50 and 70. Within the limited purple region can be seen the use of DR shown in red, in the contiguous periods to the periods 50 and 70, inclusive. As explained in the methodology, the use of DR allows to reduce or shift the consumption for other periods. For this reason, for the periods 50 and 70, the final consumption is less than the initial. However, the consumption reduction in these periods originates in adjacent periods an increase in consumption due to the shifting of consumption.

In Fig. 5 can be seen that there were consumption reduction and shifting by comparing the lines representing the initial and final consumption. The consumption shifted is originated from the periods 50 and 70. Therefore, in the periods 50 and 70 consumption is effectively reduced, for period 50 is reduced 572,10 kW, and period 70 consumption reduction is 452,90 kW, through consumption shifted. However, the other periods will increase its consumption. In this scenario, the consumption cluster ct3 has no scheduled by VPP.

The scheduling by VPP considers consumption incoming between the periods 72 and 76, from period 70, through the consumption shifting. Simultaneously, in these same periods, the consumption is reduced, allowing to substantially reduce the consumption shifted in period 70. Thus, the final consumption is similar to the initial consumption, in these periods, as shown the Fig. 5.

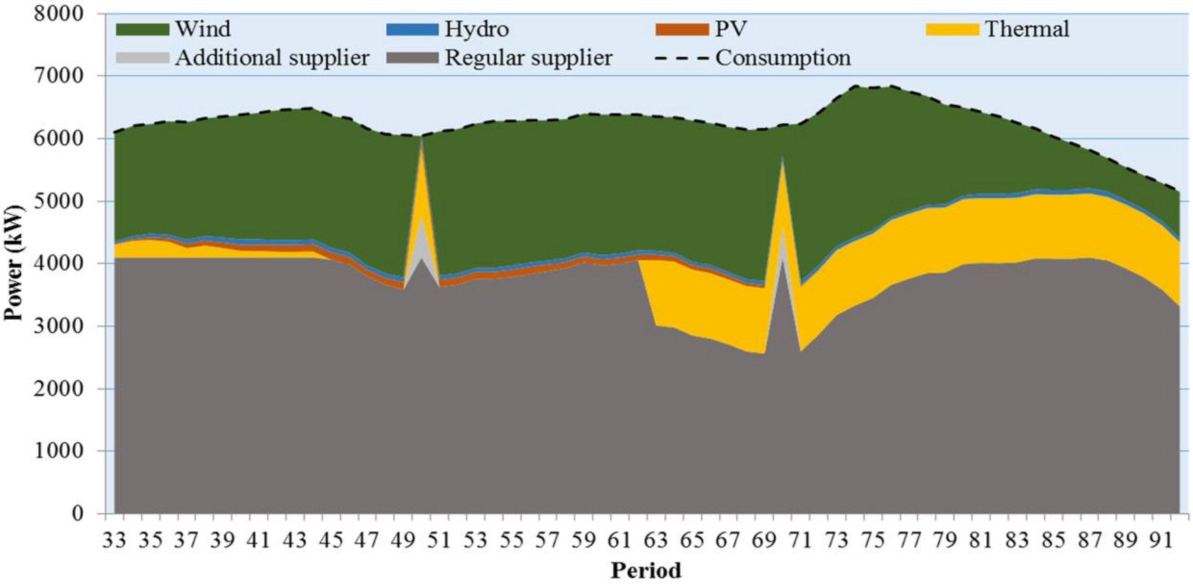

Fig. 4 Resource schedule with wind unavailability, in ScenA

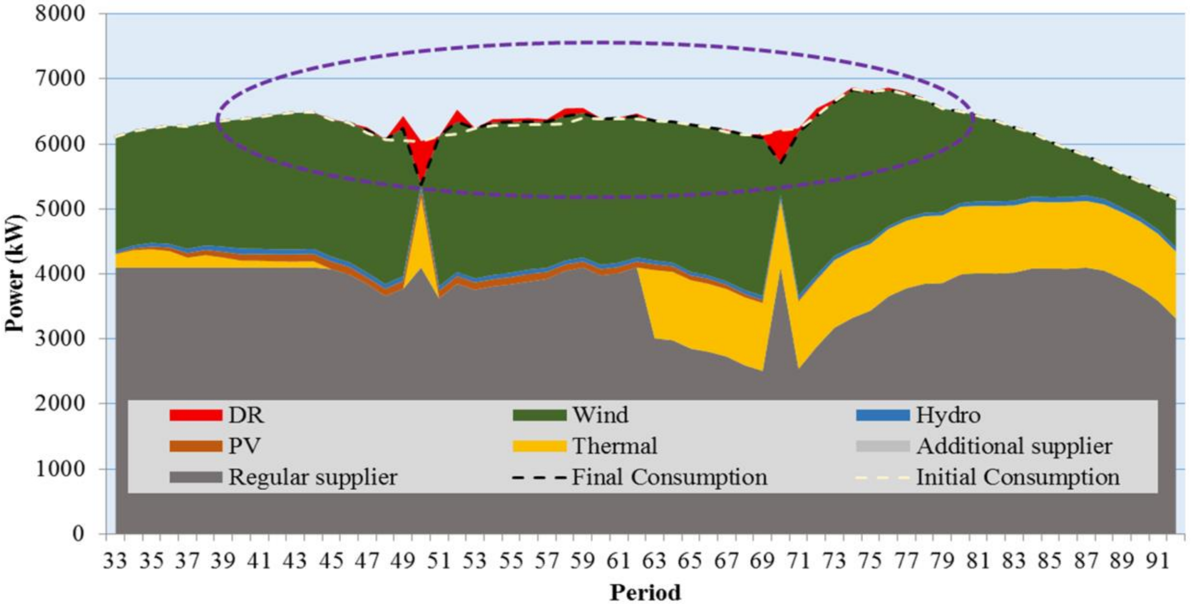

Fig. 5 Resource Schedule with wind unavailability and implementation of DR, in ScenB

C. Resources schedule in scenario ScenC

