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Additional Information

Design and validation of a methodology for standardizing prequalification of industrial demand response resources

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Abstract

Current energy policies around the world are encouraging integration of renewable electricity generation into the power system. However, these resources are so unpredictable and variable that the need of more flexible resources increases. Demand Response (DR) resources may be a realistic solution, but increasing the credibility among agents by means of the standardization of DR procedures is necessary.

This paper proposes a methodology based on an energy analysis of industrial processes to quantify and validate the flexibility potential of industrial customers in order to contribute to create a certification procedure. This methodology can be helpful for industrial customers themselves, energy service companies (ESCO) and DR aggregators, among others.

The methodology was validated in three different factories whose industrial segments have a high-energy intensity in Europe: a paper factory (Klingele, Germany), a meat factory and a refrigerated logistics centre (Campofrio, Spain).

Keywords: Industrial production, Renewable integration, Demand response, Practical demonstration, Load management.

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1 Introduction

The progressive integration of Renewable Energy Sources (RES) in the mix of electricity generation brings unquestionable environmental benefits. However, it requires wider variety of solutions to guarantee the electricity supply due to the variability of RES. In this context, Demand Response (DR) could be an important resource to integrate RES [1-3], considering demand-side resources in electric usage, shaping their normal consumption patterns in response to the variations in the electricity price over time or to incentive revenues designed to induce lower electricity usage at times when system reliability is jeopardized [4].

According to this, DR policies and directives have already been established to address the demand side participation in electricity markets in many countries, such as EU member countries [5], United States of America (National action plan-FERC) [6], China [7], etc. There are several examples in Europe, and especially in the United States, of DR programs that have already been offered by system operators or utilities [8]. For instance, large industries such as metal industry, cement, chemistry, iron and steel and vehicle manufacturing have traditionally been willing to reduce part of their energy consumption in exchange for some economic benefits [9-12]

There are different prequalification procedures to validate balancing resources in which the conventional generators must be qualified according to some technical specifications that are tested before taking part into balancing markets [13, 14]. However, there is not a common standardized procedure to guarantee the reliability of DR resources.

In this vein, the only DR standards that currently exit around the globe are related to communication protocols for control systems in commercial and residential sectors [15]. Some examples are "ISI/IEC 15067-3:2012" that is an international smart appliance standard [16], "Open Automated Demand Response (OpenADR)" developed in the United States [17], "AS/NZN 4755" that is from Australia [18] and "Echonet Life" from Japan" [19].

Due to a lack of specific standards for the certification of DR resources, most system operators have developed their own procedures to guarantee the reliability of customers' DR bids prior to take part into their energy markets [20, 21].

In fact, there are some studies with special focus on the technical aspects of the procedure for the validation of DR resources [22], but they focus on the specific problems that aggregators could have using this kind of resources instead of on the flexible demand of customers.

In this context, , a standardized procedure for the certification of DR resources was proposed in the "Demand Response in Industrial Production (DRIP)" project [23] attending to three different points of view: Certification of DR Providers, Certification of DR Products and Certification of Energy Service Traders [24]. Regarding the certification of DR Providers, it could be used to prove if an industrial customer is able to reliably implement their DR actions, which are defined as the technical specifications associated with a change in the electricity usage of a particular industrial process in response to specific request from a system operator on a type of day.

Industrial customers can hide a high DR potential in their production processes [25-27], but it is necessary to carry out sophisticated analyses to take into account all the constraints linked to critical parameters of production processes such as temperature, humidity and pressure, among others. In other words, the inadequate implementation of DR actions could affect to the final quality of products, which could be a relevant barrier for the participation of industrial customers in any DR option [28].

As a whole, this paper presents a novel methodology whose main objective is to determine and demonstrate the flexibility potential that exists in industrial customers (DR Provider). This methodology could be used as a basis for the development of a certification procedure of reliable industrial DR resources. In order to address the abovementioned objective, the following issues were performed:

- The actual minimum reducible or interruptible power for each identified DR actions was demonstrated in a set of field tests whose results were compared with the theoretical values identified on the flexibility audits previously performed.
- The evolution of the critical parameters of the industrial processes was analysed to determine the potential impact on the final products during the field tests.
- The potential participation of industrial customers in reserve electricity markets was validated by means of the implementation of a set of DR events in order to simulate a real situation.

The methodology was applied to three different customers with sensitive production processes: a paper factory (Klingele, Germany), a meat factory and a logistics centre of the same segment (Campofrio, Spain).

These customers were selected because both the paper and the food industries represent a high percentage, 11.7% (10,071 ktoe) and 11.65% (9,981 ktoe) respectively, of the total electrical consumption in the industrial sector (235,665 ktoe) [29].

Additionally, the aforementioned segments have a high degree of replicability in Europe, as it can be observed in the following figures that present the number of European factories [30]:

- Around 2,300 paper factories manufacture pulp, paper and paperboard.
- Around 28,000 meat factories manufacture pork products.
- Around 2,400 refrigerated logistics centres belong to the meat segment.

This work was carried out in the framework of the aforementioned DRIP project that was co-funded by the Environment LIFE programme of the European Commission and developed by six partners with different roles: a grid operator, two industrial customers, a certifier, a retailer and a research centre.

The paper is structured as follows: Section 2 describes the proposed methodology that includes two relevant points such as the description of the verification process for the assessment of a DR event and the technical parameters of DR actions according to the presented methodology. In Section 3, the DR actions implemented in the industrial processes involved in this study and the results obtained are described in detail. The final conclusions are drawn in Section 4.

