A novel tool for the evaluation and assessment of demand response activities in the industrial sector

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Abstract

This paper introduces a novel tool for industrial customers to perform a cost-benefit analysis regarding the implementation of Demand Response (DR) strategies in their facilities with the final goal of softening the impact of RES intermittency in the grid. The dynamic simulation tool focuses on assessing the participation of industries in reserve energy markets in the same conditions as generators offering capacity reserve, energy reserve or both of them and taking into account all the technical restrictions of production processes as well as possible extra costs due to the implementation of DR (additional labour cost, productivity losses, etc.) Main innovations of the methodology are the DR assessment carried out per process and the introduction of the "margin of decision" as a decision making strategy for the energy consumer.
Along the paper, the methodology behind this tool is introduced step by step in order to show how the technical, economic and environmental analyses are performed. At the end, it is included the application of the methodology to a real paper factory in Germany. Results of the

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dynamic simulation tool are provided and discussed, showing the potential of the paper manufacturing in DR programmes as well as the benefits associated to it.

Nomenclature

B_{NE}, expected benefit for the customer (€)

B_R, real benefit (€)

C_0, initial investment (€)

CE_k, CO_2 emission balance in the period k (tonCO_2/kWh)

CF, annual cash flow (€)

C_{VAR}, variable cost (€)

E_1, energy reduced during a DR event (kWh)

E_2, additional energy consumed before a DR event (kWh)

E_3: additional energy consumed after a DR event (kWh)

EB_{Total}, *total* energy balance involved in a DR process and month (kWh)

f_k, CO_2 emission factor in the period k (tonCO_2/MWh)

M_D, margin of decision (€)

p_k, price of the electricity in the time period k (€/kWh)

P_M, revenues from the DR program operator (€)

ΔP_{R1}, average power reduced or interrupted during a DR event (kW)

ΔP_{R2}, average power increased before a DR event (kW)

ΔP_{R3}, average power increased after a DR event (kW)

P_{RES}, residual power during a DR event (kW)

S_{ij}, availability of the process *i* in the quarter-hour *j*

S_{MA}, economic savings in a DR action due to extending the useful lifetime of machines (€)

S_S, economic balance in the implementation of a DR action (€)

r, discount rate (%)

T_{av}, availability time (h)

T_D, duration of a DR event (h)

T_{IA}, notification time in advance (h)

T_{MIN}, minimum time between two DR events (h)

T_{PR}, duration of the preparation period (h)

T_{RC}, recovery period (h)

1 Introduction

Horizon 2020 context is promoting the reduction of CO_2 emissions, which is related to the increasing integration of Renewable Energy Sources (RES) in the electricity generation mix as it appears in the European Directive (2009/28/EC). However, higher penetration of fluctuating energy sources, such as solar and wind, makes difficult the task of maintaining a predictable and reliable system operation at all voltage levels [1]. Therefore, the implementation of mechanism allowing a specific regional transmission system operator (TSO) to interact directly with demand response resources could be beneficial from different points of view: a) environmental, reducing the required capacity reserve of thermal power generation and avoiding curtailments of RES in periods of excess generation; b) for customers, enhancing their opportunities by means of providing ancillary services to the grid; and c) for TSOs, increasing the number and quality of fast resources for balancing the grid which allows cheaper and more reliable operation [2].

According to this, demand response (DR) can be a significant resource to integrate RES where customers will shape 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 with high wholesale market prices or when system reliability is jeopardized [3]. Traditionally, industrial customers have had a passive role in European power systems, where only large consumers (i.e. melting furnaces or electrolytic cells) have provided (if any) some kind of interruptibility services to the grid. However, it is a fact demonstrated in different research and applications [4-6] that many medium industrial customers may be also able to offer DR services to the TSO if they were allowed, directly or through an aggregator. For this reason, it is important to provide them with new tools and mechanisms so as to enable them for estimating the DR potential that could remain hidden in their production processes [7, 8].