The scenario ScenC presents the results that consider the complex contracts. In addition to the constraints of complex contracts, Fig. 6 shows the scheduling done by the VPP, considering what happens in two periods of wind unavailability. As can be seen considering the complex contracts, the scheduling done by VPP addresses distinct results in comparison with results presented in 5.2. The scheduling considers one increase participation of DR resource (shifting and reduction consumption) and an increasing amount of power provided by an additional supplier, in contrast to the regular supplier resource that decreases the providing. The use of DR resources allows that at certain times the final consumption is less than the initial consumption and vice versa, for optimal scheduling.

The use of complex contracts implies an increase in the participation of DR resources in the scheduling as can be seen by comparing Fig. 5 and Fig. 6. Fig. 7 illustrates the contribution of each consumption cluster for periods 50 and 70, as well as to check the amount of consumption shifted in each period. Fig. 7 concerns with consumption shifted to each period for each cluster consumption, from period 50 and 70. Thus, it can be verified that the consumption cluster ct2 does not perform any consumption shifting. Comparing the scenario ScenB (without restrictions of complex contracts) and this scenario ScenC (with complex contracts), in addition to increasing the participation of DR resources, there is a change in the paradigm of consumption clusters. By analyzing Fig. 7 it can be seen that at certain periods there is incoming of consumption from other periods, while consumption reducing is scheduled in the same periods, namely, for the periods 52, 53 in the first event DR and periods 69, 71, 72, 73, 75 and 76 to the second DR event.