2 Proposed methodology

The methodology was developed to demonstrate the actual potential flexibility of industrial customers that will enable their involvement in a reserve electricity market to provide ancillary services in a profitable way for both the customers themselves and the power system. Figure 1 presents an overview of the proposed methodology:

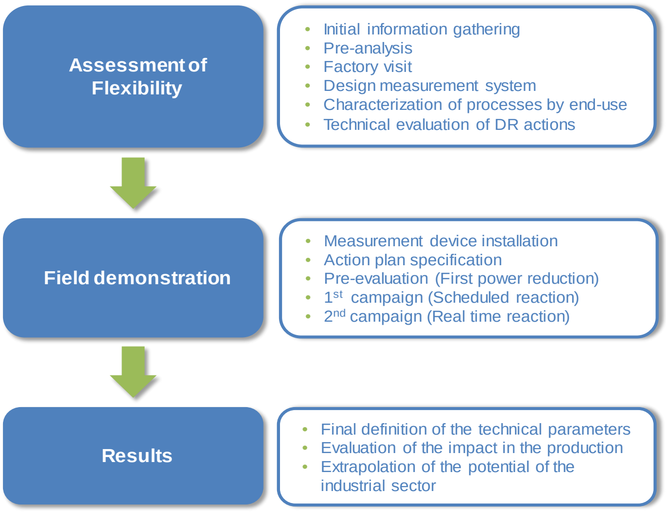

Figure 1. Proposed methodology.

According to the Figure 1, three main stages are proposed. The first stage focuses on the theoretical assessment of the flexible industrial processes. Firstly, the most relevant information related to the industrial facilities and their production processes are requested to the industrial customer. Secondly, this general information is analysed to prepare the visit to the plant. At this point, some potential flexible processes or DR actions should be identified. Then, the potential impacts on the production process and the internal interdependencies among them are analysed in collaboration with the engineers and technical staff of the plant. The aim of this analysis is to guarantee that the identified DR actions can be carried out and quantify the potential cost associated with the implementation like the extra labour cost due to implementation of the flexible actions. Apart from the technical evaluation, an economic assessment, which is completely described in [31], is also performed at the same time.

In addition, the **measurement system** has to be designed taking into account the further tasks of flexibility validation in the field demonstration. Moreover, the total electricity consumption of the factory is disaggregated by flexible processes in which some DR actions can be implemented. According to this, a total number of 31 power meters was installed in the three factories and they were integrated into the control and monitoring system provided by the "**Polytechnic University of Valencia"** (UPV) [32]. Apart from this, one of the most relevant tasks at this stage is the technical evaluation of the DR actions in which all the technical parameters described in Section 2 are properly assessed. The second stage is the field demonstration where the DR actions in each industrial customer are tested empirically. A detailed **action plan** has to be designed for the implementation of the field tests, and customers have to receive it and accept it before starting the pre-evaluation. The field demonstration was divided into three parts: pre-evaluation, first and second campaign.

In the **pre-evaluation,** customers have to carry out the first reduction in their production processes in a controlled way. The main objective is to demonstrate their ability for reducing demand power without considering the duration time of the implementation. Once the pre-evaluation is finished, a more intensive campaign of implementation of scheduled DR actions started in the three factories (**first campaign**) and it lasted around three months. In this period, each customer had to perform at least four valid implementations for each DR action. In the first campaign, the customers were not allowed to change any scheduled event without a notification prior to the event day. They received some feedback after each implementation with the technical results and some recommendations to improve the performance.

As mentioned above, the last part of the field demonstration was the **second campaign** that is defined as a set of unscheduled implementations of the involved DR actions. The main goal of the second campaign is to check the ability of customers to react to prices or any signal sent by a DR requester

(TSO/DSO/DR aggregator) in real time taking into account the different notification time in advance defined for each flexible process. Therefore, each involved customers received a notification in advance (telephone call or email) for each DR event and they had to react according to the technical parameters included in the notification. In this stage, the date and time of each DR event was unknown for the customers until they received the notification.

Finally, the **evaluation and assessment** of the implementations of each DR action is performed taking into account the results of the field demonstration. Then, it is obtained the final definition of the technical parameters of each DR action. The different parts of a DR event are shown in Figure 2:

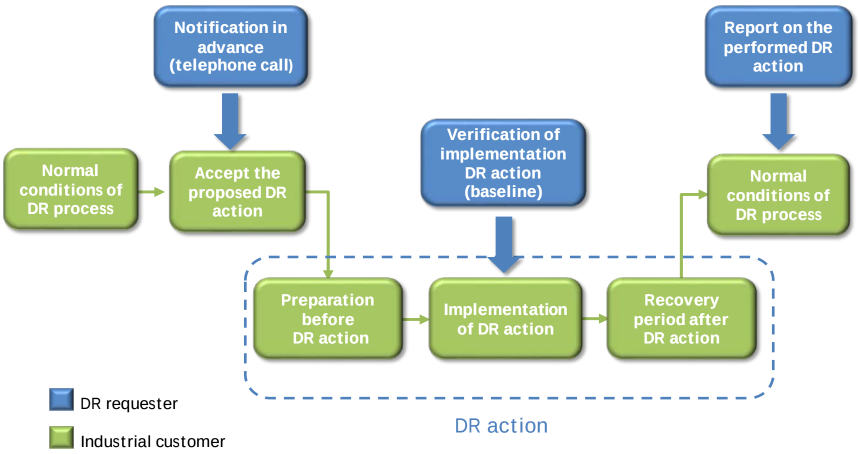

Figure 2. Process of DR events implemented during the second campaign.

