

A Survey of Industrial Applications of Demand Response

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Abstract

Industrial consumers have traditionally provided flexibility for power systems through various Demand Response (DR) programs in different regions of the world, but below their real potential. Utilizing DR in industries will reduce the need for more expensive alternative forms of flexibility like storage or backup plants. In current increasingly flexible electricity market, it is an excellent chance for the industrial sites to carry out the most of energy management with DR, especially for those plants that are already equipped with the required facilities for DR, such as those with the on-site control and communication facilities (e.g., data centres), or industries with inherent capacities for DR like refrigeration and cooling systems. The main objective of this paper is to provide a comprehensive review of applications of DR in the industrial sector. On this basis, this survey firstly presents the contribution of ancillary services and their potential in industries and then introduces different types of industries with higher potential for DR programs. Finally, the main barriers that hinder the widespread utilization of these programs in industries are presented and categorized.

Keywords: Demand response, Ancillary services, Energy Management, Industrial Applications

1. Introduction

At its first introduction, Demand Response (DR) was considered as a solution to improve the reliability of the power system by actively following the supply or quickly reacting to system contingencies. Due to the advent of smart grid concept, to the increasing use of distributed generation and to the contribution of end users into the electricity market, DR is effectively considered as a new kind of resource [1].

Considering that industrial plants are extensive energy consumers having an already applied infrastructure endowed with sensors, metering technologies and personal operators, a larger amount of DR participation in this sector is expected if compared to residential and commercial ones [2]. However, based on the recent literature, it is contrariwise. This is mainly due to the fact that the industrial potential of DR is not completely comprehended, especially with regard to the emerging modern technologies in smart grids [3]. Figure 1 illustrates the following factors that lead to a potential increase of industrial DR: environmental concerns related to the increase of fuel

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consumption, reliability concerns to prevent blackouts, advancement in smart meters technology that allows controlling and monitoring responsive loads in near real-time scales, advent of aggregators that can manage smaller loads participating in power markets, and the Auto-DR promising technology.

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In some aspects, it is more complicated to implement DR for electrical loads in industrial plants if compared to non-critical loads of residential or commercial consumers mainly due to the reliability management that is more complicated for industrial plants. An interruption of service may lead, in fact, to stoppage of production and/or violate the daily operational and production constraints of the plant. In some cases, processes are indeed dependent and have correlations that make them hard to isolate, interrupt or shed separately. Moreover, in some other changes materials should be stored for every process interruption and this operation is costly and complex. In fact, large scale and energy demanding operations, that are generally based on a single source of demand, are potentially the best solution for the application of DR in the industrial sector [4].

Besides, many manufacturing processes are critically dependent on time and must be scheduled exactly with high timing precision. In contrast to the residential or commercial consumers, where load control in near real-time data suffices, in most of the industrial plants, monitor and control on a millisecond scale is, indeed, vital [3].

Generally, an industrial consumer manages electrical demand by utilizing distributed generation, energy storage, load shifting, interruption of noncritical loads such as lighting, ventilation, or by temporary interruption of one or more possible processes [5]. Storage devices are employed to proactively store energy to compensate for the uncertainty due to renewables sources. However, storage devices at larger industrial scales are not an economic solution, instead, DR approaches can be considered in order to provide flexible load solutions to increase renewable resources exploitation and reduce costs related to energy consumption.

Recently, some review articles in different areas related to smart grids and DR have been published [6-13]. In [6], some developing technologies, like smart metering, energy control and communication systems are introduced by analysing real industrial case studies. In [7], four major aspects of DR including programs, issues, approaches and future extensions are surveyed. The means and tariffs that the power utility takes to incentivize users to reschedule their energy usage patterns are described. Then, the existing mathematical models and problems are analysed followed by the state-of-the-art approaches and solutions to address these issues.

In [8], various DR schemes and programs are classified according to their control mechanisms, the motivations offered to reduce the power consumption and the DR decision variables. Various optimization models for the optimal control are also categorized based on the target of the optimization procedure.

DR is investigated as a way to plan and schedule the operation of renewable energy resources [9] and a comprehensive cost/benefit evaluation of DR is also reported. In addition, several assessment methods in combination with impacts of DR on electricity prices are presented.