Currently, some tools for the estimation of the DR potential of customers in the primary and tertiary sectors (agricultural sector and commercial buildings) are available in different sources [9-12]. However, such tools are just focused on buildings [13] (like the Demand Response Quick

Assessment Tool –DRQAT- described in [14]), existing a significant gap regarding industrial applications. Existing models are focused on very specific processes (for example, air conditioning or lighting), which have been traditionally used for DR applications. However, more specific processes of industrial consumers have not traditionally been involved in DR issues due to misgivings about potential risks in the degradation of the production processes. This is especially true when DR actions are applied to sensitive processes directly related to the quality of the final product, which tend to make customers wary of changing any element or parameter of those processes. The tool here presented permits the modelling of industrial and non-industrial processes so as to evaluate the impact of specific DR actions and providing a detailed economic, technical and environmental evaluation every 15 minutes. In addition, the tool provides a holistic approach, linking the impact of DR actions on a process with each other, so that the application of any specific action is constrained to what happened with the rest of processes. Moreover, the tool provides a detailed analysis about when and how the different types of DR actions may be implemented in order to maximize the economic benefit for both the consumer and the power system.

On the other hand, existing tools deal with economic models using Time-of-use or similar fix price schemas [15] but neither research studies nor tools have been found so as to evaluate the economic benefit of the participation of industrial customers in reserve energy markets (offering capacity reserve, energy reserve or both of them). Conversely, this tool provides the simulation of customers participation in ancillary services based on a dynamic prices scheme with the possibility to consider a set of different prices for different services (capacity reserves, balancing services, interruptibility, etc.) every 15 minutes.

In this paper, a dynamic simulation tool based on previous works of the authors (described in [16]) is presented so as to fill this gap. This tool does not consider industrial customers as a black box, but they are evaluated as a sum of parts (manufacturing processes) which can be modified individually while the effect in the total electricity pattern of consumption for the whole facility is analysed. In this regard, the results of the economic evaluation are obtained for each DR process enabling customers to select the most cost-effective options. Moreover, the simulation tool includes an environmental evaluation that calculates the reduction of CO_2 emitted by the replaced thermal power generators to the atmosphere.

The tool was developed in the framework of the project “Demand Response in Industrial Production (DRIP)” [17], co-funded by the Environment LIFE Program of the European Commission[3], and it was empirically validated in the four factories involved in that project, which belong to some of the most suitable segments for DR implementation [18]: a paper factory in Germany, two meat factories in the Netherlands and Spain (respectively) and a logistics warehouse for food products in Spain.

The paper is organized as follows: Section 2 describes the calculation methodology of the new simulation tool. In Section 3 the methodology is applied to a paper factory. Finally, some conclusions are drawn in Section 4.

2 Calculation methodology

2.1 General description

In order to assess the potential benefit of the participation of an industrial customer in a particular reserve energy market, a set of information is required:

- On one hand, information related to the customer, such as the load curves of the processes, the definition of DR actions of the processes according to standardized parameters (see section 2.2) and electricity contract.
- On the other hand, the reserve energy market prices where the participation of the consumer would be simulated and CO_2 emission factors, which depend on the country where the consumer is located.

Based on this information, the simulation tool performs the technical, economic and environmental evaluation of the DR potential in the customer facility considering all the complex relationships among all the variables in a mathematical model that takes into account the chronological order of events. Figure 1 shows an overview of the required information (inputs) and the main results of the simulation tool (outputs).

2.2 Required information (Inputs)

Most of the medium industrial customers are not aware of their energy consumption profile and the possible flexibilities in their production processes due to the fact that they usually do not

[3] Detailed reports and more information about DRIP can be found in the website www.drip-project.eu [17]

have experts specialized in energy and flexibility trading [19]. In order to address that, a flexibility audit has to be performed to characterize the electrical consumption of the different processes and to identify the DR actions that could be implemented in the industrial customer facilities.