2.1 *Baseline calculation for the verification process*

When a DR event is carried out, the load curve of the involved process changes and it is not possible to know what would happen in the absence of the DR event. Therefore, the only way to assess the reduced power is to compare the actual load curve with a baseline for that period. There are several methodologies to calculate a baseline for demand response purposes [33-36]. Taking into account the type of electric load linked to the flexible process, it was chosen a baseline calculation with a multiplicative adjustment, as it is recommended in [35], with a 10-in-10 non-event day selection and other additional exclusion rules, which are explained below.

The values of the selected baseline for the evaluation of a DR event are calculated as follows:

$$B_i = IB_i \times SA_i \quad (1)$$

Where:

B_i is the value of power related to the baseline at the time “i”, in kW.
IB_i is the value of the initial baseline at the time “i”, in kW.
SA_i is the adjustment factor at the time “i”.

On the one hand, a period prior to the event day (D) has to be defined depending on the variability of the daily load profiles of each flexible process because of the selection of a set of days with similar electrical consumption. The most common value among the studied DR processes was 30 days, but it was necessary to increase this value up to 90 days for some of them. In this vein, a set of tests were carried out to adjust it for each DR process in order to minimize the difference between the calculated baseline and the load curve using non-event days.

On the other hand, some of the selected days were excluded to calculate IB_i according to the following **exclusion rules**:

- **Event days**. An event day is any day on which a DR action has been implemented, and therefore, they cannot be considered as a normal day to estimate the initial baseline.

- **Holidays/weekends**. Electric energy consumption on holidays (or weekends) is usually different to electric energy consumption on working days. For example, if a DR event is performed on a working day, the holidays and weekends included in the selected period have to be excluded.

- **Type of day**. The days that have a different electrical consumption pattern comparing with the event day cannot be considered in the calculation of the initial baseline.

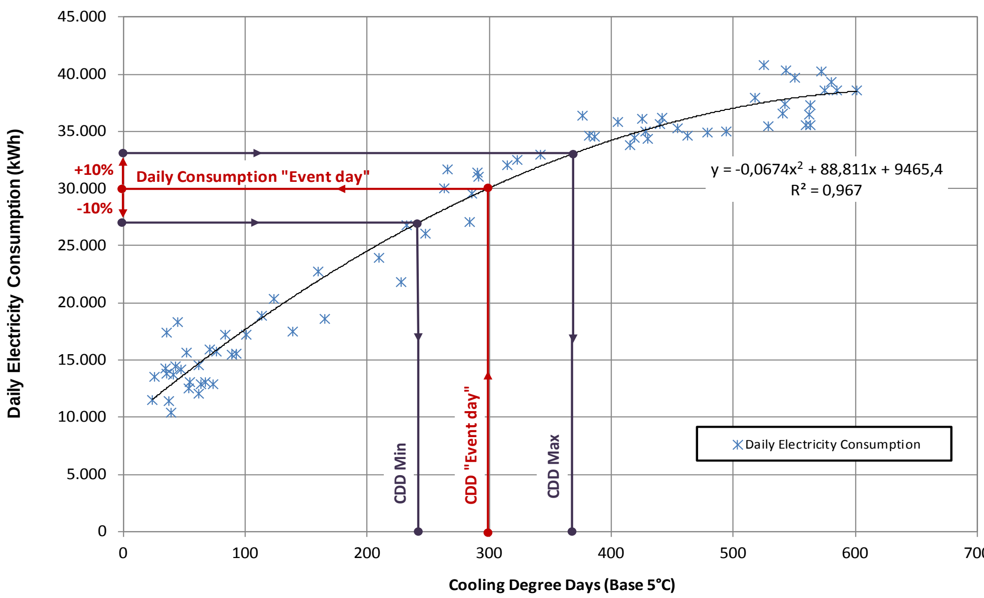

Figure 3. Regression analysis between CDD and daily electricity consumption on weekdays.

- **External temperature**. In some cases, the external temperature can directly affect the electrical consumption of an industrial process (i.e. cooling production and ventilation). The relation between the two parameters is considered using the regression function of the cooling or heating degree days (CDD or HDD) and the daily energy consumption. The minimum and maximum values of CDD or HDD are established depending on the daily energy consumption of a DR event day. Figure 3 shows an example of the "Cooling production and ventilation process" in the logistics centre of Campofrio (Spain), where a range of +/-10% of the daily energy consumption of the event day is defined to determine the upper and lower CDD limits that are used to exclude some days from the selection.

- **Lower RMSPE** (Root Mean Square Percentage Error) of the previous hours of the DR event. This condition, which has never been used as an exclusion rule before according to [35], is only used with DR processes that do not present a clear electricity consumption pattern. RMSPE (Expression 2) represents how much the baseline deviates from the reference load curve and it is calculated as follows:

$$RMSPE = \sqrt{\frac{\sum_{i=1}^{n} \frac{(y_i - x_i)^2}{x_i^2}}{n}} \quad (2)$$

Where:

i: time interval counter i= 1,…,n.

n: number of time intervals (of 15 minutes) during which the baseline was calculated n=1,…, 96.

x_i: value of the reference load curve.

y_i: value of the evaluated load curve

According to this criterion, the days with RMSPE value higher than a fixed limit have to be excluded. After the selection process, IB_i is calculated as an average of the ten closest selected days prior to the event day (D). It is important to highlight that the baseline is calculated in the period between the beginning of the preparation and the end of the recovery period because this is the period when the load curve changes due to the implementation of a DR event.

