Energy Resource Aggregator Managing Active Consumer Demand Programs

João Spínola, Pedro Faria, Zita Vale
GECAD - Knowledge Engineering and Decision Support Research Center
PP - Polytechnic of Porto
Porto, Portugal
jafps@isep.ipp.pt, pnfar@isep.ipp.pt, zav@isep.ipp.pt

***Abstract* — The relevance of flexibility resources in today's energy systems is underestimated due to the conventional ideologies of operators and users, however, the recent rise in demand response popularity has allowed considerable changes to how and how should power systems operate. In this paper, it is presented an aggregator's methodology to include and manage distributed energy resources, namely, distributed generation and demand response. The focus is given to aggregation and remuneration of resources managed by the aggregator based on the resource's scheduling solution. Different kinds of aggregation considerations are explored. In this way, three data sets are used to analyze aggregation results: maximum reduction capacity, final consumption per consumer, and scheduled consumer reduction. The methodology is validated on a 937-bus Portuguese network.**

***Index Terms*—Clustering, Demand Response, Distributed Resources.**

Nomenclature

Variables

$P^{Supplier}$	Scheduled power in supplier
P^{DG}	Scheduled power in a DG unit
P^{DR}	Reduced energy through DR

Parameters

$C^{Supplier}$	Supplier cost
C^{DG}	Distributed generation cost
P^{MaxSup}	Maximum power schedule for suppliers
P^{MaxDG}	Maximum power schedule for DG resource
P^{Load}	Total consumption value
P^{MaxDR}	Bill for all consumers with DR
C^{DR}	DR energy price for all consumers

Indexes

N	Maximum number of distributed producers n
K	Maximum number of suppliers k
C	Maximum number of consumers c

I. Introduction

Aggregators are entities that can optimally manage distributed energy resources [1], achieving their integration as active parties in energy system's operation. The inclusion of consumers into the aggregator's planning (as demand response - DR) considers several features, such as access to real-time consumption values, reduction amount available, and the cost of that reduction [2]–[4]. Representing consumers through analyzers or smart meters can be very practical when the aggregator needs to perform the optimal scheduling of resources. In this way, several consumers can represent a building or separate individuals. These are either way interpreted as unique loads that need to be managed according to what is occurring in the power system's operation. The scheduling of resources allows the aggregator to obtain its operation costs, and consider options for any given situation. At this point, the aggregator isn't far different from a balance responsible party, however, when clustering is included the prospect of making groups of resources allows a simplification to management and control. How the groups are made can be a complicated choice, since one needs to find individual patterns that are not at sight, unveiling them to create groups where resources are much alike. Results from the scheduling and clustering grant the aggregator several tools and data to work in the best interest of both sides (aggregator and consumer).

The control over reduction utilities can be of the aggregator (applying direct load control) or of the consumer (manual/local automatization) [5]. Aggregators are currently implemented throughout the world, mainly in the United States and some countries of Europe. United States, although still having its majority of energy markets regulated (without competition), the advances in active consumer programs are very promising, existing already several online platforms and forms that can be

The present work has been developed under the EUREKA - ITEA2 Project SEAS (ITEA-12004), AVIGAE Project (P2020 - 3401), and has received funding from FEDER Funds through COMPETE program and from National Funds through FCT under the project UID/EEA/00760/2013.

used by the consumers to join these programs. Europe, although not so advanced as the United States, has begun recently updating its energy markets (mostly deregulated) to adapt to active consumer programs, thus integrating consumers as a flexibility resource [6]–[9]. However, the number of consumers, when in comparison with the number of suppliers or power plants, is significantly larger, which means a more difficult resource to manage. In this way, aggregators can provide a solution to distributed resources operation in the eyes of the system operator or a balance responsible party. The aggregator can therefore manage a group of resources, obtaining himself a schedule. When the time comes to the system operator to perform its duties, it can ask the aggregator for a simplified solution of its control region, reducing by far the number of variables considered by the operator for that region. In this context, the aggregator can be very much like a distribution operator.