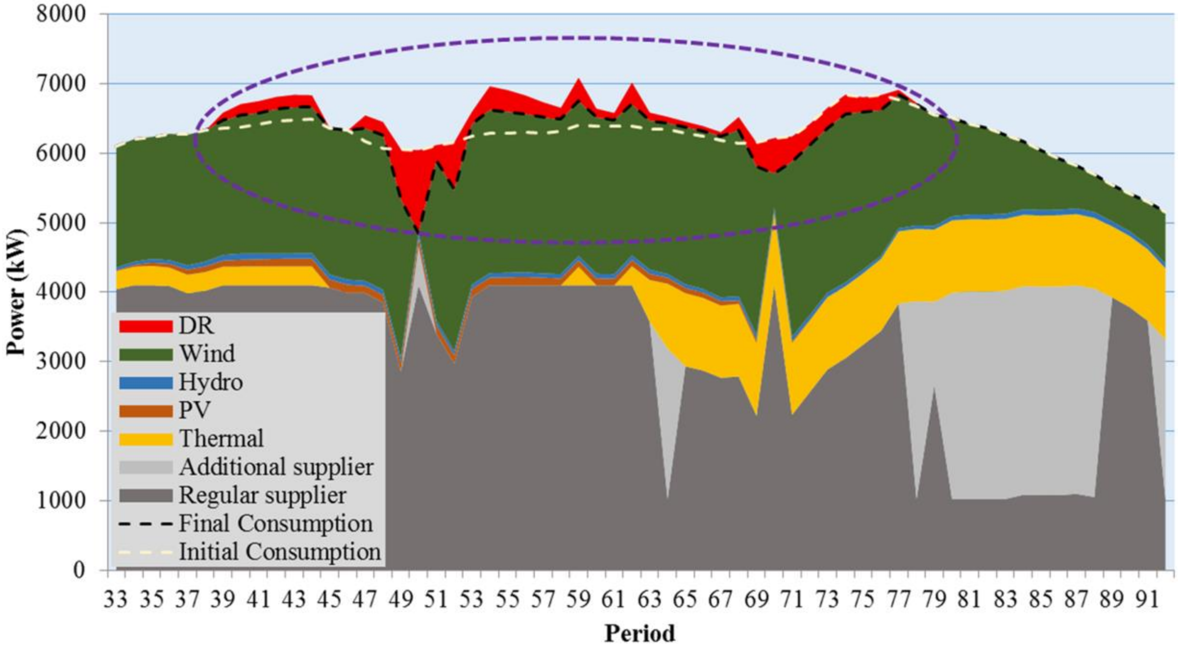

Fig. 6 Resource Schedule with wind unavailability and implementation of DR, in ScenC

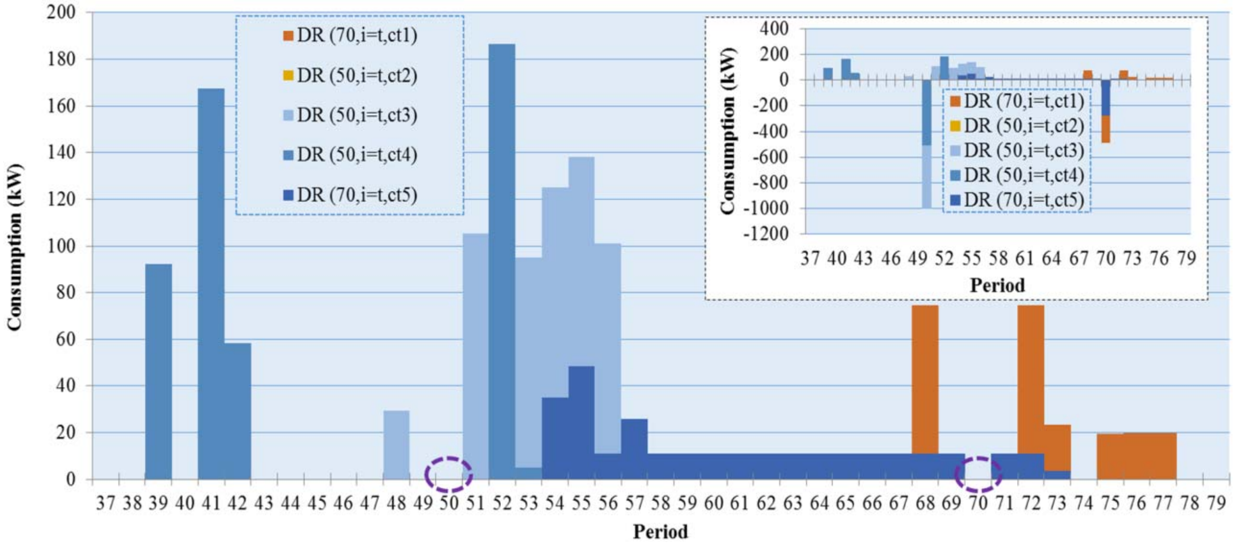

Fig. 7 Resource Schedule with wind unavailability and implementation of DR, in ScenC

D. Comparison of the results in each scenario

This sub-section presents the scheduling for each resource in each of the three distinct scenarios studied. Fig. 8 refers to the supply and generation resources of electric energy, while Fig. 9 identifies the scheduling of each consumption cluster ct. For consumption clusters ct only presents the results obtained in ScenB and ScenC scenarios, since for the first scenario (ScenA), the VPP only considers in scheduling the suppliers and distributed generation resources.