According to [21, 35], IB_i is proposed to be adjusted with an adjustment factor (SA_i) that is limited to a typical value of DR programs +/- 20%. The aim of this adjustment factor is to adapt the calculated baseline to the specific conditions on the event day. This kind of adjustment is known as "symmetric multiplicative adjustment" and it can be calculated using Expression 3:

$$SA_i = \frac{CH_A}{CH_B} \quad (3)$$

where CH_A is the energy consumption (kWh) in the three hours prior to the event and CH_B is the total energy (kWh) in these three hours of the initial baseline that is calculated as the average of the non-event days. Finally, the final baseline is obtained using Expression 1, and the DR event is evaluated comparing the load curve on the event day with the calculated baseline.

2.2 *Definition of technical parameters of DR actions*

According to the presented methodology, all the DR actions have to be defined using the same parameters [31] that are represented in Figure 4:

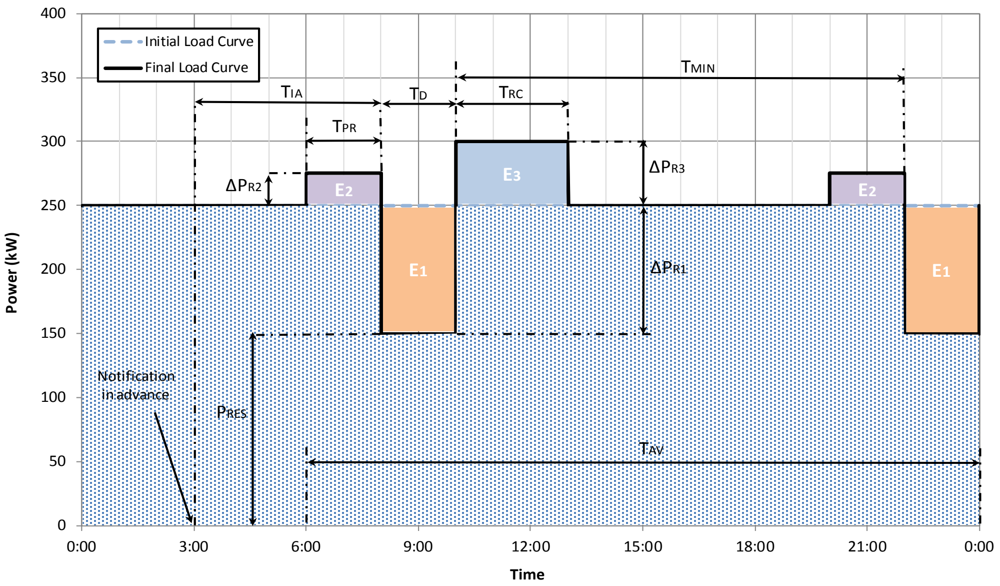

Figure 4. Technical parameters of DR actions.

A brief definition of these technical parameters is included below:

- **ΔP_{R1}**: Maximum reduced power over the expected value that a flexible process is able to certainly decrease during the implementation of a DR action. This value is calculated as the minimum reduced power that is obtained during the field demonstration (kW).
- **P_{RES}**: The residual power is the amount of demanded power that can be measured during the reduction. This parameter is relevant because some DR options compare this value with a specific limit as a verification method that is known as "firm power level" (kW).
- **ΔP_{R2}**: Increased power over the expected value required to accumulate additional energy (thermal, potential, kinetic, etc.), prior to the load shedding, in order to guarantee the proper implementation without any impact on the production process (kW).
- **ΔP_{R3}**: Increased power over the expected value required to recover the normal working conditions of the manufacture process in which the reduction was implemented in order to avoid any impact on the final product (kW).
- **T_{av}**: Operation time. It is defined as the time windows in which a DR action is available to be implemented.

- **T_D**: Duration of the action. This is the maximum time in which a load shedding in an industrial process can be maintained in order to guarantee that there is not any impact on the final products (Hours).
- **T_{PR}**: Duration of the preparation period. If it is necessary, this is the time before a load shedding in which the flexible process is prepared to the reduction or interruption (Hours).
- **T_{RC}**: Duration of the recovery period. If it is necessary, this is the time after a load shedding in which the flexible process recovers the normal working conditions (Hours).
- **T_{IA}**: Notification time in advance. This is the minimum time in which a DR action can be implemented to guarantee that the reduced power is delivered to the power system on a specific time. This period starts with the receipt of the system operator's notification (Hours).
- **T_{MIN}**: Minimum time between DR events. This parameter is defined as the time between the end of a load shedding and the beginning of the next one; Therefore, T_{MIN} must be equal or higher than $T_{PR} + T_{RC}$. T_{MIN} represents the minimum time needed to guarantee that there will not be any impact on the final product if two DR actions are implemented consecutively (Hours).

Regarding the energy balance of a DR event, it is calculated as the difference between the reduced energy (E_1) during the load shedding and the additional energy consumption before (E_2) and after (E_3) the power reduction, in the preparation and the recovery periods respectively.

3 Field demonstration and results

As mentioned in Section 2, after the pre-evaluation, a more intensive campaign for the implementation of DR actions started in the three factories. The first campaign lasted three months for each factory and several DR events were scheduled to be implemented in the flexible processes studied in the project.

During the first campaign, it was defined that the customers had to carry out at least four valid reductions for each DR action. In order to avoid a high impact on the production schedule of the factories, each industrial customer who took part in this study proposed before starting the **first campaign** a set of suitable days on which the DR actions associated with their different flexible processes could be tested. Although they were allowed to plan the dates and times for the implementation of the DR actions, they were banned to change anything related to this once the first campaign started, at least without sending a formal notification in advance. Therefore, any load shedding or shifting performed out of the initial plan was considered invalid and it had to be repeated.