A review of DR is presented in [10], including the existing applications and a possible implementation strategy in smart grid environments. Furthermore, classification and status of DR programs in different U.S. electricity markets have been also discussed.

Possible business models for energy efficiency and DR providers in different electricity market segments are analysed in [11]. The analysis covers three types of characteristics: Demand Side Management (DSM) transaction characteristics, renewable energy correlation and load control characteristics.

DR modelling approaches and their impact on operations and outcomes of home energy management systems are surveyed and analysed in [12]. An outline of the impact of policy and regulation changes, electricity market enhancements and technical advancements on DR participation is provided in [13].

In general, the previous review papers mostly refer to DR in residential or commercial sectors and in some of the mentioned papers only few articles focus on DR in the industrial sector. Nevertheless, implementing DR in industries is a more challenging task and careful knowledge and attention are needed. In addition, it is necessary to understand the importance of ancillary service programs more than ever before as they are able to add higher flexibility into the smart grid. On the other end, due to an increasing level of renewable power penetration into the grid, it should be useful to provide ancillary services making also the use of DR where industrial consumers may play a central role.

In order to clarify the difference between this study and the reported surveys, Table 1 and Table 2 are presented. Table 1 summarizes the main objectives of the survey studies, and Table 2, categorizes the scope of these surveys.

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By investigating previous surveys, they are mostly classified in the four main categories as presented in Table 2. Categories 1 and 4 are not in the scope of this paper. Regarding category 3 that is about barriers and issues, in [7], some DR issues are mentioned that are specifically related to residential consumers, and in addition, it is not considered general and applicable for all cases.

Regarding category 2, for market approaches, in [10], an overview of the status of DR participation for some well-known markets in the U.S. is presented. Ref. [13] analyses the changes in power markets that have led to an enhancement in DR participation. Therefore, there is a gap found in the area of assessment of the required characteristics of suitable loads and their potential for DR programs in different power markets. Therefore, in this paper the focus is mainly on analysing industrial loads' characteristics and their potential for participating in different kind of ancillary services.

Another major contribution of this paper that is not addressed in other surveys is to present a complete review on introducing different types of high potential industries for DR. The specifications of suitable industries, their potential for DR, the economic and in some cases technical evaluations of applying DR and the way DR is applied in these industries are reviewed in this paper.

The remainder of this paper is organized as follows. In Section 2, the participation of industries in ancillary service programs are reviewed. Several types of industries attending in DR programs are surveyed in Section 3. In Section 4, a summary on classifications of dominant barriers to industry sector participating in DR is presented. Finally, Section 5 is devoted to conclusion remarks.

2. Industrial sector participation in ancillary service programs

Most industries that take part in DR programs are participating through ancillary services programs; due to the importance of this topic in DR for the industrial sector, a survey of the industrial sector participation in ancillary service programs will be presented in this section.

Ancillary services are known as services and actions that are essential in supporting a reliable, secure and a high-quality power system. By increasing the level of renewable resources penetration into the power grid, additional ancillary services and grid flexibility is needed more than before. Moreover, the retirement of old generators and increase in their operating cost lead to an increase in load participation for providing ancillary services. To this end, advancements in real-time communication technologies and automatic controls help to increase the participation of smaller loads that are suitable for providing frequent and instantaneous DR [14]. While the potential of loads for ancillary service is huge, currently, DR resources are only minor players in most ancillary service markets [15].

The major differences between traditional applications of DR and DR for ancillary services are the reduction of notification time and more complicated technical requirements in terms of speed and accuracy of measurements. Additionally, ancillary services are typically needed year round not just during peak hours and requirements vary by location and adoption of different technologies; for example, in some regions regulation is needed more while in other regions spinning reserve is in greater need. While ancillary services require small amounts of energy, their real value is in the large capacity that should be held in reserve to be capable of reacting reliably and quickly when needed [15]. One possible way to evaluate and estimate loads for ancillary services is by using power system models to obtain optimal economic operation by means of security constrained unit commitment and security constrained economic dispatch processes [15].