2.2.1 *Identification of typical days and building of typical day profiles*

Typical days represent repeatable daily patterns of consumption for the customer during the year. Using the quarter-hourly load curves collected during the flexibility audit, the typical daily consumption profiles are calculated with the help of the simulation tool. Figure 2 presents an example of the average daily load curve on working days in the Spanish meat factory involved in the abovementioned DRIP project.

In order to obtain the cited daily load curves it is necessary to carry out the process described below.

- The first step is to identify and remove the days that enclose anomalous data (lack of data, blackouts, maintenance periods, etc.).
- Then, the daily profiles are compared and clustered by groups (type of day) according to similar energy consumption patterns trying to reduce the standard deviation of each group as much as possible. When the standard deviation value of all the groups becomes acceptable, the average electrical load curve of all the selected days is considered representative of each group (typical day).

As aforementioned, the simulation tool allows customers an easy performance of the previous analysis and building of the typical load curves by means of a friendly user interface. Figure 3 shows an example of the typical profile of a working day in July (peak season) in the same Spanish meat factory. When seasonality (or other factors) affects the shape of the load curve of any process, it results on a new typical day.

2.2.2 *Definition and standardization of DR actions*

Once all the typical days are defined, the DR actions are specified for each process. Each DR action is characterized according to the technical parameters proposed in [20]. In this regard, the relevant technical parameters considered in this analysis are represented in Figure 4. The figure illustrates a theoretical flat load curve for a process when a flexibility action involving the reduction of an amount of energy E1 during the time T_D is applied. For a period of time T_{PR}, an amount of energy E2 is consumed in order to make adaptations to prepare for an interruption. Similarly, at the end of the interruption, the reduced supply is switched back on, and an extra consumption E3 is produced to re-establish the original settings. Once the period T_{RC} has happened, the load curve returns to the initial level of demand. The time T_{IA} represents the notification in advance that is necessary for the customer before the implementation of the action.

The technical parameters involved in each DR action need to be specified for each type of day and month in order to take into account the possible variations due to changes in the boundary conditions (external temperature, scheme of productions, etc.)

2.2.3 *Economic and environmental inputs*

Regarding the information needed to the economical evaluation, the characteristics of the electricity supply contract of the studied industrial customer (electricity prices) are required, as well as the historical prices of the reserve energy market in which the industrial customer could participate and their future trends for a more sophisticated estimation.

Lastly, regarding the environmental evaluation, the hourly CO_2 factors associated to the electricity generation mix are necessary, as explained below.

2.3 Calculation process

2.3.1 *Identification of the availability: when flexibility is activated or not*

Firstly, the availability of the interruptible power for each DR process is evaluated at each quarter-hour (j), which is the time step (so-called “Programme Time Unit”) in most of the European reserve energy markets [21], taking into account its technical parameters. The state of the analysed DR process *i* at the quarter-hour *j* (Sij) is calculated based on the state of the previous quarter-hour (j-1) in order to determine if the DR process *i* is available to be interrupted during the quarter-hour *j* or not. In this regard, the reasons why a DR process *i* at the quarter-hour *j* (PR_{ij}) could not be available to be interrupted (Sij = 1) are described below:

- The DR process *i* is in the middle of a DR event, and therefore it is already interrupted.
- It is in the preparation period or recovery period of other DR event.

- It is between two DR events, and although the first DR event is finished, the DR process needs an additional time (minimum time between interruptions) in order to implement the second one without causing any impact in the production process.

If the DR process *i* is available to be interrupted for example at the quarter-hour *j* (S_{ij} = 0), an economical evaluation will be performed to determine the margin of decision (M_D) that is the difference between the real benefit (B_R), which is the net amount of money that receives the industrial customer due to the participation in the reserve energy market, and the expected benefit for the customer (B_{NE}):

$$M_D = B_R - B_{NE} \quad (1)$$

This parameter, proposed in [16], is used to verify the potential participation of a customer in a DR program at a specific time:

- If $M_D \leq 0$, the customer will not participate in the DR program because economic benefits are not obtained.
- If $M_D > 0$, the customer will provide the DR Service, modifying the power load according to the DR event requirements and obtaining economic benefits.