After the first campaign, the initial definition of each DR action was updated according to the results obtained and taking into account customers' experiences during the first campaign. An example of the technical parameters of the four valid reductions performed in the "Stock Preparation" process in the paper factory during the first campaign is detailed in Table 1.

Table 1. Technical parameters of "Stock Preparation" process during the first campaign.

Technical Parameter	**28/04/14**	**08/05/14**	**15/05/14**	**22/05/14**	**Final**
Start time of the reduction	10:00	10:00	10:00	10:00	-
Duration of the reduction (min)	30	30	30	30	30
Maximum reduced power (kW)	1,059	992	1,116	1,198	1,198
Minimum reduced power (kW)	776	775	710	1,189	710
Average reduced power (kW)	917	883	913	1,193	977
Total reduced energy (kWh)	459	442	456	597	488
Maximum residual power (kW)	1,093	1,089	1,381	914	-
Minimum residual power (kW)	882	884	974	900	-
Average residual power (kW)	988	986	872	907	1,015

The technical parameters in the "Stock Preparation" process were calculated using the four reductions that were carried out in the first campaign. Consequently, the average of the interruptible power in "Stock Preparation" was 977 kW and the average of the reduced energy was 488 kWh. The average residual power of all the reductions was around 1,015 kW.

As an actual example, Figure 5 compares the daily load curve and the baseline implemented in "Stock Preparation" process on an event day. Moreover, this figure presents the most relevant technical parameters related to this DR event such as the reduced energy (E1), the energy required associated with the preparation (E_2) and the energy related to the recovery period (E_3), among others.

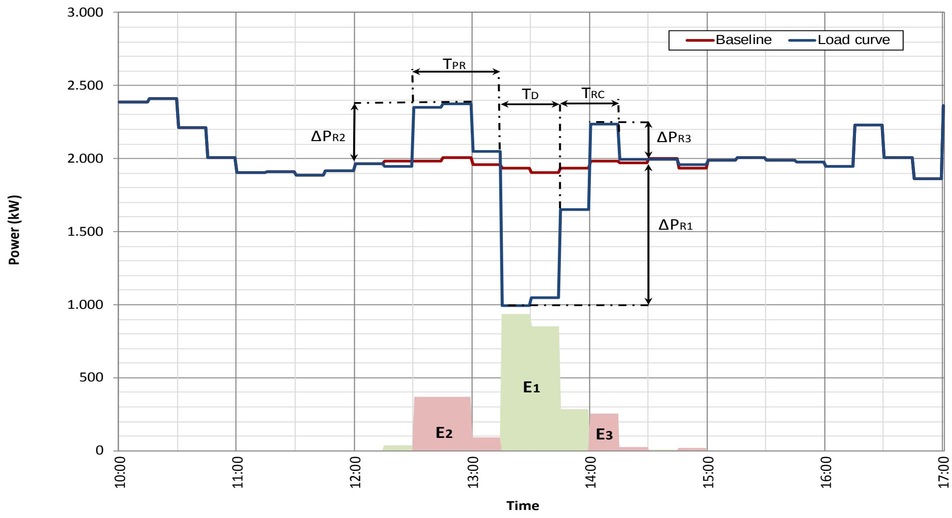

Figure 5. Load curve and baseline of "Stock Preparation" process on an event day.

Figure 6 shows the details of the load curve and the evolution of the tank level during an event day implemented in "Stock Preparation" process. As it can be observed, the critical parameter of this process (tank level) was within the valid range (30-90%) during the DR event, but the high rates of emptying presented after the disconnection of the pulpers highlights the relevance of monitoring critical parameters in order to avoid any problems during the implementation of DR actions in industrial process.

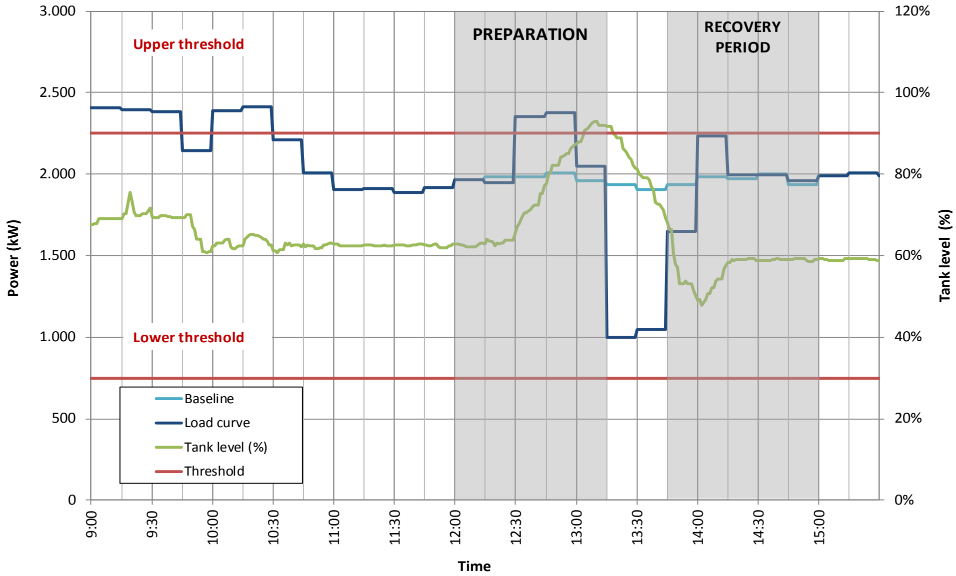

Figure 6. Load curve and tank level of "Stock Preparation" process on an event day.