Based on the mentioned differences between a typical DR and DR used for ancillary service, it has to be mentioned that when DR tends to participate in both the energy and ancillary service markets, its load control strategies are quite different. In order to participate in the ancillary services market, the electrical load needs to be dispatched more frequently and accurately while participants of energy markets are considered for load curtailment only for infrequent, peak periods [13].

The classification for ancillary services is different between countries due to nationwide regulatory concerns and these services are not treated equally all over the world [16]. Some of these different classifications in the literature are summarized in Table 3. For example, the commission of federal energy regulatory (FERC) in U.S. identifies almost seven different ancillary services in the U.S. [17]. Contrariwise, some other reports include ancillary services like frequency control inside balancing markets [18], or in Nordic countries, tertiary frequency regulation is related to balancing markets [19].

"See Table 3 at the end of the manuscript".

Different types of ancillary services can be identified by their physical characteristics such as the speed and duration of response or frequency of deployment [20]. Table 4 presents a classification based on these specifications. In addition, Figure 3 shows time and duration characteristics of ancillary service programs. As shown in Table 4, contingency reserves (spinning and non-spinning reserves) are deployed very fast, a few seconds to a few minutes for as often as every couple days or as seldom as every couple hours. The average response duration is 10 minutes

and usually not longer than 120 minutes. Instead response for regulation is needed as fast as about 1 minute and is called based on random unexpected deviations in scheduled load. On this basis, ancillary service programs usually are more suitable and preferable for retail customers and smaller loads that find frequent and short curtailments more appealing than infrequent and long ones [15]. Based on their different characteristics, ancillary service products are valued differently in the market. Regulation and spinning reserve are two of the most valuable ancillary services. For reference, non-spinning reserves tend to be about 7% to 50% of the value of spinning reserves, depending on the ISO (Independent System Operator)/RTO (Regional Transmission Organization), and replacement reserves are less valuable than non-spinning reserves [21].

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Most of DR resources are technically able to provide ancillary services. Moreover, in some cases, they act better than generators since load curtailment is usually much faster than ramping thermal power plants. When loads provide ancillary services, the capacity of generators can be free to provide energy. In addition, when generators keep some of their capacity in order to provide ancillary services, there would be a fuel consumption penalty due to the lower efficiency and also non-steady-state operation in the case of regulation. Moreover, more units may need to be committed and online, that leads to higher marginal, start up and shutdown costs [15].

Some loads have special capabilities that enable them to provide ancillary services, like facilities or processes that have sufficient storage capacitance or fuel-switching capability to provide frequent, short interruptions without adverse effects. These loads include industrial batch processes like smelters, refrigerated warehouses, electric water heaters, dual-fuel boilers, water pumping, and compressed air processes. The mentioned storage can be in the form of thermal or cold storage (like space heating and cooling inertia, hot water reservoirs) or product storage (like stockpiling manufactured or process products or water for irrigation and wastewater treatment) [22]. Some loads show special attributes for particular kind of ancillary services e.g. the ability to have a fast cycle on and off, natural repetition, high level of availability and sectional distribution [23]. Flexibility is correlated to the load's operational attributes and limitations. The availability of DR for ancillary services can be changed according to seasonal and weather changes. A brief description of each type of ancillary services is given in the following.

2.1 Regulation

Regulation is defined as a very fast and accurate control or capacity service that provides near real-time continuous balancing of generation and load in normal conditions. DR resources that provide regulation services are authorized by the ISOs to change their output in order to follow an automatic generation control (AGC) signal of the system operator's energy management system. In some ISO/RTOs, regulation is divided into separate up and down products. DR resource in this case is asked only to provide a deviation from its normal operating point in one direction. However, in some markets resources can bid asymmetrically, which is preferable for loads.

Although regulation is always the most expensive ancillary service and therefore the most financially rewarding service if a load provides this service loads usually prefer to have less frequent interruptions. Therefore, only the loads which have special characteristics like the ability to be quickly cycled on and off tend to provide regulation [24]. In this service, providing a long time load curtailment is not required. A load with large adjustable speed drives

(solid state control) is a suitable resource for implementing the regulation. Smelting pot of aluminium is electronically controlled and can precisely track automatic generation control signals. Therefore, it is considered as a suitable resource for providing regulation and spinning reserve [24], [25].