The present document details the mechanisms of a methodology to support an aggregator in its operation regarding active consumer programs and distributed generation. The proposed aggregator model is divided in three main stages: data input, optimization (scheduling), and clustering with remuneration.

Previous work has been made regarding the themes above described, namely, in [10], [11], however, the output of information from the methodology and how the results should be interpreted were never focused features. In this way, the proposed methodology is intended to provide context and an environment of application to the methods developed for the aggregator. As one can see by Figure 1 and Figure 2, the results can be applied throughout several kinds of equipment, since also guidelines are provided during the process.

After this introductory section, the proposed methodology is explained in Section II and the mathematical formulation in Section III. Further, Section IV details the case study applied in this paper, Section V the results obtained from the case study, and the conclusions are presented in Section VI.

II. Proposed Methodology

The aggregator model here proposed considers that this entity performs the management of resources enclosed within a certain agreement that is established between the two, that can be of several conditions, namely, only energy production, only energy supply, flexibility services, or all together or mixed (energy supply, energy production, and flexibility services). The proposed methodology will be detailed in the present section, using three sub-sections: data input, optimization, and clustering - Figure 1 and Figure 2. The methodology is implemented in MATLAB, using TOMLAB [12], [13].

A. Data Input

In this stage, the characteristics of every resource are gathered by the aggregator to perform their scheduling. The algorithm is based on a function that receives certain input parameters allowing control over how the algorithm processes. The following Figure 1 shows how the algorithm is organized from the input (Table 1 is considered) to the output data process, while Figure 2 shows the implementation context behind the proposed methodology, with a building example.

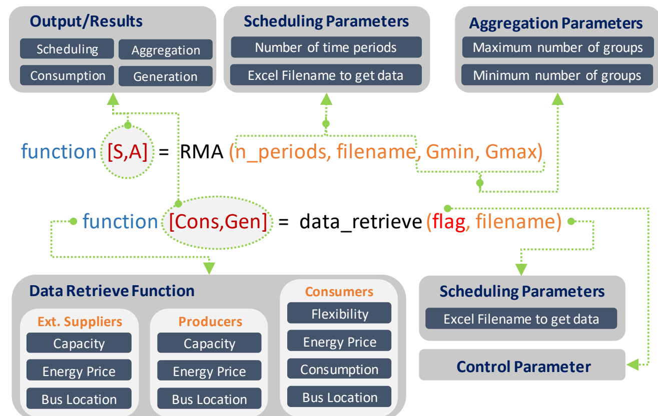

Figure 1. Scheduling inputs.

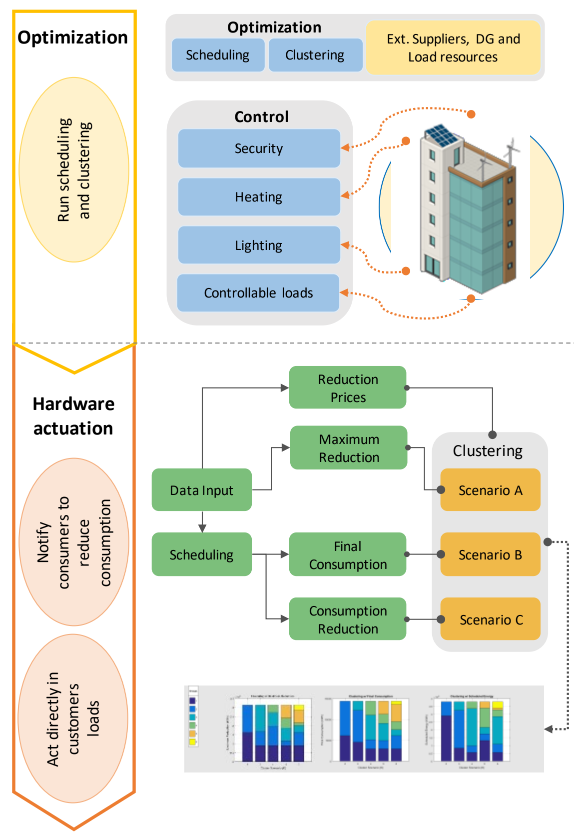

Figure 2. Proposed methodology.

