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Maximizing the Social Welfare of Virtual Power Players Operation in Case of Excessive Wind Power

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Abstract

The integration of growing amounts of distributed generation in power systems, namely at distribution networks level, has been fostered by energy policies in several countries around the world, including in Europe. This intensive integration of distributed, non-dispatchable, and natural sources based generation (including wind power) has caused several changes in the operation and planning of power systems and of electricity markets. Sometimes the available non-dispatchable generation is higher than the demand. This generation must be used; otherwise it is wasted if not stored or used to supply additional demand. New policies and market rules, as well as new players, are needed in order to competitively integrate all the resources.

The methodology proposed in this paper aims at the maximization of the social welfare in a distribution network operated by a virtual power player that aggregates and manages the available energy resources. When facing a situation of excessive non-dispatchable generation, including wind power, real time pricing is applied in order to induce the increase of consumption so that wind curtailment is minimized. This method is especially useful when actual and day-ahead resources forecast differ significantly. The distribution network characteristics and concerns are addressed by including the network constraints in the optimization model.

The proposed methodology has been implemented in GAMS optimization tool and its application is illustrated in this paper using a real 937-bus distribution network with 20.310 consumers and 548 distributed generators, some of them non-dispatchable and with must take contracts. The implemented scenario corresponds to a real day in Portuguese power system.

1. Introduction

European Union energy policy goals led to a significant increase of wind power generation and other renewable energy resources [1]. This increase is still verified, namely in the case of wind power generation.

Analyzing the wind energy penetration as the percentage of demand covered by wind energy in a certain region, normally calculated on an annual basis, it is possible to see the importance of this resource in the operation and planning of respective power systems. The values of wind energy penetration for European countries in 2011 are presented in Figure 1[2].

The country with the highest value of wind energy penetration is Denmark with 25.9%. The second position is occupied by Spain with 15.9%, closely followed by Portugal with 15.6%. In 2011, almost all the countries have increased the wind power penetration, with exception to Slovakia, Slovenia, and Malta, which have null wind power penetration. This paper focuses on the Iberian (Portugal and Spain) case, especially on Portugal.

Portugal has followed the European Union tendencies and directives applied to wind generation and other renewable resources. 8000 MW of wind power generation are expected for 2020, which corresponds to an increase of 100% of the value of the year 2010 [3].

Since most of the renewable generation resources are non-dispatchable, special concerns must be taken in the situations of demand lower than the generation obtained from those resources as this leads to situations of wind curtailment. Obviously other non-dispatchable resources generation could be curtailed. However, the especially large integration of wind power generation makes us to usually refer to wind curtailment [4]. Wind curtailment situations result in inefficient resource use and often cause abnormal market clearing prices, in face of the actual demand and generation bids. The curtailed capacity may lead, in some cases, to some compensation for wind generators owners, namely because wind farm contracts are often established on a must-take basis.

Demand response corresponds to the intentional change of consumption profiles by end consumers due to changes in the electricity prices or to incentives received in situation in which reliability or economic concerns are verified in the system [5]. Demand response can be efficiently used to address the wind curtailment problem [6]. Real time pricing, one of the most important type of demand response programs, is adequate to achieve a more efficient power system operation, including the reduction of wind curtailment [7-8].