The load may be considered as a preferred regulation resource if it causes little incremental cost in order to be ready to respond. These extra costs consist of the investment cost for preparing the load to be able to respond, the efficiency losses for process control and the opportunity costs related to production reduction and/or schedule changes. Some large industries in U.S. that have a high potential to supply regulation are induction and ladle metallurgy furnaces, air liquefaction, gas and water pumping, electrolysis (aluminium, chloralkali, potassium hydroxide, magnesium, sodium chlorate and copper) [24].

Regulation is not only the most expensive ancillary service, but also the most complex one from the communication and control point of view as it should continuously respond to the power system operator's AGC signals [24].

Thermostatically Controlled Loads (TCLs) e.g. air conditioners, heat pumps, water heaters, refrigerators and freezers have a great potential for providing the regulation service. TCLs must meet the following requirements in order to be able to supply regulation service. Firstly, there is a need for telemetry and metering. Second, a minimum available power is required in some markets in order to be able to participate in the frequency regulation market. Even if load aggregation is a solution, it must be mentioned that in some markets this aggregation is not allowed in ancillary service markets. Third, the resource should follow the constraint for minimum continuous energy delivery time. Fourth, minimum performance threshold of tracking accuracy (in some markets of e.g. 50%) for both regulation up and regulation down measured monthly is required. If a resource fails to meet this threshold within 90 days another authorization is required from the ISO. Fifth, the participating resources are required to ramp to their maximum capacity in a specified minimum time (e.g. 10 minutes).

Even if passing most of these limitations can be easily achieved by considering an aggregation of DR resources, for engaging more loads to participate these limitations should be relieved.

In [26], a cost and revenue analysis is carried out to estimate the potential of employing a practical centralized control framework for providing regulation by using TCLs. Based on the need of the operator some of the TCLs must be turned on (or off). The mentioned control framework sets a priority to turn on (or off) TCLs. The unit with the highest priority will be turned on (or off) first, and then units with lower priorities will be considered in sequence until the desired regulation is achieved. On this basis, this priority-stack based control strategy minimizes the on/off switching actions for each unit, which decreases wear and tear of the mechanical equipment. This study reveals that the potential of TCLs in California is more than enough for both current and predicted near-future regulation requirements. In addition, it is concluded that the potential revenue of air conditioners and heat pumps is highly sensitive to weather.

Similarly, in [27] a real case study of DR implementation for frequency control is suggested which is in agreement with suggestions proposed by the European Network of Transmission System Operators for Electricity. Such a control strategy is designed for supporting primary frequency regulation by means of TCLs, e.g., refrigerators and water heaters. The rules designed by the European Network of Transmission System Operators for Electricity for autonomously controlled TCLs are that if the grid frequency is within a band around the nominal frequency, the

thermostat logic will not be adjusted. But if the grid frequency exits from that band, the temperature set-point is changed according to the frequency deviation. On return to normal conditions a random time delay of up to 5 minutes must be considered.

2.2 Contingency reserves (spinning and non-spinning reserve)

By definition, spinning reserve is a fraction of the unloaded capacity of generation units connected or synchronized to the grid to be ready for delivery in 10 minutes and the non-spinning reserve is the capacity that can be potentially synchronized and ramping to a specified load within 10 minutes.

The capacity of resources that is taken into account for providing spinning reserve is usually much larger and called less frequently than those required for regulation services. The response in case of contingency reserves must be fast, even if an immediate response is preferred, full response within 10 minutes is acceptable.

Loads and processes that require no notification time to response are best resources for providing contingency reserves. Good examples are thermal loads, air compression, water pumping and some other loads with inherent storage capability and that in most cases do not need advance notification for their response.

In [4], some industrial processes consisting of chloralkali electrolysis, aluminium electrolysis, cement mills, wood pulp production and electric arc furnace are investigated in terms of their economic profit of providing non-spinning reserve capacity in power markets. The results showed that these processes are capable of providing roughly 50% of non-spinning reserves for the balancing market in 2020. In another study [35], spinning reserve is provided by employing smelting plants. The smelter can supply spinning reserve to the power system when its power consumption is higher than its lower bound.