Table 1. Data input needed for the methodology.

External Suppliers	Distributed Generation	Consumers
Minimum capacity	Minimum capacity	Maximum reduction
Maximum capacity	Maximum capacity	Price per energy unit reduced
Price per energy unit generated	Price per energy unit generated	Consumption

B. Run Optimization

The scheduling optimization is implemented in TOMLAB, defined as a "powerful optimization platform and modelling language for solving applied optimization problems in MATLAB". The use of MATLAB in these kind of applications allows an easy interpretation of the problem with matrix structures and formulation.

For the current methodology, the problems are assumed to be linear in all aspects (objective function and constraints), and thus its definition becomes simpler and easier to configure. It is important to know the type of problem considered and how one can define it (e.g. linear or non-linear objective function and constraints, mixed-integer or not, amongst others). TOMLAB uses different kinds of parameters according to the problem at hand.

C. Run Clustering

The clustering is based on the K-means algorithm, thus in that way, MATLAB allows an easy integration of this algorithm through the function "*kmeans*". K-means algorithm is a partition clustering method that iteratively moves resources amongst the existing groups, so that the distance (distance meaning dimension) is minimized as possible, i.e. a resource is assigned to a group, if its distance to the group's center is the lowest when compared with the distances to the centers of the other groups. The distances can be computed considering many methods, where these distances represent the differences verified amongst the observations of several variables. The distance calculation method considered in this case, is the squared Euclidean, as represented in Equation 1, where x represents objects, i and j are observations, and t the number of variables.

$$D_{ij} = \left(\sum_{t=1}^{d} \left| x_{it} - x_{jt} \right|^{\frac{1}{2}} \right)^2 \quad (1)$$

The formation of groups is made separately by type of resource, i.e. consumers will form groups apart from the distributed generation, thus implementing different aggregation simulations for each type of resource. As mentioned above, three scenarios are considered regarding the data used as basis to perform the clustering – the data served as input to the clustering defines how the resources are allocated to the groups, and thus also the values obtained from the distances calculated. The three scenarios for consumer's aggregation are:

- <u>Scenario A: Reduction Capacity</u> – the values entered in the clustering to define the groups are the maximum capacities of reduction by consumers;
- <u>Scenario B: Final Consumption</u> – the values entered in the clustering to define the groups are the final value of consumption of the consumers, where this means the initial load minus the reduction made;
- <u>Scenario C: Consumption Reduction</u> – the values entered in the clustering to define the groups are the scheduled load reduction of the consumers.

In order to avoid the introduction of false prices into the groups, the resources that are not scheduled by the aggregator, also won't be considered in the clustering process. Although, this strategy reduces the number of individuals in the groups, one must consider that keeping resources in the clustering that do not participate in the scheduling is pointless for this methodology and not towards the reality of operation, since the group tariff would be influenced by these.

The resource's remuneration is performed by computing the average of the resource's prices, for each group, remembering that the non-used in the scheduling are not considered. The price obtained is then used for all resources belonging to the same group, thus some will receive more than expected while others less. This ensures that the most efficient resources are well compensated, serving as incentive for their participation in the aggregator's scheduling. The following chapter presents the mathematical formulation in the basis of the present methodology regarding scheduling.

III. Mathematical Formulation

In the present chapter, one will address the mathematical formulation that composes the methodology proposed. Equation 2 presents the objective function considered in the scheduling, accounting upon three types of resources: distributed generation, external suppliers, and demand response resources (consumers).

$$\begin{aligned} Min\ Costs = & \sum_{n=1}^{N} P_{(n)}^{DG} \times C_{(n)}^{DG} + \\ & + \sum_{k=1}^{K} P_{(k)}^{Supplier} \times C_{(k)}^{Supplier} + \sum_{c=1}^{C} P_{(c)}^{DR} \cdot C_{(c)}^{DR} \end{aligned} \quad (2)$$