According to the described methodology, the **second campaign** consists of a set of DR events designed to verify the ability of customers to react to prices or any signal sent by a DR requester in order to change their load. In this part, some real situations were simulated in which a DR requester called a DR event to reduce their electricity consumption. The involved customers received a notification in advance (telephone call or email) for each DR event according to the technical definition that was specified in the assessment of flexibility (table 6), and then they had to implement the load shedding or load shifting according to the technical parameters defined in the notification. As mentioned above, the date and time of each DR event was unknown to the customers before getting the associated notification, but they were notified following the technical parameters of the different DR actions. This stage lasted two months, and the three customers had to carry out at least two valid reactions for each DR action during this period.

The results of the DR events performed in the "Stock Preparation" process during the second campaign are presented in Table 2. Additionally, the first column named "Expected" includes the initial theoretical values that were updated taking into account the results of the first campaign.

Table 2. Technical parameters of "Stock Preparation" process during the second campaign.

Technical Parameters	**Expected**	**26/06/2014**	**18/07/2014**
Notification time in advance (h)	1	1	1
Duration of the reduction (min)	30	30	30
Maximum reduced power (kW)	1,198	835	1,206
Minimum reduced power (kW)	710	762	268
Average reduced power (kW)	977	798	737
Reduced energy (kWh)	488.5	399	368
Average residual power (kW)	1,015	986	1,584

As it can be observed in Table 2, despite the average reduced power was similar in both DR events, the minimum reduced power on 18th July 2014 (268 kW) was a great deal lower than the expected value due to an incorrect execution in which the loads were switched on before the expected ending time of the reduction. As a result, this DR event was not considered in the final evaluation of the second campaign. Furthermore, it can be claimed that it is highly recommended the full automation to implement DR actions in order to obtain the expected reduced power along the whole DR event.

In this regards, it can be concluded that the final average reduced power in the second campaign was 798 kW, which is the result of the only DR event implemented during the second campaign. Due to the fact that this value is lower than the value obtained during the first campaign (977 kW), the results of the second campaign were considered more reliable to describe the final definition of the technical parameters, as it can be observed in Table 3.

Table 3. Final definition of the technical parameters of "Stock Preparation" process.

Technical Parameter	**First campaign**	**Second campaign**	**Final definition**
Duration of the reduction (h)	30	30	30
Maximum reduced power (kW)	1,198	835	835
Minimum reduced power (kW)	710	762	762
Average reduced power (kW)	977	798	798
Reduced energy (kWh)	488	399	399
Average residual power (kW)	1,015	986	986

In order to evaluate the accuracy of the implementation of the DR actions performed in the second campaign, the real-time data of the electricity consumption of each flexible process just before and after the reduction was analysed. A detailed analysis of the disconnection and reconnection process (ramp down and ramp up respectively) of the involved electric loads was performed to characterize the execution of the presented DR actions. For example, the DR event carried out between 9:00 and 11:00 on

23rd July 2014 in "Cooling production and ventilation" process of the logistics centre (second campaign) is represented in Figure 7 with a sample rate of 5 seconds. As can be observed, all the involved electrical loads were completely turned off in less than three minutes.

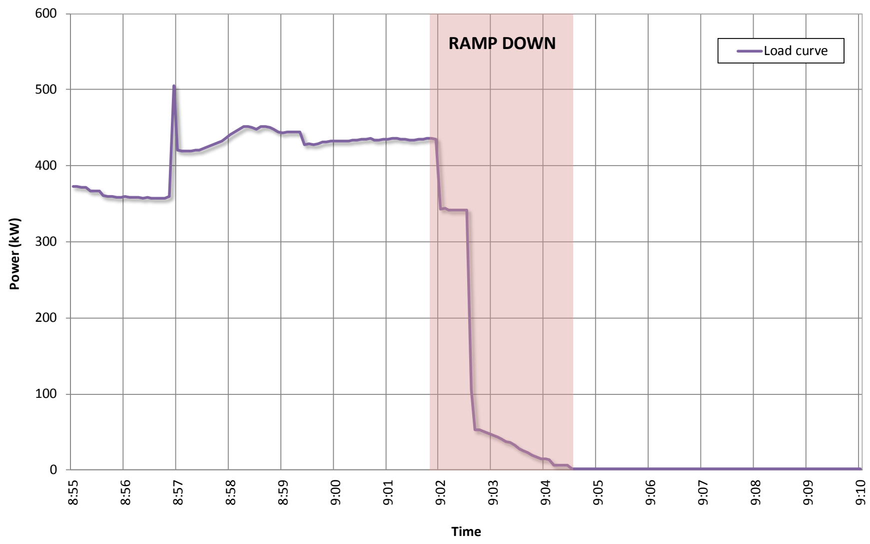

Figure 7. Ramp down of "Cooling Production and Ventilation" process in a DR event.

The implementation of the DR action was semi-automatic and the reduction started around 2 minutes later comparing with the proposed start time. In order to improve the local control system to implement a full-automatic response, it is necessary, not only the automation of the implementation of the DR actions in the facilities, but also the automation of the communication between the DR requester and the DR provider using specific communication protocols like OpenADR. Around 90% of the expected total reducible power was reached in around 1 minute (Table 4):

Table 4. Analysis of the ramp down of "Cooling Production & Ventilation" process in a DR event.

Time stamp	Ramp time	Ramp time (%)	Reducible power (%)	Residual power (kW)
9:01:55	0:00:00	0%	0%	435
9:03:12	0:01:17	50%	91%	40
9:04:30	0:02:35	100%	100%	2

Regarding the advance notification time, it is divided into five stages as explained below (Figure 8):

- **Customer feedback**: it is the period between the receipt of a notification and the response to the DR requester, and it includes the customer decision-making.
- **Implementation of preparation**: it is the period required to carry out the preparation process for the implementation of a DR event manually or automatically.