While some loads (e.g. thermal loads) instantly provide a full response, for some other loads it takes the time to go through shutdown procedures due to the delay to operate their control devices, like relays or valves. In these cases, this kind of loads must meet ISO requirements for a full response within 10 minutes. Moreover, the ISO has some time limitation for restoration time that must be met by responsive loads. Although these rules generally relate to the time when generators were the only available resources and even if thermal generators usually need more time between their shut down and start up in order to prevent damage, these time requirements are easily achieved by many loads due to their inherent storage characteristics. On the other end, meeting restoration time requirement is especially vital for loads with limited storage capacity since they must return to service as quickly as possible after a contingency event in order to be available for other probable contingencies.

The cost of spinning reserve is defined based on a resource opportunity cost, as any capacity that is considered as a reserve cannot participate in markets [14]. The probability of using load to respond to this service is usually very low. For example, the need for contingency reserves (spinning, non-spinning) in some ISOs is near 5% to 7% of load, of which half is usually devoted to being spinning. Customers in most cases tend to offer their capacity to the operator in order to be curtailed under special circumstances, thus they are not generally interested in frequent load curtailments [14]. In addition, the customers get more financial rewards for supplying spinning reserve since the price of this service is higher. The opposite case is true for generators since they tend more to supply non-spinning and replacement reserves rather than spinning reserve as these services are slower and therefore easier to provide by generators [22].

The basic idea of providing spinning reserve by responsive load is to rapidly curtail load as a response to any emergency signal, maintain this situation until the time next category of reserve (10 minutes non-spinning) is ready and restore the reserve (load) as rapidly as possible to be ready for the next contingency [22]. For these actions, loads are needed to have storage and control capability. Moreover, communication and monitoring systems are required for observing the reaction and situation of responsive loads. The additional cost for communication and monitoring systems and the amount of payment for supplying spinning reserve can be reduced if loads with an inherent control and monitoring capabilities are chosen. In addition, if loads that are already considered for load curtailment are used for spinning reserve even more reduced costs can be achieved [22].

Costs of providing spinning reserve by loads usually starts low but rises dramatically after the inherent storage is terminated. As a reference when considering cold storage systems, when the temperature reaches a point that is risky for the materials damage it would cost a lot. While for generators it is contra-wise, since the cost is roughly constant after their start up.

2.3 Replacement Reserve Service

Replacement or supplemental reserve must be synchronized and ready for providing power to the system within 30 minutes. Therefore, generally those loads that are able to respond within a 30 minute notice are able to provide this type of reserve. In some ISO/RTOs this service is not available. Although this type of service has slower response time it is usually required for longer periods. As its name shows, it is typically used to supplement or replace spinning reserve in restoring system frequency and stability. Replacement reserves include a broad range of resources, response times and durations, and they can be activated both automatically and manually. Like spinning reserves, replacement reserves are required less frequently but must be reserved through beforehand capacity payments to be available at any time on short notice.

Telemetry and minimum size requirements, that were two main barriers to an increased load participation in ancillary service markets, are significantly lower in this service [14]. Therefore, these services are more easily available by most types of DR resources.

2.4 Opportunities and challenges of providing ancillary services by DR

The UK was one of the first countries to take advantage of loads for providing ancillary services [14]. This early participation was due to their market structure and reliability rules that were developed in such a way that both loads and generation resources could easily achieve them. As mentioned before, some of the requirements for participating in ancillary service market are very old and must be revised as they were established when generators were the only resources in the power system. ISO/RTOs must find ways to change the ancillary service product requirements such that the quality of the service is maintained but the pool of resources that can provide may be expanded to include DR.

Another successful country for engaging load participation in ancillary service market is U.S. In U.S. the platform named the Green Button initiative helps customers to share energy data [13]. The customers can easily and securely access to their energy usage information in a consumer and computer friendly format. Other countries can develop this kind of database in order to ease energy monitoring and make decisions about market participation.