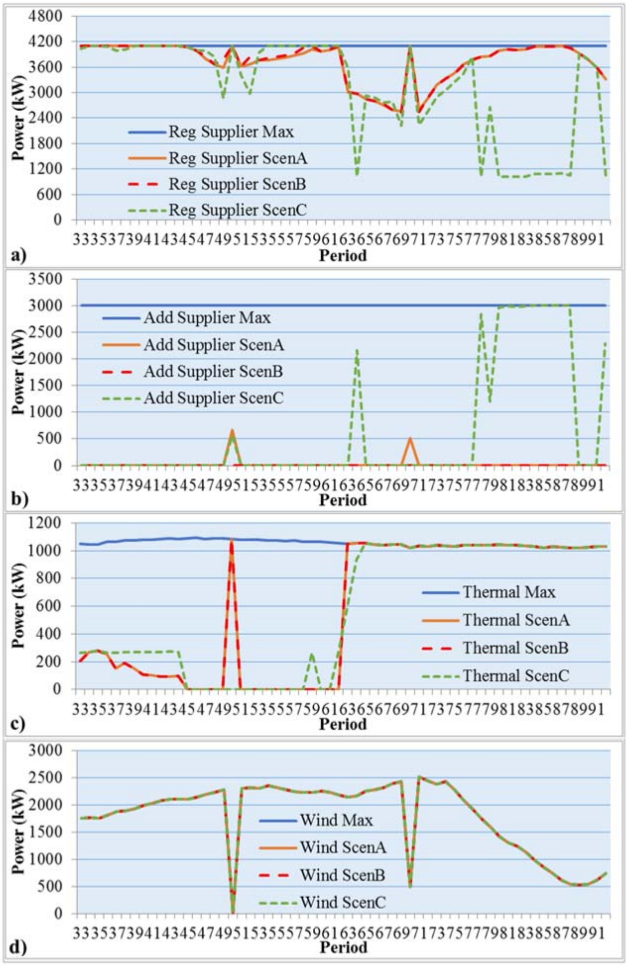

Fig. 8 Generation resources use comparison

The case of a) and b) of Fig. 8 corresponds to the regular supplier and the supplier additional, respectively. Regarding the results obtained from the regular supplier, shown in a), it appears that both the ScenA as to ScenB, the resulting scheduling for this resource is similar, with a high amount of use compared to the maximum capacity. For ScenC scenario, there is a decrease in the quantity scheduled.

In b) is illustrated the scheduling of additional supplier; the results are similar for the first two scenarios (ScenA and ScenB). However, in these scenarios there is a little amount of power scheduled by the VPP. In ScenC there is a considerable increase in the amount provided by this resource, mainly because of complex contracts. Somehow the amount supplied by this resource corresponds to the amount decreased in scheduling by the regular supplier. The VPP can schedule DG of four types, namely: Thermal, Photovoltaic (PV), Hydro and Wind.

The results are shown in c), and d), for thermal and wind. For each of the scenarios designed, only the scheduling for the thermal resource, in c), shows results with small variations in the amount scheduled between scenarios. For other resources, the values obtained in the schedule are identical in all scenarios.

Concerning the scheduling of DR resources are presented in Fig. 9 in which each consumption cluster is shown the consumption reduction and consumption shifted in a) ct1, b) ct2, c) ct3, d) ct4 and e) ct5. The values of the amount of DR resources scheduled by VPP are distinct in both scenarios.

In almost all the DR resources the amount scheduled by VPP in scenario ScenC is higher compared with the ScenB, except for the consumption cluster ct2, in b).

An interesting aspect is that the consumption cluster ct3 is only scheduled in scenario ScenC. It is noted that for the first DR event, DR1, the consumption clusters that are scheduled by the VPP are the ct2, ct3, and ct4. While for the second DR event, DR2, scheduled consumption clusters correspond to ct1 and ct5.