- **Preparation period**: it is the necessary period to prepare the process for the reduction, and it is generally related to an increment of the demanded power before the load shedding.
- **Implementation of the disconnection or reduction**: it is the time required to carry out the complete disconnection or power reduction of the electric loads associated with a flexible process manually or automatically and this time generally depends on the type of load.
- **Ramp down**: it is defined as the period between the disconnection of the electrical loads and the time at which the demanded power reaches the expected interruptible or reducible power.

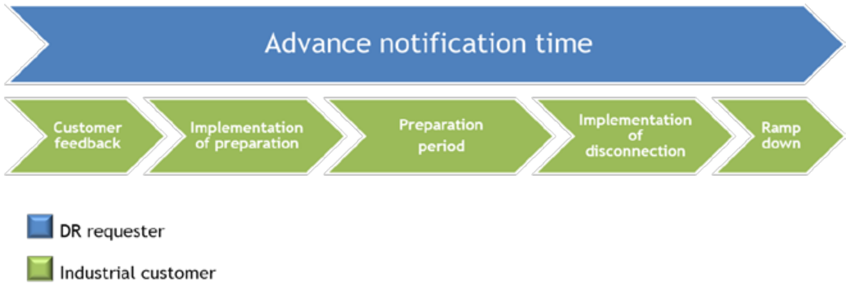

Figure 8. Structure of the advance notification time.

Table 5 summarizes the defined notification time in advance and the calculated ramp down for each DR action during the second campaign:

Table 5. Results of the analysis of the advance notification time for each DR action.

Factory	DR Action	Advance notification time	Ramp down duration
Paper factory (Germany)	Stock preparation	1 h(1)	2 min
	Short maintenance	24 h	13 min
	Winder	15 min	0 sec
	Storage	10 min	0 sec
Meat factory (Spain)	Drying	15 min	1 min
	Maturing	15 min	2.5 min
	Freezing store 81	15 min	3 min
	Slicing	15 min	30 sec
Logistics centre (Spain)	Cooling production and ventilation	30 min	2.5 min
	Freezing tunnel	30 min	30 sec
	Recharge of batteries	30 min	5 sec

(1) The preparation period lasted around 1 hour

In Table 5, the values of the column named "Advance notification time" were estimated by the industrial customer at the beginning of the project and the values of the ramp down duration were obtained by observing the load curve registered every second during each DR event, as it was presented in Figure 7. In this vein, it was found out that the ramp down duration was not properly considered by the industrial customers in the implementation of the DR events that took place in the second campaign, as it was seen in the mentioned load curves. On the other hand, if the implementation process of these DR actions, apart from the "Stock preparation" process that needs a preparation period, were adequately performed by an automatic control system, the advance notification time would be lower than one minute because the customer feedback would not be removed and the time required to the disconnection would be considerably reduced. After the field demonstration, the expected parameters (Table 6) were updated with the results of the field tests as shown in Table 7.

Table 6. Theoretical parameters of the studied DR actions.

DR action	ΔPR_1	ΔPR_2	ΔPR_3	T_D	T_{AV}	T_{PR}	T_{RC}	T_{IA}	T_{MIN}	**P**	**L**
Unit	kW	kW	kW	hour	hour	hour	hour	hour	hour	(2)	(3)
Paper factory											
1-Stock preparation	665	665	0	0.5	24	0.5	0	1	2	N	2
2-Short maintenance	7,800	0	7,800	1	7-13 Tu	0	1	24	164	N	1-3
3-Winder	30	0	30	0.5	24	0	0.5	0.25	23.5	Y	2
4-Storage	12	0	12	0.5	22-6 Sa-Su	0	0.5	0.2	1	Y	-
Meat factory											
1-Drying	261/234	0	55/49	2/2	24	0	1/0.75	0.1	22	N	-
2-Maturing	93/89	0	93/89	2/3	24	0	2/3	0.1	22/21	N	-
3-Freezing Store 81	44/26[1]	0	44/26[1]	2/3	24	0	2/3[1]	0.25	22/21	N	-
4-Slicing	65/35[1]	0	65/35[1]	1/2[1]	Mo6-Sa6	0	1/2	0.1	23/22	N	-
Logistic centre											
1-Cooling/ventilation	337/183[1]	0	337/183[1]	2	24	0	2	0.5	22	N	-
2-Freezing tunnel	89	0	89	2	-	0	2	0.5	22	Y	-
3-Recharge batteries	23	0	23	2	Mo0-Sa0	0	2	0.5	22	Y	-

(1) Summer / Winter
(2) If it is possible to postpone the recovery period. Y (yes) and N (no)
(3) Number of the DR actions that cannot be implemented at the same time.

Table 7. Final definition of the technical parameters of the studied DR actions.