Moreover, in order to encourage more participation of responsive loads in ancillary service markets, governments should create technical standards to ensure the compatibility of DR technologies and devices and encourage aggregation to scale up DR and minimize risks. In addition, system operators can play a crucial role in order to behave like a coordinating agency that influences the opportunities for loads to provide ancillary services since they are responsible for developing and interpreting reliability rules and operating protocols. Finally, regulators and other policymakers can also address business model concerns and find possible ways in order to ease the process of this participation [15].

3. Type of industry

The objective of this section is to briefly introduce and then classify the type of industries that implemented DR programs. A summary of this classification is presented in Table 3. Based on the literature, dominant industries that have applied DR are cement, metals such as aluminium and steel, and refrigeration for the food industry.

"See Table 5 at the end of the manuscript".

On an individual plant, dominant electricity consumer processes or equipment are machine drives, electrical heating and electrochemical processes [3]. These processes and equipment can be mainly categorized into production and support services. The first category refers to those process or equipment that are part of the industrial process itself like furnaces, pumps, motors, etc.; the plant production would halt without power to these loads. The second category refers to those loads that are not required for production directly, but they are used for site personnel such as lighting, cooling, heating, ventilation, and office equipment. Implementing DR for supporting loads is more easily achieved as more flexibility they have. These second type of loads account for a small amount of the total consumption; for instance, with regard to chemicals and primary metals, around 12% and 8% of whole electricity is used for support services respectively [3].

Some industrial processes have serious sequential relations. Therefore, for scheduling purposes, careful attention and knowledge about their correlations as well as their roles in the overall production is inevitable [3]. A more detailed description of the processes and the methods that are presented for DR implementations in each of these dominant industries is described in the following.

3.1 Metals: aluminium and steel

Electrolytic aluminium is a significant industry for DR implementation or energy saving. Figure 3 illustrates the amount of electricity consumption of processes from mining to electrolysis in a typical aluminium production industry [28]. As shown, electrolysis is considered as the dominant electricity consumption process of producing aluminium.

"See Fig. 3 at the end of the manuscript".

Aluminium smelting is based on an electrolytic process for converting alumina to aluminium that is considered as the primary material for a vast majority of industries from car making to packaging can industries. Smelting consumes approximately 46% of the total energy consumed in U.S. manufacturing of aluminium. In a common aluminium smelter, 30% to 40% of the total cost of producing primary aluminium is devoted to electricity costs [24], [25]. Compared with cement or steel manufacturing, it has a fairly simpler production process. One of its

energy intensive processes is aluminium smelting pot; indeed, a good potential for DR is primarily found on the pot line. The smelting pot is electronically controlled and could precisely track automatic generation control signals [24].

Aluminium smelting takes place in pots, where a DC electric current is passed through a cryolite bath in order to separate the aluminium from the oxygen and remains the molten metallic aluminium at the pot bottom. Aluminium oxide and electric current should be added continuously and aluminium metal is periodically extracted. Typically, smelting pots are operated at high direct current, as much as several hundred thousand amps, and very low voltage, often below 10 volts. Potlines usually consist of hundreds of pots that are operated frequently to form a connected series load. Total power consumption for a potline can reach to as much as hundreds of MW's and a smelter may consist of multiple potlines [24].

Aluminium smelting pots operate at very high temperatures to maintain the aluminium that is produced in a molten metal form. The huge energy intensity of 15MWh for every ton of aluminium is required for starting the smelting process up to the right temperature. During the operation, thermal balance, which is essential for the proper pot operation and can modify the power consumption, is achieved by regulating the input voltage of each pot [4], [24]. Indeed, the power consumption of a pot line can be adjusted by changing the output voltage of the rectifier that supplies a DC current to the pot line. By doing so, the power consumption rate can be adjusted very quickly (within seconds) and accurately. In cases when the load reduction takes longer times, a recovery period should be defined in order to reach to previous normal or above normal specifications. Each pot has a large amount of thermal mass with a multi-hour thermal time constant that allows for instantaneous electric power variations that do not greatly impact the pot thermal balance. However, average power over a few hours would be critical.