In order to calculate the real benefit (B_R) at the quarter-hour j, it is necessary to assess a set of parameters in advance such as the economic balance (S_S), the benefit of the extension of machinery useful life (S_{MA}), the variable costs (C_{VAR}) and also considering the payment offered by the TSO in the reserve energy market:

$$B_R = S_S + S_{MA} + P_M - C_{VAR} \quad (2)$$

2.3.2 *Technical evaluation*

The energy balance (EB_{Total}) involved in the DR process *i* in the month *l* is calculated as the difference between the energy reduces during the DR events (E_1) and the additional energy consumed before and after these DR events (E_2 and E_3 respectively):

$$EB_{Total} = E_1 - (E_2 + E_3) = \sum_{h=1}^{p} E_1^h - \left[\sum_{h=1}^{p} E_2^h + \sum_{h=1}^{h} E_3^k\right] \quad (3)$$

where *h* is the number of the DR event and *p* is the total number of DR events in the month *i.*

2.3.3 *Economic evaluation*

The economic balance (S_S) during a DR event is the difference between the economic savings due to the energy not consumed and the extra costs generated by the additional energy consumed before and after the interruption (preparation and recovery periods):

$$S_S = \sum_{k=1}^{n} E_1^k \cdot \mathrm{p_k} - [\sum_{k=1}^{n} E_2^k \cdot \mathrm{p_k} + \sum_{k=1}^{n} E_3^k \cdot \mathrm{p_k}] \qquad (4)$$

where p_k is the electricity price in the time period k (i.e. prices of electricity for on-peak, shoulder and valley periods.)

The tool calculates S_S during the whole month *l* for each DR process as the difference between the economic savings due to the energy not consumed and the extra costs generated by the additional energy consumed before and after the implemented interruptions (preparation and recovery periods), and it is assessed using (2) as explained above.

When the production machinery stops during the implementation of a DR event, its useful lifetime will be generally increased, which is considered as an economic saving. Occasionally, the benefit of the extension of machinery useful life (S_{MA}) may also have an opposite effect. In this regards, if the start/stop cycles of the production machinery due to the interruptions have a high frequency, their life time could be lessened. In this case, S_{MA} will be zero and the possible extra cost will be included as a variable cost in the simulation tool.

As stated above, B_R also includes the variable costs (C_{VAR}) associated with the implementation of DR actions such as the labour cost that is the extra cost paid to the employees for overtime work and the possible cost due to the loss of productivity (if it exists).

Taking into account the previous considerations, it can be concluded that the revenue offered by the TSO (marginal price) has to be higher than the minimum price required by the customer. In this case, the matching will be achieved and the DR process *i* will be interrupted during the quarter-hour *j* (S_{ij} = 2), reducing the available interruptible power (P_{ij}). Otherwise, the customer will not tender the flexible power. The following equation summarizes the above statements:

$$P_M \geq C_{VAR} + B_{NE} - S_S - S_{MA} \qquad (5)$$

This equation is represented in Figure 5.

Using (4), the simulation tool calculates the quarter-hourly offers of all the DR processes during the simulated month "m". Figure 6 represents an example of a quarter-hourly offer on a working day in the cited Spanish meat factory, which includes four different processes sorted by price. In this example, if the TSO offers 43 €/MWh at the quarter-hour *j* and all the DR processes are available to be interrupted, the customer could interrupt the maturing and drying processes in a cost-effective way resulting in a total interrupted power of 354 kW.