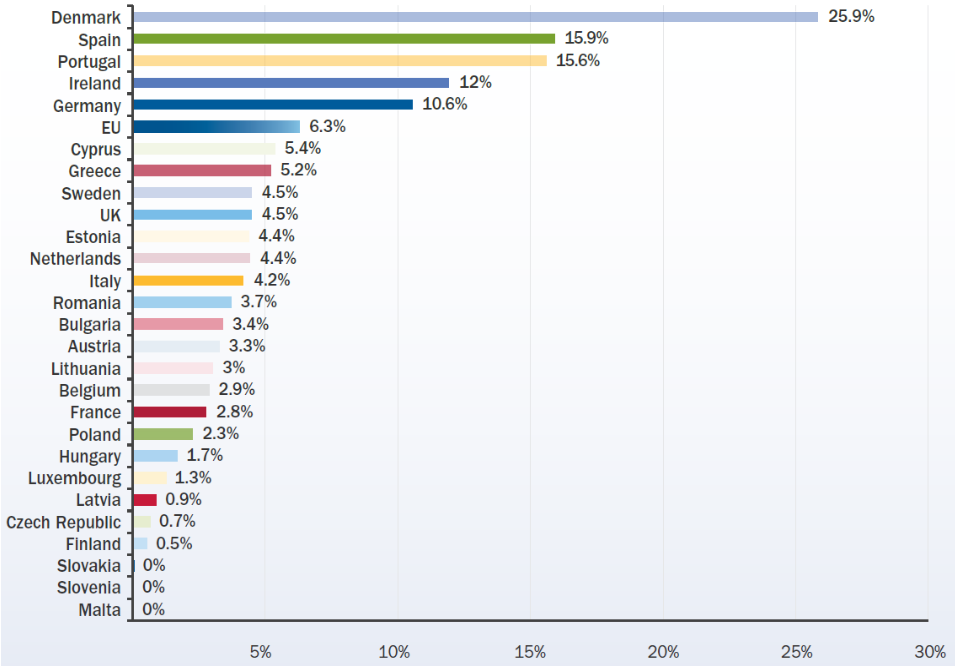

Figure 1: Wind energy penetration in European countries in 2011 [2].

The present paper proposes a real time pricing based methodology to reduce the curtailment of non-dispatchabale energy generation resources (hydro run-of-river, wave power, and thermal power generation plants, and wind farms with must take contracts), reducing the impacts of the referred power curtailment. A Virtual Power Player (VPP) [9] that operates the distribution network and manages the installed energy resources performs the energy resources scheduling maximizing the inherent Social Welfare (SW). In periods in which the demand is lower than the available non-dispatchable power, the VPP is able to make use of real time pricing. Based on the price elasticity of the consumers, the decrease in the electricity price for each consumer is calculated in order to achieve the desired demand increase. VPP can also acquire energy to several electricity suppliers physically connected to the managed distribution network through the connection to the upstream network.

Departing from works developed by the same authors of the present paper [10-11],, the methodology proposed in the present paper addresses network technical concerns, by including the network line thermal limits and bus voltage constraints in the formulation of the optimization problem, which has been implemented in GAMS optimization tool [12].

After this introduction, Section 2 presents some material concerning the increase of wind power, Section 3 presents the proposed real time pricing model as well as its mathematical formulation, and Section 4 presents an illustrative case-study concerning a real distribution network and the characteristics of a special day in the Portuguese power system. The last section, Section 5, presents the main conclusions of the paper.

2. The increase of wind power

The present section begins with a presentation of the Iberian electricity market, in sub-section 2.1, especially in what concerns the share of the use of generation resources. Then, in sub-section 2.2, some facts about wind curtailment are presented.

2.1. Iberian electricity market

The present sub-section introduces some information regarding the Iberian electricity market (MIBEL). This information regards the October 2012 situation [13]. The total amount of electricity generation was 21573 GWh in Spain and 3155 GWh in Portugal. The installed power was 61610 MW in Spain and 12053 MW in Portugal. Portugal has exported 40 GWh of energy to Spain, while Spain has exported 852 GWh to Portugal, during October 2012.

The mix of generation by generation technology, in each country, from August to October 2012, is presented in Figure 2a) for Portugal and in Figure 2b) for Spain. In the legends of Figure 2, CCGT stands for combined-cycle gas turbine; CoGen stands for combined heat and power; and PRE represents the special producers. Those producers (denominated in Portuguese as PRE) are producers with renewables based generation technologies that make use of special condition tariffs in order to improve the use of endogen renewable energy.

It is important to note that the generation mix regarding PRE is not negligible (about 30% in each country). As PRE producers are benefiting from special tariffs, it is important to take the most possible advantage of the energy available from these producers.