Equation 3, 4, and 5, present the limits for each of the variables considered in the objective function. These limits correspond to the values supplied in the data input stage.

$$0 \le P_{(n)}^{DG} \le P_{(n)}^{MáxDG}, \quad \forall n \in \{1,...,N\} \quad (3)$$

$$0 \le P_{(k)}^{Supplier} \le P_{(k)}^{MáxSup}, \quad \forall k \in \{1,...,K\} \quad (4)$$

$$0 \le P_{(c)}^{DR} \le P_{(c)}^{MáxDR}, \quad \forall c \in \{1,...,C\} \quad (5)$$

Finally, Equation 6 considers the balance of the network, taking into account all the resources that are managed by the aggregator.

$$\sum_{n=1}^{N} P_{(n)}^{DG} + \sum_{k=1}^{K} P_{(k)}^{Supplier} + \sum_{c=1}^{C} P_{(c)}^{DR} = \sum_{c=1}^{C} P_{(c)}^{Load} \quad (6)$$

As one can see, the mathematical formulation is quite simple and represents the objective of the aggregator. Also, since an aggregator is often an individual entity with no access to the network in its physical operation, the network constraints are not considered in the schedule. However, by performing the balance equation, the results of the scheduling can be later communicated to the network's operator in order to verify that the technical conditions are certified by the values assigned by the scheduling.

IV. Case Study

The proposed methodology is applied to a real 30 kV distribution network, connected to the main grid through a high voltage substation (60/30kV) with 90 MVA of power capacity. The distribution network is composed of 937 buses, 20310 consumers, and 548 distributed generators of distinct types. Also, the connection to the main grid grants access to 10 suppliers, that can also provide for the network. The consumers are classified into five distinct types: Domestic (DM), Small Commerce (SC), Medium Commerce (MC), Large Commerce (LC) and Industrial (ID) – see Table 2. Total demand for the considered network, is 62,63 MW. Regarding generation, the resources are classified into seven different types: Wind, Photovoltaic (PV), Co-generation (CHP-Combined Heat and Power), Biomass, Waste-to-energy (WtE), Fuel cell and Small Hydro. Their characteristics are shown by Table 3. Suppliers located outside of the distribution network, are also presented in Table 3. The data can be further studied in [14].

Table 2. Consumers and demand response programs.

Type	# Load	IDR		RTP		
		Capacity (kW)	Average Price (m.u./kW)	Max. Load Reduction (kW)	Elasticity	Initial Price (m.u./kW)
DM	10168	4684,7	0,20	0	0,27	0,21
SC	9828	3991,7	0,16	0	0,33	0,18
MC	82	5627,4	0,19	10 129,3	0,37	0,20
LC	85	0	0,18	9 792,4	0,41	0,19
ID	147	0	0,14	20 828,2	0,53	0,15
	20310	14 303,7	-	40 749,9	-	-

The data input for the aggregator is a crucial task, since it defines all the values needed to perform the scheduling (maintain network balance) and clustering (define the groups and group tariffs).

Table 3. Generation sources characterization.

Resource	Average Price (m.u./kWh)	Capacity (kW)	No. Of Units	Resource	Price (m.u./kWh)	Capacity (kW)
PV	0,150	7061,2	208	Supplier3	0,25	3000
Wind	0,071	5866,0	254	Supplier4	0,23	3000
CHP	0,001	6910,1	16	Supplier5	0,24	3000
Biomass	0,086	2826,5	25	Supplier6	0,22	3000
WtE	0,056	53,1	7	Supplier7	0,26	3000
Hydro	0,042	214,0	25	Supplier8	0,23	3000
Fuel cell	0,028	2457,6	13	Supplier9	0,21	10000
Supplier1	0,23	3000	-	Supplier10	0,21	10000
Supplier2	0,21	3000	-	Total DG	25388,5 kW	

In Figure 3, the prices for each type of resource are presented, in order to provide the scheduling incentives, i.e. the aggregator minimizes its operation costs by choosing the resources with the most attractive tariffs (the less expensive). In this case study, the cost of using external suppliers is almost equivalent to using certain kinds of demand flexibility, namely, domestic and medium commerce consumers.