Following with the description of the calculation process, the simulation tool saves the information related to the state and interrupted power for each DR process *i* at the quarter-hour *j*. Then, the described part of the algorithm is repeated from the next quarter-hour (*j+1*) to the last one (m) in the month *l*. After that, the simulation tool applies this procedure to the rest of DR processes from *i+1* to *n,* that is the total number of DR processes identified in the industrial customer facilities.

Figure 7 shows an example of the results of the calculation procedure applied to the "Winder" process in the paper factory on a working day (5th of December 2013). The upper graph shows the final load curve and the margin of decision comparing the minimum payment required by the customer with the payment offered by the TSO while the lower graph provides the associated economic evaluation in detail.

Using the saved results of the simulations of all the DR processes in the month *l*, a monthly technical, economic and environmental evaluation is performed for each DR process.

2.3.4 *Environmental evaluation*

The environmental impact of all the DR events associated with all the DR processes in the month *l* is calculated as the CO_2 emission balance (CE_{Total}) between the avoided CO_2 (CE_1) and the extra CO_2 emitted to the atmosphere due to the extra electrical consumption before and after all the DR events (CE_2 and CE_3):

$$CE_{Total} = CE_1 - (CE_2 + CE_3) = \sum_{k=1}^{n} E_1^k \cdot \mathrm{f_k} - \left[\sum_{k=1}^{n} E_2^k \cdot \mathrm{f_k} + \sum_{k=1}^{n} E_3^k \cdot \mathrm{f_k}\right] \quad (6)$$

where *k* is associated with the time period of each different CO_2 emission factor (i.e. CO_2 emission factor of on-peak, shoulder and valley periods.)

As explained above, the aforementioned CO_2 emission factors should be calculated taking into account the CO_2 emission factors of the replaced technologies used in the reserve energy market in each quarter-hour. It is important to point out that the emissions impact here calculated is only related to the use of electricity. It means that the amount of CO2 emitted or avoided into the atmosphere evaluated by the tool is just related to the carbon footprint linked to the technology producing the electricity used by the consumer. It means that the evaluation of the CO2 impact related to the use of fuel for other purposes (thermal energy, transport, etc.) is out of the scope of this research.

After that, the described calculation process is carried out for each month of the selected year from January to December in order to obtain the annual results for each DR process. Based on these results, the final economic profitability of each DR process is evaluated using the Net Present Value (NPV), the Internal Return Rate (IRR) and the Discounted Payback Period (DPP). To that end, the involved fixed costs (initial investment) are calculated as all the expenses incurred by the customer and needed before providing DR services such as the initial flexibility audit, the acquisition and installation of all the required equipment (monitoring and control systems and metering devices), etc. The expressions that are used to evaluate the economic profitability of each DR process (NPV, IRR and DPP) are presented below:

$$NPV = \sum_{t=0}^{n} \frac{CF}{(1+r)^t} - C_0 \quad (7)$$

$$NPV = \sum_{t=0}^{n} \frac{CF}{(1+IRR)^t} - C_0 = 0 \quad (8)$$

$$DPP = \frac{-\ln\left(1 - \frac{C_O \times r}{CF}\right)}{\ln(1+r)} \quad (9)$$

where t is the number of the year and n is the total number of years associated with the investment.

After selecting the cost-effective DR processes and discarding the rest, the total annual results of the technical, economic and environmental evaluations are obtained as the sum of the particular results of all the selected DR processes during the whole year.

Figure 8 schematizes the presented calculation process in a flowchart:

Lastly, the final economic profitability of providing DR services for an industrial customer is calculated with the expressions (7), (8) y (9) using the aforementioned total annual results of the economical evaluation.

3 Application of the simulation tool in a paper factory

In this section, the results of the participation of the paper factory in the German reserve energy market using the simulation tool are presented. Currently, the tender block size required by TSOs [22] is too high for medium industrial customers in most cases, so an aggregator is required to use the DR services offered by them. Generally, the aggregator is a legal organisation that consolidates or aggregates a number of individual customers and/or small generators into a coherent group of business players [23]. This implies that changes in the regulation of some countries around the world could be necessary to encourage medium industrial customers to contribute to the improvement of grid management.