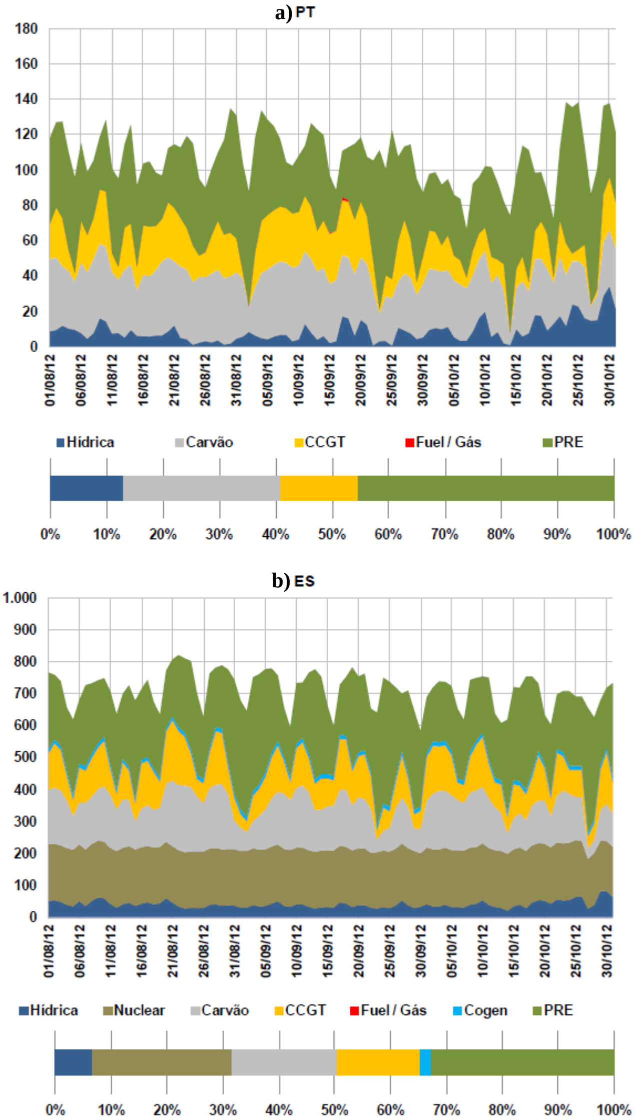

Figure 2: Generation mix (GWh), from August to October 2012 [13] – a) in Portugal and b) in Spain.

Almost half of the PRE energy in Portugal regards the wind generation [14]. The work presented in this paper has been developed in order to make use of all the PRE energy in a distribution network that is under influence of the referred system and market conditions.

2.2. Wind curtailment

The present sub-section presents some facts about wind curtailment with special focus on the Spanish case.

Reference [4] presents several examples of wind energy curtailment practices. The trigger, i.e. the reason or the event that originates wind curtailment, includes the economic schedule, network congestions, situations of reduced demand, technical limitations on system reserve response, and system reliability. The curtailed capacity may lead, in some cases, to some compensation for wind generators owners, namely because wind farm contracts are established on a must take basis. The most common case is the payment of the energy generation that would be expected if the units were not scheduled to be turned off. This compensation may be based on the guaranteed price for wind generator or on the electricity market price.

In what concerns the examples of wind curtailment in several countries, reference [15] includes some facts about the experience in United States and in other countries. In what concerns Europe, it includes the experience in Spain and Germany.

Let us focus on the case of Spain, which has installed more than 20,000 MW of wind power capacity. Let us note the following facts regarding wind curtailment in Spain:

- Wind curtailment can be due to congestion, stability concerns, inadequate active/reactive levels, etc.
  - Until 2009 – the main cause was congestion;
  - After 2009 – the main cause has been the wind generation being greater than minimum load.
- Wind curtailment can be announced/decided in the day-ahead market or in real time (in periods of 15 minutes);
- 23,9 GWh of wind curtailment was verified in 2007, corresponding to 0,09% of the available capacity;
- 54 GWh of wind curtailment was verified in 2009, corresponding to 0,15% of the available capacity;
- In the 1st trimester of 2010, 1% of wind curtailment was verified, corresponding to 10M€ loss;
- In 2010 February 24th, 800MW were curtailed;
- In 2010 February 25th, 1000MW were curtailed.

On February 25th 2010, 7000MW of nuclear generation remained unchanged. This is due to the fact that technologically, wind power output can be rapidly and easily changed, which is not the case of nuclear power plants. Nevertheless, considering the recent large increase in wind power generation, new generation management policies should be discussed.

3. Real time pricing model

The present section begins by presenting the explanation of the proposed methodology in sub-section 3.1. The mathematical formulation of the social welfare optimization problem is presented in sub-section 3.2.

3.1. Proposed demand response model

The present sub-section presents the developed demand response methodology. The proposed methodology is developed in order to be used by a Virtual Power Player (VPP) that operates a distribution network and manages the available resources. The resources scheduling is done maximizing the Social Welfare (SW) resulting from the obtained schedule.

Figure 3 shows the schematic representation of the resources parameters related to both forecast (inputs) and schedule results (outputs) of the proposed methodology.

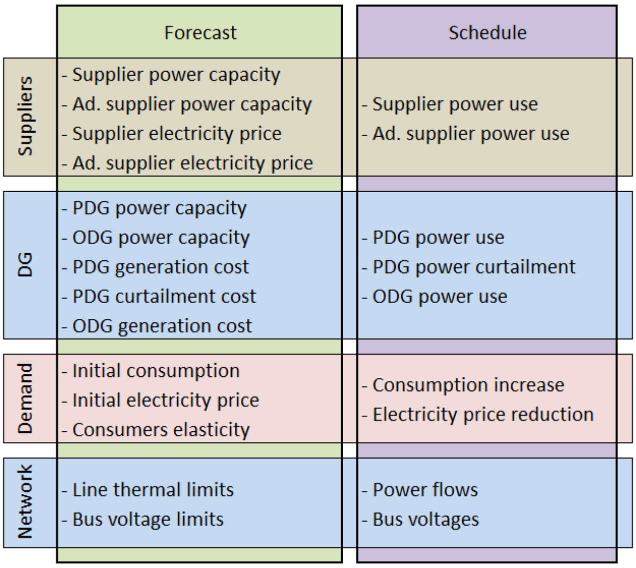

Figure 3: Proposed methodology diagram.