On the other hand, distributed generators are the cheaper resources in this case study, and could in other situation become free if they'd belong to the aggregator or network manager. In this case, one considers that the distributed generators have independent owners, which make them a paid resource. This kind of scenario can be interpreted as what happens in reality, since, per example, in the case of producers there is the need to pay them for using the energy produced by their generators (e.g. photovoltaic panel, small wind turbine), or in other words, the injected power across time.

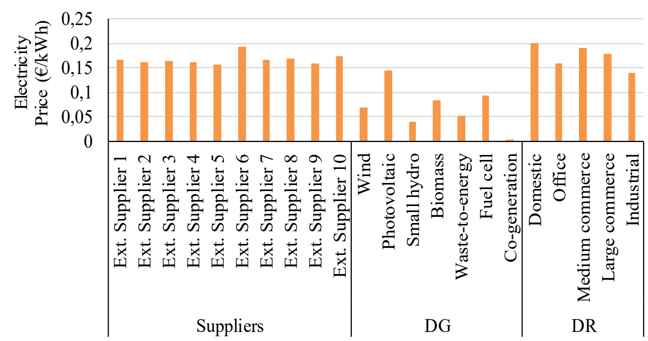

Figure 3. Resource's price to participate in the scheduling.

V. Results

In this section, the results are presented regarding the case study considered. Results address the three main stages of the methodology: scheduling, aggregation, and remuneration. In Figure 4 and Figure 5, it is presented the scheduling for the resources considered by the aggregator, namely, external suppliers, distributed generators (seven different types) and consumers (five different types), respectively.

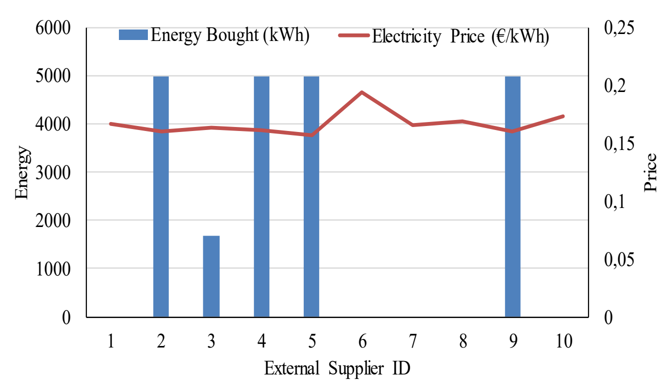

Figure 4. Supplier's scheduling.

In Figure 5, one can see that the distributed generators were used to the fullest, since they also present the less expensive prices, when compared to external suppliers and demand response initiatives. Although the consumer's participation is lower than the other resources, it still has contributed to the aggregators operation, namely, due to the contributions of small commerce and industrial consumers.

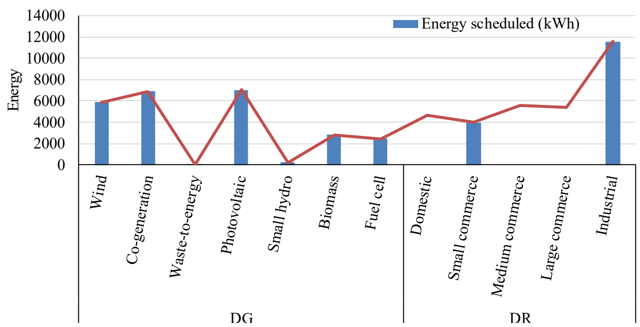

Figure 5. Distributed generator's and consumer's scheduling.

As mentioned before, three types of aggregation data are considered to perform the clustering, with the intent of evaluating the influence of each one in the resources assigned group. Also, aside from the changing features, the costs of demand response are always considered, i.e. aggregation is always based in the demand response costs.