Assuming the above mentioned requirements, the participation of industrial customers in the reserve energy markets was simulated considering possible restrictions due to the reaction time of the analysed DR actions. Moreover, it was considered that all the DR actions are implemented automatically or semi-automatically depending on the required reaction time. Consequently, the associated costs of control were included in the total flexibility expenses for all DR actions.

The description of the results of the application of the simulation tool in a paper factory is structured as follows: Subsection 3.1 describes of the relevant production process in the studied paper factory and the final technical evaluation. In Subsection 3.2 the results of the economic evaluation of each DR process and as a whole are presented. Finally, the environmental effects of providing DR services are presented in Subsection 3.3.

3.1 Description of the paper factory and technical evaluation

The analysed manufacturing plant is devoted to the production of test liner paper with different grammages, winding the paper throughout reels. The production is continuous and stable at all times except during maintenance periods. It exists long and short maintenance stops, the first one occurs every 6 weeks while the other one happens every week for a 3 to 4 hours period.

The manufacturing process of the paper factory begins on the reception of raw materials classified and directly supplied from the **stock preparation**. In this section the pulp is prepared to supply the paper machine and depending on the state of the tanks, the pulpers and the turboseparators used to prepare the pulp could be switch off. This is the first DR action identified in the industrial process.

Next, the pulp feeds the paper machine distributing the pulp and producing the layers which compose the paper sheet. Following, the vacuum pumps drains the water and the paper sheets go through different pressing rolls. Subsequently, in the dryer section, a high percentage of dry content is achieved by means of steam heated drying cylinders.

Afterwards, the paper is treated with starch, colour and/or synthetic glues and it is wound in reel drums throughout the winding section. Once the drum leaves the paper machine, the paper is re-winded according to the characteristics required by the final customers. At this stage, the **winder** can be interrupted so that several drums can be stored at the end of the winding section to be re-winded and cut later (second DR action).

The final product is driven to the **storage** for its shipment. At this point, there are two suction lifts to move the reels in the warehouse which work using vacuum. The use of these machines could be managed in order to avoid their use when a reduction is required (third DR action).

Table I shows the main parameters of the three DR actions found in the performed flexibility audit.

3.2 Economic evaluation

In order to calculate the economic evaluation, it was assumed that the customer will receive the same payment (PM) as a generator that is participating in the German reserve energy market when a DR event is implemented.

According to this, it was used the average imbalance pricing system (reBAP) that is based on TSO's payments or proceeds for the activated control energy (secondary and minute reserve) in the whole Germany. On the basis of these prices, it was simulated a whole year using the tool.

As explained in section 2.3, the involved fixed costs (initial investment) were calculated as the sum of expenses incurred by the customer that are needed before providing DR services, such as the initial flexibility audit, the acquisition and installation of all the required equipment (monitoring and control systems and metering devices), etc. In this regard, the total initial investment for providing DR services was estimated around 130 k€, considering the mentioned fixed costs and the installation of an additional pulp storage tank for ensuring the duration of interruptions.

After that, the economic profitability of each DR process was evaluated in order to exclude from the final results the DR processes that are not cost-effective according to the proposed scenario. As discussed before, the economic profitability of each DR process is evaluated using the Net Present Value (NPV), the Internal Return Rate (IRR) and the Discounted Payback Period (DPP).

Table II shows the NPV for the different DR processes and different discount rates considering a total of 3 years to recover the investment. Additionally, it is summarized the IRR and the DPP for each DR process.

According to Table II, the “Stock preparation” process is the most profitable one with a DPP of around two years and two months, the highest values of IRR and NPV in this group of three DR processes. “Winder” process has a DPP of three years and the IRR is 12.1 %, consequently it was also considered as a cost-effective process in the final economic evaluation of the factory. On the other hand, the “storage” process can be considered as a non-profitable (DPP>5 years).