DR action	ΔPR_1	ΔPR_2	ΔPR_3	T_D	T_{AV}	T_{PR}	T_{RC}	T_{IA}	T_{MIN}	**P**	**L**
Unit	kW	kW	kW	hour	hour	hour	hour	hour	hour	(2)	(3)
Paper factory											
1-Stock preparation	798	200	200	0.5	24	1	1	1	2	N	2
2-Short maintenance	6,659	0	6,659	1	7-13 Tu	0	1	24	164	N	1-3
3-Winder	36	0	4	0.5	24	0	4.5	0.25	4.5	Y	2
4-Storage	5	0	2,5	0.5	22-6 Sa-Su	0	1	0.2	1	Y	-
Meat factory											
1-Drying	283	0	0	2	24	0	0	0.25	22	N	-
2-Maturing	102	0	15	3	24	0	21	0.25	21	N	-
3-Freezing Store 81	70/45[1]	0	30/27[1]	3	24	0	7/5[1]	0.25	21	N	-
4-Slicing	82/36[1]	0	82/72[1]	1/2[1]	Mo6-Sa6	0	1	0.25	22	N	-
Logistic centre											
1-Cooling/ventilation	230/95[1]	0	368/380[1]	2	24	0	1.25/0.5[1]	0.5	22	N	-
2-Freezing tunnel	67	0	67	2	-	0	2	0.5	22	Y	-
3-Recharge batteries	22	0	22	2	Mo0-Sa0	0	2	0.5	22	Y	-

(1) Summer / Winter
(2) If it is possible to postpone the recovery period. Y (yes) and N (no)
(3) Number of the DR actions that cannot be implemented at the same time.

After comparing Table 6 and Table 7, it can be observed that there are relevant differences between the theoretical values and the results in the field demonstration, especially the minimum amount of electric power reduced, as well as the parameters associated with the preparation and recovery periods. In most cases, the average power during the recovery period was lower than the theoretical value since the recovery period was longer than the expected value. The duration of the action or the operation time were equal to the theoretical values that were proposed by the facilities manager during the visit to the plant.

According to the customers' feedback, most of the DR actions performed during the field demonstration did not produce any impact on the production, so that it can be assumed that the DR events carried out during the field demonstration do not affect either the quality of the final product or the productivity of the plant. However, it was found out some restrictions in some of these industrial processes:

- **Refrigerated working rooms** (i.e. "Slicing" process in the meat factory): the temperature in the working rooms on the days with extreme weather conditions increases quickly until the safety limit during the implementation of a DR action, consequently, on these days the duration of DR actions have to be shorter than in normal conditions.
- **"Sewage treatment" processes** (paper factory): the critical parameters of this process have to be monitored in real-time in order to be able to perform a secure and accurate DR action without any impact on the production process according to the customer experience.
- **"Drying" processes** (meat factory): the relative humidity inside the drying rooms reached the upper limit during the implementation of some DR events. If some DR events are implemented successively, it could cause a negative effect in the final product according to the customer's quality department. For this reason, the minimum time between two DR events of this industrial process was increased during the second part of the field demonstration.

On the other hand, most of the analysed DR actions need some additional energy after their implementation in order to restore the normal working conditions in the process. In most cases, industrial processes, which did not retrieve the reduced energy after the implementation of a DR action (for example, "the speed reduction in the paper machine drives" or "Drying" process), often produce an impact on the production. This impact should be quantified as an additional cost of using this flexibility. In conclusion, the total reducible power validated in the field demonstration for each factory is presented below:

- In the paper factory, the total reducible power on working days was 839 kW.
- In the meat factory, the total reducible power on working days was 537 kW and 466 kW in summer and winter respectively.
- In the logistics centre, the total reducible power on working days was 319 kW and 184 kW in summer and winter respectively.

Lastly, according to these figures and the mentioned high replicability in Europe, it can be claimed that the segments associated with the three factories present a high DR potential, which should be considered to increase the integration of renewable energy in future scenarios.

4 Conclusions

According to the presented results, it can be concluded that the implementation of DR actions has to be completely automated (communication, monitoring and control) in order to avoid human errors, as well as to reduce the required advance notification time. The automation of the implementation of DR actions is essential to comply with the time restrictions associated with the reserve electricity markets (secondary reserve, tertiary reserve or balancing services). However, if the disconnection and reconnection processes of the electric loads associated with a DR action are not properly studied and included in the required advance notification time, especially the ramps up and down, the automatic response does not guarantee that either the power reductions or reconnections will take place on the precise time according to the system operator's requirement. To this end, the methodology includes the study in detail of the ramps up and down of each test performed in the field demonstration.

On the other hand, due to the nature of industrial customers, it is important to highlight that there are always inevitable and unpredictable situations that will produce invalid reactions such as unplanned changes in the production schedule and maintenance tasks (none of them related to the implementation of DR actions).

One of the most relevant aspects of the proposed methodology is the way of controlling the risk of the potential impact on the production processes or final products. To this end, the methodology considers three key points: the monitoring of critical parameters to find the main restrictions (e.g. temperature of refrigerated working rooms), the progressive increment of the duration of tests (e.g. sewage treatment plant) and the involvement of technical staff during the whole evaluation process.

Another good point of the proposed prequalification process is the replicable assessment and characterization of the technical parameters, especially the preparation and the recovery periods. These aspects are not generally considered in this kind of evaluations, but they could be as relevant as the reduced power for the system operator in a scenario with a high share of DR resources. If the aggregation of DR resources of several customers can help the system operator balance out the generation and demand, the aggregation of unexpected increase of electricity demand due to the simultaneity of preparation and recovery periods of several processes could cause the opposite effect jeopardising the balance of the power system.

In conclusion, this paper provides a novel methodology to test and validate the flexibility potential of industrial customers prior to provide ancillary services. The proposed methodology includes a specific procedure that can be applied to any type of industrial customer as it is based on an analysis performed by processes and considers the main characteristics to be analysed in this kind of facilities. Finally, it can be concluded that this methodology could serve as a basis for the development of a new prequalification procedure for industrial DR resources, although it will be probably necessary additional efforts in this line to definitively standardise it due to the huge diversity of different types of processes that are present in the industrial segment.

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