The energy acquired from the upstream network to one or several suppliers is divided into a quantity previously obtained at a given price, and an additional amount available at a distinct price.

Some of the generation resources, referred as prioritary (PDG), are the ones that are non-dispatchable (as the case of wind power generation), which are wasted if not used, and their generation is paid anyway. The remaining energy resources are referred as ordinary (ODG).

In the day-ahead planning of the operation of the system, the forecast of both demand and generation are performed. This includes the determination of both power capacity and prices of each resource.

To avoid the curtailment of PDG generation power and the respective payment, in situations in which the PDG power is higher than the demand, the VPP can make use of real time pricing in order to make the demand at least equal to the forecasted generation.

Since the VPP is operating a distribution network, it is important to consider the network constraints. So, as inputs of the model, the line thermal capacity and the bus voltages limits are defined.

3.2. Mathematical Formulation

The present subsection explains the developed mathematical formulation of the optimization problem that performs the resources scheduling included in the proposed methodology.

The objective function of the problem has been implemented in order to maximize the Social Welfare (SW) resulting from the operation of the network and its resources by a virtual power player. The objective function, presented in equation (1), considers the values of the demand forecast and of the demand increase and the respective prices (initial price and price reduction), for each consumer *C* of each *Type*.

The energy acquired from the upstream network from one or several suppliers is divided into a quantity previously obtained (from Supplier *Sp*) at a given price, and an additional amount available at a distinct price.

Regarding the distributed generation resources, those are divided into ordinary (ODG) and prioritary (PDG) ones. The prioritary ones regard the resources that should be entirely used, as the case of non-dispatchabale energy generation resources (hydro run-of-river, wave power, and thermal power generation plants, and wind farms with must take contracts) that are not storable. Otherwise, a cost (curtailment cost) is paid due to the generation curtailment.

$$
\begin{aligned}
&Maximize\ \ SW \\
&= \left[\begin{aligned}
&\sum_{Type=1}^{NType}\sum_{C=1}^{NC}\left[\begin{aligned}&\left(E^{Forecast}_{Demand\,(Type,C)}+E^{Increase}_{Demand\,(Type,C)}\right)\\ &\times\left(C^{Initial}_{Demand\,(Type,C)}-C^{Reduction}_{Demand\,(Type,C)}\right)\end{aligned}\right] \\
&-\left(\begin{aligned}
&\sum_{Sp=1}^{NSp}\left[E_{Supplier\,(Sp)}\times C_{Supplier\,(Sp)}\right] \\
&+E^{Additional}_{Supplier\,(Sp)}\times C^{Additional}_{Supplier\,(Sp)} \\
&+\sum_{PDG=1}^{NPDG}\left[\begin{aligned}&E^{Prioritary}_{DG(PDG)}\times C^{Prioritary}_{DG(PDG)}\\ &+E^{Curtailment}_{DG(PDG)}\times C^{Curtailment}_{DG(PDG)}\end{aligned}\right] \\
&+\sum_{ODG=1}^{NODG}\left[E^{Ordinary}_{DG(ODG)}\times C^{Ordinary}_{DG(ODG)}\right]
\end{aligned}\right)
\end{aligned}\right]
\end{aligned}
\tag{1}
$$

The active power balance constraint for each, in each single period, bus is the one in equation (2). This equation includes the bus voltage magnitude *V* and angle *Θ* in each bus *b*. For further information related to network constraints, reference [16] can be consulted.

$$
\begin{aligned}
&\sum_{Sp=1}^{NSp}E^{i}_{Supplier\,(Sp)}+\sum_{PDG=1}^{NPDG}E^{Prioritary;\ i}_{DG(PDG)} \\
&+\sum_{ODG=1}^{NODG}E^{Ordinary;\ i}_{DG(ODG)}+E^{Additional;\ i}_{Supplier\,(Sp)} \\
&-\sum_{Type=1}^{NType}\sum_{C=1}^{NC}\left[E^{Forecast;\ i}_{Demand\,(Type,C)}+E^{Increase;\ i}_{Demand\,(Type,C)}\right] \\
&=\sum_{j=1}^{Nb}\left[V_{i(t)}\times V_{j(t)}\left(\begin{aligned}&G_{ij}\cos\left(\theta_{i(t)}-\theta_{j(t)}\right)\\ &+B_{ij}\sin\left(\theta_{i(t)}-\theta_{j(t)}\right)\end{aligned}\right)\right]
\end{aligned}
\tag{2}
$$