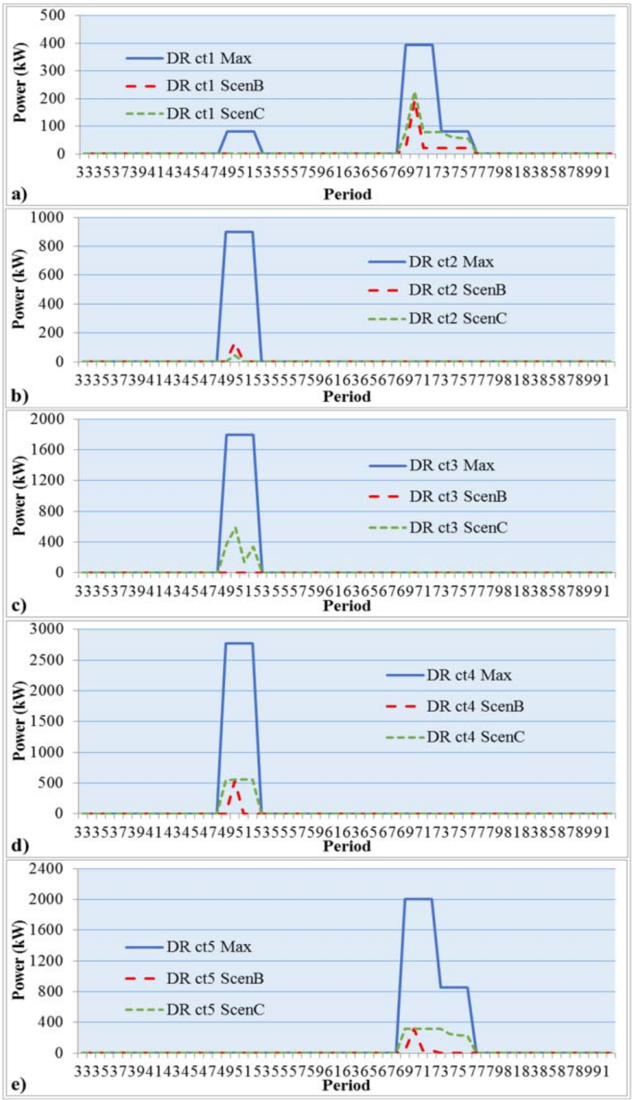

Fig. 9 Demand response resources use comparison

VII. CONCLUSION

The methodology proposed in this paper considered the use of DR resources by reducing and shifting consumption, as well as DG resources, and suppliers, in the scheduling done by the Virtual Power Player (VPP). The innovative content relies on the definition and implementation of complex contracts in order to accommodate contractual conditions established between the VPP and each DG and DR resource. In this way, it was possible to understand and agree on the conditions in which each resource can be scheduled, achieving in this way a more reliable operation of the VPP resources. As the consumers and producers agreed on their expectations and limitations, their actual response to a DR event will be closer to the expected.

The case study of 218 consumers aggregated into 5 clusters, four types of DG (thermal, PV, wind and hydro), and two types of suppliers, considered the wind unavailability in two distinct periods.

The VPP was able to use DR programs to overcome the wind unavailability while reducing consumption or shifting consumption to minimize operating costs. The participation of each resource was scheduled according to the consumers' and producers' expectations, namely regarding the incentive payments (remuneration), achieving also a lower dependence of external suppliers.

Comparing Fig. 4 with Fig. 5, it is possible to see the adequacy of DR to handle the lack of supply due to wind unavailability. DR avoided to use additional suppliers, which are costly. In Fig. 6, by adding the complex contracts, which are the focus of this paper, it is possible to see that the amount of DR has increased. In one hand, it is benefic to achieve a higher amount of DR and ensure while such increase is realistic as it was agreed with the consumers and producers in the complex contracts. On the other hand, such amount of DR was achieved because consumers have contracted to have a certain minimum amount of incentive (remuneration) when they are called to provide consumption reduction.

As to the results in Fig. 8, in can be seen that for thermal distributed generation, after applying complex contracts, in the first periods of the day a minimum amount of power was respected. Otherwise, the dispatch of this type of resource would be changing period after period. In Fig. 9 can be seen that, in general, the activation of each consumption cluster for DR has increased as complex contracts are established. This is in line with the results in Fig. 6.

The established complex contracts are a rather simple and clear way to specify the conditions in which each resource is scheduled and remunerated, so the distributed resources are easily aware of the scheduling results. Overall, even if these contracts lead to higher operation costs for the VPP, the way that, in complex contracts, consumers and producers are called and dispatched according to their expectations is advantageous as the response of these resources will meet the VPP schedule.

Future work should include the definition of complex contracts in a dynamic way, depending on the context (season, temperature, according to the incentive, etc.).

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