After discarding the non-profitable DR processes, the final economic evaluation was carried out where the annual net benefit (€/year) that was calculated as the sum of the difference between the monthly incomes and variable costs of the considered DR processes throughout a year was around 70 k€ per year. In this regards, Figure 9 shows that the maximum unitary benefit for the customer was in December (68 €/MWh).

Using the annual net benefit and the initial investment, the final economical evaluation of the participation of the studied paper factory in the German reserve energy market is presented in Figure 10 where the NPV that was calculated using different discount rates. The intersection between the NPV curve and the abscissa axis is the discount rate value of the IRR, equals to 30.3% as shown in Figure 10.

In this regard, the DPP of the considered investment was around two years and two months.

According to the results of the previous economic evaluation, the participation of the studied paper factory in the German reserve energy market was considered as a cost-effective measure to be implemented in the customer facilities.

3.3 Environmental evaluation

In order to assess the amount of CO_2 emitted into the atmosphere when a DR action is performed, the hourly CO_2 emission factor curve (tonCO_2/MWh) was calculated using PLEXOS® [24] in the studied year and considering the conventional generation used in the German reserve energy markets. After analysing this information, it was observed that there is not a direct relationship between CO_2 emissions and market prices since it strongly depends on the constitution of the generation mix for each particular country. Consequently, the possible environmental effects of the implementation of DR actions could be even negative. During the simulation, the result of the DR events triggered by the market price had a tiny positive environmental effect avoiding 397 ton CO_2 emissions per year.

The European emission market, regulated under the Directive 2003/87/CE, is related at present to the CO_2 emitted when consumers use fuels for their main activity. Therefore, a paper factory can trade emission rights related to the emissions linked, for example, to the combustion of a fuel to produce steam. On the contrary, the CO_2 related to the use of electricity in different periods of time is not considered in the current emission market rules. Therefore, there are not incentives for consumers so as to use of electricity in periods when the technologies producing power are less contaminant (e.g. when the share of renewables is higher) and vice versa. Although currently there is not an economic incentive scheme for the reduction of the CO_2 emissions using DR resources in Europe, it is presumable that this fact will change in the coming years. Then such time comes, this simulation tool will allow industrial customers to estimate the environmental benefits of providing DR services, based on the aforementioned results.

4 Conclusions

Considering the increment in electricity cost as well as RES integration in the grid, the need for simulation tools capable to provide a "decision-support" approach for quick decision making is valuable not just for customers but also for the agents who must guarantee the optimal power system management.

As highlighted above, there are different tools for assessing DR potential; however, none of them provides the economic profitability for industrial customers participating in a specific operation market, where consumers may provide different services such as capacity or energy reserve. The novel simulation tool that is here presented performs this kind of evaluation, as well as the evaluation of the potential impact based on processes that DR actions may have in the usual pattern of consumption of industrial customers. In addition, the potential environmental impact related to the use of DR is also quantified taking into account the carbon footprint of the replaced generators.

The tool provides an innovative approach to the customer flexibility evaluation throughout a detailed analysis of customers' DR potential. This "processes approach" analyses the impact of the proposed DR actions at each individual energy consuming process in the manufacturing course. Instead of simply assessing the impact of a given DR action in the total energy demand of the customer, the effect of different DR actions is studied in every superposed process, thus contributing to fill the gap in consumer knowledge on load management.

Finally, the tool has been empirically validated in four real industrial sites from different parts of Europe (Germany, The Netherlands and Spain). As an example of the validation process, it was presented the simulation of the participation of a paper factory in the German reserve energy market. According to the results, it was demonstrated that industrial customers can provide DR services to the power system in a cost-effective way, with significant benefits not just for the customer but for the whole power system.

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