The consumers' behavior is addressed by the price elasticity of demand of each consumer [7], as modeled in equation (3). The remaining constraints (4) – (8) concerns the resources maximum operation limits, and the maximum electricity cost variation (9), since the electricity cost cannot be largely reduced. In the same way, the demand increase must respect limits.

$$
Elasticity_{(C)}=\frac{E^{Increase}_{Demand\,(Type,C)}\times C^{Initial}_{Demand\,(Type,C)}}{E^{Forecast}_{Demand\,(Type,C)}\times C^{Reduction}_{Demand\,(Type,C)}}
\tag{3}
$$

$$E^{Increase}_{Demand(Type,C)} \leq E^{MaxIncrease}_{Demand(Type,C)} \tag{4}$$

$$E_{Supplier(Sp)} \leq E^{Max}_{Supplier(Sp)} \tag{5}$$

$$E^{Additional}_{Supplier(Sp)} \leq E^{MaxAdditional}_{Supplier(Sp)} \tag{6}$$

$$E^{Prioritary}_{DG(PDG)} \leq E^{MaxPrioritary}_{DG(PDG)} \tag{7}$$

$$E^{Ordinary}_{DG(ODG)} \leq E^{MaxOrdinary}_{DG(ODG)} \tag{8}$$

$$C^{Reduction}_{Demand(Type,C)} \leq C^{MaxReduction}_{Demand(Type,C)} \tag{9}$$

The network constraints are modeled as in equations (10) and (11), respectively for the bus voltage magnitude and angle limits and for the line thermal limits. For the slack bus, the voltage angle and magnitude values are fixed and defined by the user.

$$\begin{aligned} V_i^{min} \leq V_{i(t)} \leq V_i^{max} \\ \theta_i^{min} \leq \theta_{i(t)} \leq \theta_i^{max} \end{aligned} \tag{10}$$

$$\left| \overline{U_{i(t)}} \times \left[\begin{aligned} &\overline{y_{ij}} \times \left(\overline{U_{i(t)}} - \overline{U_{j(t)}} \right) \\ &+ \overline{y_{sh\_i}} \times \overline{U_{j(t)}} \end{aligned} \right]^* \right| \leq S_{Ly}^{max} \quad \forall i \neq j \tag{11}$$

The problem has been implemented in GAMS - General Algebraic Modeling System [12]. The results of the application of the model are the final electricity prices, the scheduling of each energy resource, and the bus voltages and power flows in lines.

4. Case study

The present section presents a case study that illustrates the application of the proposed methodology. It begins with the description of the characteristics of the distribution network, in sub-section 4.1. Then, in subsection 4.2, the scenario of 28th October 2012, which is a special day in the Portuguese power system, is presented. Finally sub-section 4.3 shows the obtained results.

4.1. Distribution network

The present section illustrates the application of the proposed methodology to a set of consumers connected to a real Portuguese distribution network, illustrated in Figure 4. More detailed information about this network can be found in [16].

The feeder 5 has been selected for this case study scenario. The 2233 consumers connected to that feeder of the network are classified into six types of consumers. According to the voltage level they are connected to, the types of consumers are the following: VHV – Very High Voltage; HV – High Voltage; MV – Medium Voltage; SLV – Special Low Voltage; NLV-2 – Normal Low Voltage group 2; and NLV-1 – Normal Low Voltage group 1. The two NLV types correspond to the consumers registered in the double tariff (NLV-2), which have two different electricity price periods, and registered in the single tariff (NLV-1).

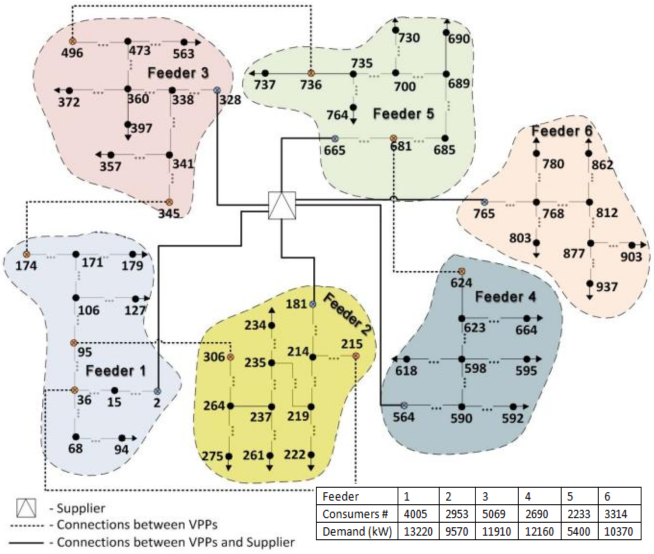

Figure 4: Distribution network.