The following Table 4 and Table 5 presents the results obtained for the three types of aggregation considered, regarding the flexibility resources. One can see by the results that there are groups with small quantities of energy scheduled, and others with more considerable amounts. In this way, maybe some of these groups will not be able to participate in the energy market, although they cluster several resources. Also, the number of flexibility resources clustered (9 975) is far inferior to the original number of consumers considered (20 310), showing how many of them were scheduled by the aggregator.

Table 4. Aggregation results for all data types, in of energy.

Scen.	K	Group number						
		1	2	3	4	5	6	7
A	5	5317,6	1093,9	15,0	19,4	1232,0	0,0	0,0
	6	19,4	5317,6	1,5	1093,9	1232,0	13,5	0,0
	7	3344,6	1,5	13,5	1973,0	1093,9	1232,0	19,4
B	5	1232,0	5317,6	1093,9	19,4	15,0	0,0	0,0
	6	19,4	1007,4	1232,0	4310,3	15,0	1093,9	0,0
	7	1091,4	1007,4	19,4	4310,3	1232,0	2,5	15,0
C	5	1093,9	19,4	5317,6	15,0	1232,0	0,0	0,0
	6	1007,4	1232,0	15,0	4310,3	19,4	1093,9	0,0
	7	15,0	4310,3	2,5	19,4	1232,0	1007,4	1091,4

Table 5. Aggregation results for all data types, in terms of resource number.

Scenario	K	Group number						
		1	2	3	4	5	6	7
A	5	6878	786	63	76	2172	0	0
	6	76	6878	7	786	2172	56	0
	7	2981	7	56	3897	786	2172	76
B	5	2172	6878	786	76	63	0	0
	6	76	1430	2172	5448	63	786	0
	7	778	1430	75	5448	2172	9	63
C	5	786	76	6878	63	2172	0	0
	6	1430	2172	63	5448	76	786	0
	7	63	5448	9	75	2172	1430	778

The aggregation results obtained for the distributed generation, are presented in Figure 6, in terms of energy and price (these are shown in the label of each group in the figure, in m.u./kWh). In each scenario, different groups are formed and also distinct prices are obtained from the remuneration computation, as one can see in Figure 6.

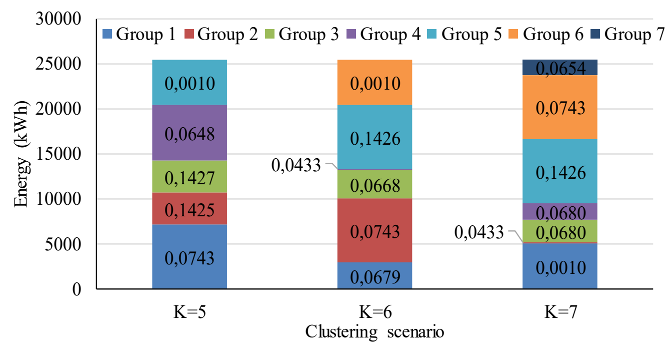

Figure 6. Distributed generator's clustering results.

To the aggregator, is important that the proposed methodology presents the results in an easily interpretative way, especially in what concerns the information passed on regarding the consumer and its participation. In this way, the present methodology proposes and output information model where the main data about the consumer and its scheduling, aggregation and remuneration, is presented simply. The model takes into account several fields, namely the following:

- Type of consumer, in text;
- Initial consumption, in kWh;
- Reduction amount to be made – reduced in the initial consumption (kWh);
- Assigned group of aggregation, considering all scenarios regarding clustering (Scenarios: {A; B; C});
- Tariff applied in the assigned group, considering all scenarios regarding clustering (Scenarios: {A; B; C});
- Payment that receives for its participation in the aggregator's scheduling at the group's tariff, considering all scenarios regarding clustering (Scenarios: {A; B; C});

Per example, the following is what an aggregator would receive for a given consumer, in this case for consumer number 103, for clustering scenarios $K \in \{5,6,7\}$:

- Type – 'Office';
- Cons. (kWh) – 3,492;
- Red. (kWh) – 1,7471;
- Assigned group – {2 4 5; 3 6 1; 1 6 7};
- Tariff (m.u./kWh) – {0,1597 0,1597 0,1597; 0,1597 0,1597 0,1599; 0,1597 0,1597 0,1599};

- Payment (m.u.) – {0,2791 0,2791 0,2791; 0,2791 0,2791 0,2794; 0,2791 0,2791 0,2794};

Per example, in scenario A, for K=6, the represented consumer is assigned to group number 4, with a tariff of 0,1597 m.u./kWh, thus obtaining a payment of 0.2791 m.u. This evaluation can be equally made for the remaining scenarios of datasets and clustering. Also, one can see by the results obtained that, depending on the dataset used, the consumer may be assigned to a group with a different tariff (most evident by scenario C). This gives the aggregator several possibilities of dealing with the consumer regarding to its aggregation and future negotiation to participate in an energy market.

VI. Conclusions & Future Work

In this paper, one addresses the operation of an aggregator, focused on demand response initiatives and on how the methodology output are translated to the manager (aggregator or operator). With the comprehension of the methodology's results, comes its appliance into real hardware, however, these results need to be simplified when reaching the aggregator/operator, so that they can be more easily performed.

The connection between the proposed methodology, and the real-time hardware (e.g. analyzers, relays, or other kind of actuator) proves to be benefic for both consumers and aggregators, since real data is explored and used to improve the efficiency of power systems, and reduce energy costs for its users.

References

[1] A. Zakariazadeh, S. Jadid, and P. Siano, "Integrated operation of electric vehicles and renewable generation in a smart distribution system," *Energy Convers. Manag.*, vol. 89, pp. 99–110, Jan. 2015.

[2] E. Koliou, C. Eid, J. P. Chaves-Ávila, and R. A. Hakvoort, "Demand response in liberalized electricity markets: Analysis of aggregated load participation in the German balancing mechanism," *Energy*, vol. 71, pp. 245–254, 2014.

[3] J. S. Vardakas, N. Zorba, and C. V. Verikoukis, "A Survey on Demand Response Programs in Smart Grids: Pricing Methods and Optimization Algorithms," *IEEE Commun. Surv. Tutorials*, vol. 17, pp. 1–1, 2014.

[4] M. Behrangrad, "A review of demand side management business models in the electricity market," *Renew. Sustain. Energy Rev.*, vol. 47, pp. 270–283, 2015.

[5] H. A. Rahman, M. S. Majid, A. Rezaee Jordehi, G. Chin Kim, M. Y. Hassan, and S. O. Fadhl, "Operation and control strategies of integrated distributed energy resources: A review," *Renew. Sustain. Energy Rev.*, vol. 51, pp. 1412–1420, Nov. 2015.

[6] EirGrid Group, "Demand Response Schemes currently in operation." 2012.

[7] PJM, "Demand response Summary," 2015.

[8] ERCOT, "Demand Response Details," 2015. [Online]. Available: http://www.ercot.com/services/programs/load. [Accessed: 21-Dec-2015].

[9] N. Grid, "Firm Frequency Response (FFR)." 2015.

[10] P. Faria and Z. Vale, "Remuneration structure definition for distributed generation units and demand response participants aggregation," *2014 IEEE PES General Meeting | Conference & Exposition*. pp. 1–5, 2014.

[11] J. Spínola, P. Faria, and Z. Vale, "Economic Impact of Demand Response in the Scheduling of Distributed Energy Resources," *Computational Intelligence, 2015 IEEE Symposium Series on*. pp. 1545–1552, 2015.

[12] "MATLAB." [Online]. Available: http://www.mathworks.com/products/matlab/. [Accessed: 01-Aug-2016].

[13] K. Holmstrom, A. O. Goran, and M. M. Edvall, *User's Guide for Tomlab 7*. 2010.

[14] P. Faria, J. Soares, Z. Vale, H. Morais, and T. Sousa, "Modified particle swarm optimization applied to integrated demand response and DG resources scheduling," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 606–616, 2013.