The consumers' characterization parameters necessary to the proposed methodology implementation are in Table I. It includes the values regarding the initial electricity price, the demand price elasticity (elasticity), the peak consumption, and the number of consumers, for each consumer type. The same price variation is considered for all types of consumers.

Consumers characteristics	Type of Consumer					
	NLV1	*NLV2*	*SLV*	*MV*	*HV*	*VHV*
Number of Consumers	600	500	1100	8	9	16
Peak consumption (kW)	380	400	790	850	750	2230
Elasticity	0.27	0.33	0.37	0.41	0.45	0.53
Initial price (€/MWh)	130	100	90	80	70	60

Table 1: Demand parameters for each consumer type.

The peak power demand in the feeder is 5400 kW. The 47 available DG units have a total rated power of 2417 kW. The detailed information concerning the generation units is presented in Table 2. It includes the generation costs, the number of units in the feeder, and the installed capacity for each generation type. In Table 2, MSW stands for Municipal Solid Wast, and CHP stands for Combined Heat and Power. The four generation types firstly presented in Table 2 are the ones that belong to the pryoritary generation, i.e. the non-dispatchable generation units.

Generation type	Generation cost *(m.u./kWh)*	Number of generation units	Installed capacity *(kVA)*
Photovoltaic	0.2	18	647
Wind	0.045	22	758
CHP	0.08	0.33	306
Small hydro	0.03	2	90
Biomass	0.15	2	338
MSW	0.11	1	5
Fuel cell	0.3	1	273

Table 2: Generation sources characteristics.

In what concerns the supliers connected to the network trough the substation, in the present case-study scenario is considered that the energy aqcuired to the regular supplier is bought at 0.028 m.u./kWh. The aditional suplier energy is paid at 0.25 m.u./kWh. The regular amount of power obtained from the supplier, along the 24 hours of the prsent case-study scenario can be seen in Figure 5.

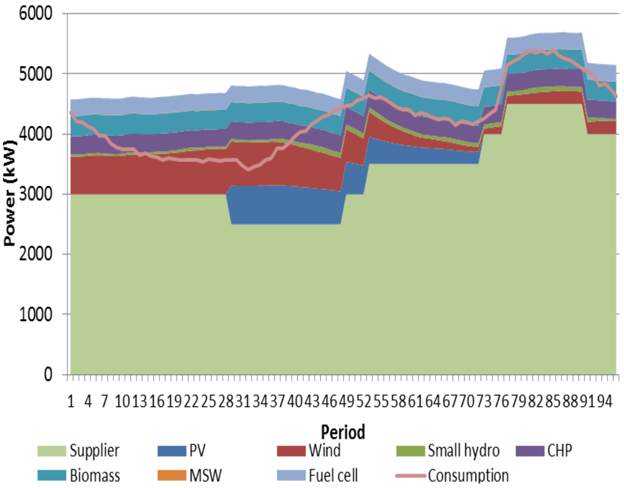

Figure 5: Power sources availability and demand.

Figure 5 also shows the amount of available resources along the day, as weel as the consumption. These values have been determined taking into acount the characteristcs of the network and of the conditions verified in the day identified in the following sub-section 4.2. The 24 hours of the day are represented by 96 periods of 15 minutes.

4.2. 28th October 2012

In order to ilustrate and validate the application of the porposed methodology to the real conditions of power systems, a special day in the Portuguese power system, and in the Iberian electricity market as well, has been selected. The selected day is 28th October 2012, a monday. Its special characteristics are exposed in the present sub-section.

The characteristics of the selected day of the Portuguese power system, namely in what concerns the PRE generation and demand are presented in Figure 6. Being a specially windy day, the PRE generation was higher than the demand in a relatively long period of the night.

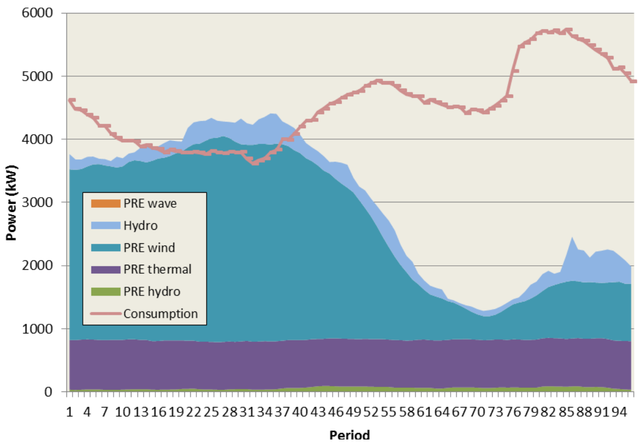

Figure 6: PRE generation and demand in the selected day, in the Portuguese power system[1].

Figure 7 shows the electricity market prices for the considered day. It can be seen that in the periods of huge wind power generation, and relatively low demand, very low market prices are verified (see hours 3 to 12).

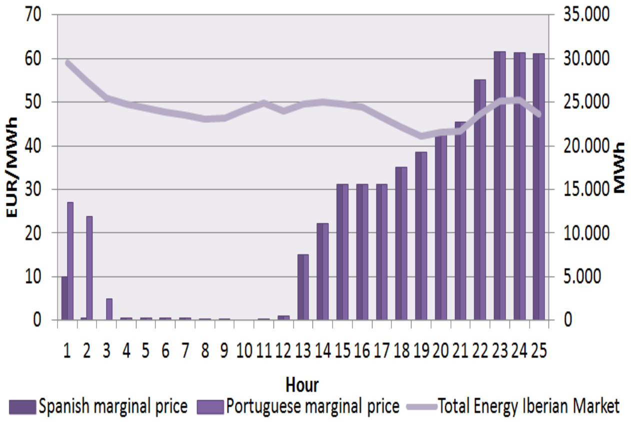

Figure 7: Electricity market prices[2].

[1] http://www.centrodeinformacao.ren.pt/PT/InformacaoExploracao/Paginas/EstatisticaDiariaDiagrama.aspx

[2] http://www.omie.es/files/flash/ResultadosMercado.swf

This scenario ilustrates the conditions in which it is possible to apply the proposed methodology. In the referred night periods, the distribution network operator (which is, in the present approach, a Virtual Power Player – VPP) becomes able to make use of real time pricing in order to increase the demand at least to the level of the available PRE generation, maximizing the Social Walfare of the obtained resources use solution.

4.3. Results

The present sub-section shows the results obtained with the application of the proposed methodology to the scenario presented above.

A virtual power player operates the distribution network, performing an optimal energy resources scheduling aiming to maximize the social welfare caused by the resulting resources use.

In this case-study, only the consumers belonging to the MV, HV, and VHV types of consumer are considered as participating in the demand response program activated by real-time pricing.

Figure 8 presents the use of the available resources, after applying the proposed methodology. The elementary period is 15 minutes; so, the 48 periods in Figure 8 correspond to the first half of the day. Figure 8 also shows the obtained demand after the application of the proposed methodology (represented by the dashed black line) for the period when the demand is originally lower than the sum of the available PRE and of the already obtained regular Supplier amount of energy (from period 20 to period 36).

Another important point of view of results obtained with the application of the proposed methodology is the one regarding the consumers' response to real-time pricing. Those results are presented in Figure 9, for the case of period 20, selected as an example.

A certain price variation is applied to the consumers' original prices, which are dependent on the type of consumer and contractual tariffs. As one can see in Figure 9, the same price reduction has been applied to the consumers of the same type, for each one of the three considered participating types of consumer, since it was decided to apply the same price to the consumers of the same type.

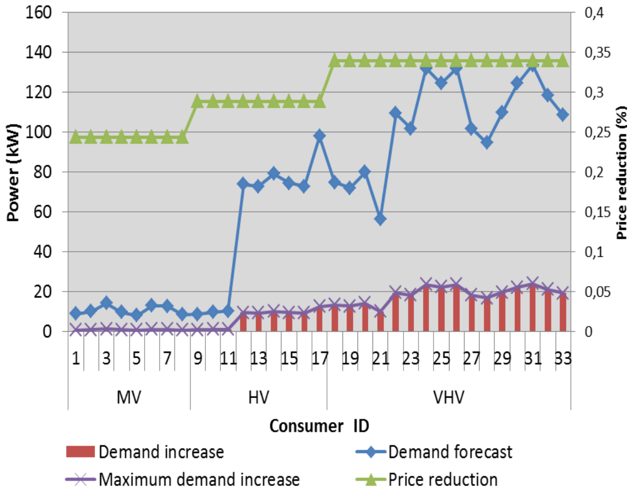

Figure 9: Consumers response to the RTP methodology in period 20.

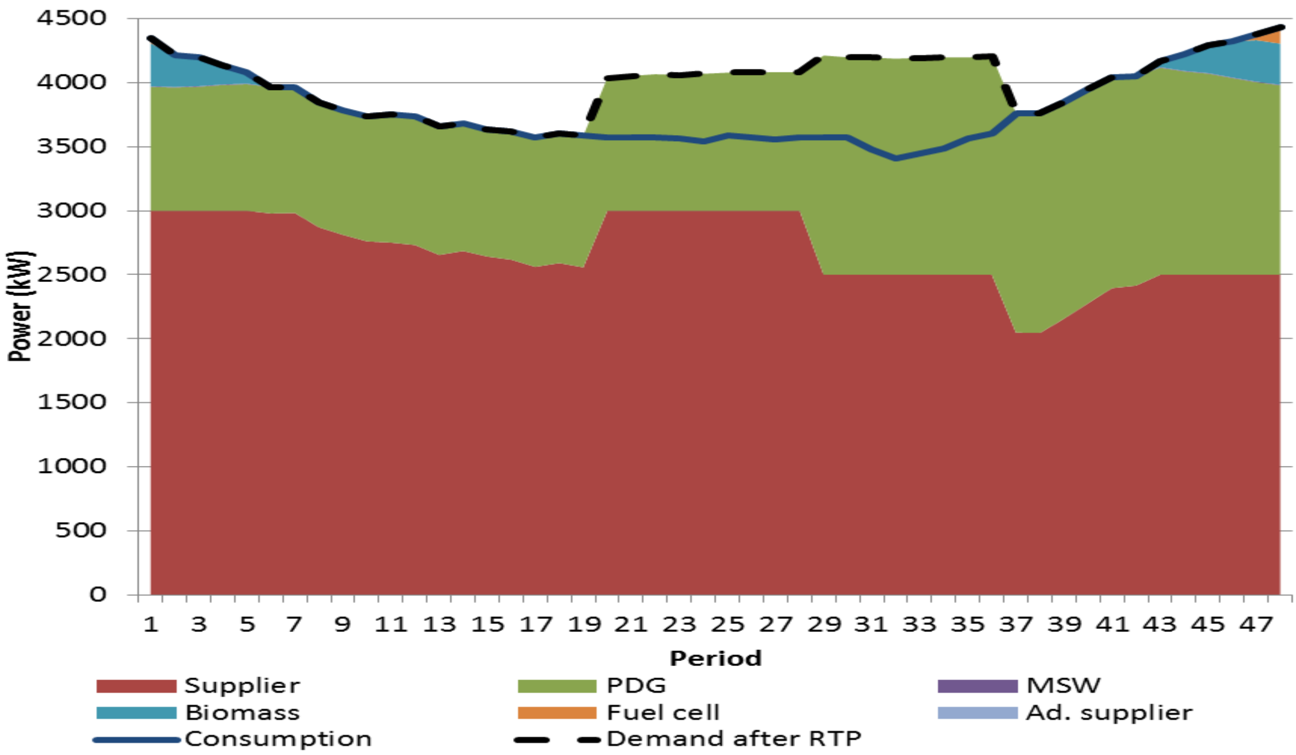

Figure 8: Generation and demand in the first 48 period.

The same price elasticity of demand was considered for the consumers of a certain type. However, since the initial consumption of each consumer is distinct, distinct demand increase is verified in each consumer.

The higher demand increase values is verified for VHV consumers due to their higher consumption increase capacity, but also due to the higher values of price elasticity of demand in these consumers. All the consumers have almost reached the maximum demand increase since this is one of the periods in which larger participation is verified, as referred before.

5. Conclusions

The way that both power systems and electricity markets are operated have been changing due, between others, to the increasing penetration of wind power generation in several countries in Europe and around the world, accomplishing energy policy directives.

The work presented in this paper proposes a methodology designed to increase the demand consumption in the periods in which the electricity generation from non-dispatchable resources, as the case of wind power generation, is higher than the demand, avoiding wind curtailment. The virtual power player operating the network uses real time pricing to induce consumers to increase the consumption at least to equal the referred non-dispatchable generation, in the periods of lower demand, maximizing the social welfare of the energy resources scheduling. In the present paper, this resources scheduling includes network constraints, as it is focused to be used by entities operating distribution networks.

A real scenario of energy resources availability has been adapted to a real distribution network, both belonging to the Portuguese power system, in order to illustrate the application of the proposed methodology. It has been proved that the methodology can bring relevant advantages namely in transferring a part of the benefits of the huge wind power situations to the consumers.

Acknowledgements

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