Another way to achieve power consumption flexibility and generate a larger amount of power change within a short time is to shut down an entire potline by switching a breaker. The smelter's flexibility enabled in this way makes aluminium smelting an ideal DR resource [25]. In that case, the duration of an interruption is more critical and can be sustained only for short periods, based on the particular plant restrictions. The interruption on a single potline may last from minutes to about two hours. Facilities with multiple potlines can rotate this interruption from line to line, enabling a longer total interruption.

Based on the above explanations, aluminium electrolysis is categorized as a suitable process for load shedding rather than load shifting in DR programs, since the utilization levels for this process is seen to be 95-98% annually. Based on experiments the power demands of electrolysis process are allowed to be reduced by up to 25% for 4 h before an undesirable interruption occur. This amount of reduction (25%) is usually sold to the power market as positive tertiary capacity. The price for calling positive reserve energy in some cases is proposed as much as 1000 €/MWh, due to the high value of lost load which is defined based on the price of aluminium and the technical risks of destabilizing the electrolytic process [4].

In [25], a stochastic optimization model is considered for aluminium smelters' participation in both energy and spinning reserve day-ahead markets. The aim of this mixed-integer linear programming problem is to obtain the day-ahead bidding strategy for the smelters. The price scenarios as a representative for future prices, besides to smelting plants parameters are fed into the problem and the energy bidding curves, the optimum spinning reserve provision

and the amount of potlines' power consumption are obtained as a result of the running program. This model is validated by case studies, and the results show that by the proposed optimal scheduling the aluminium smelting plant would advantage from both electricity markets participation and aluminium production. Some of the results obtained from the bidding curves and the spinning reserve provision curves are as follows. In some hours of the scheduling day the plant is more conservative in terms of selling energy as the smelter asks for a very high price for selling the low amount of energy. Therefore, the smelter would focus on producing aluminium rather than selling energy during these hours. On the other hand, the bidding curves are more aggressive in some hours of the day in which the smelter bids significant amounts of energy into the market. Due to the higher energy prices during these hours, the smelter will be aggressive in selling energy.

The spinning reserve provision results show that the smelter has the tendency to provide more reserve when the reserve prices are higher and provides little reserve at peak hours. It is due to the fact that the smelter would sell the higher amount of energy in these hours, as the energy prices are comparably higher than the spinning reserve prices. Thus, the potlines' load during these peak hours is very low, allowing lower spinning reserve. The available spinning reserve capacity is upper bounded by the difference between the potline's loading level and its minimum loading level. In other words, if the smelter lowers the potlines' loading levels in order to sell energy, then lower amount of spinning reserve capacity would be remained.

Contra wise to aluminium industry, steel manufacturing processes are known as one of the most complicated industries to schedule. It is considered as a large-scale, multilevel, and multiproduct industry which consists of parallel tools, complicated processes and energy limitations [29]. Figure 4 shows a simple diagram of steel supply chains. In this Figure, the most energy intensive process which is the melt shop is bolded with a red line. Melting scrap steel is a large energy consuming process for producing steel. The energy intensity of the process is measured at nearly 0.525MWh/t of steel produced [4]. In this process, heat is generated by an electric arc furnace or by means of induction, which let the scrap metal start melting in the furnace. Although the process is able to halt instantly, the melting process has to resume again if the disruption exceeds half an hour, since the scrap metal begins to cool down after that. Extra costs would emerge if the process is disrupted for longer than half an hour. It is reported that melting scrap steel in this process lasts approximately 45 min and near 15 min to fill the furnace again for another round. The factory can halt the process entirely in order to sell the contracted power on the spot market or on the market for regulating energy. As mentioned in this report, up to the year 2011, approximately 50% of steel mills in Germany have pre-qualified their furnaces in the tertiary reserve market as positive capacity. Capacity prices tend to be reasonable and lower compared to prices of reserve energy, and this is based on the high value of lost loads in this process [4].

"See Fig. 4 at the end of the manuscript".

Ref. [29], presents the scheduling problem of a steel plant by considering energy constraints. The suggested optimization model follows pre-contracted load profiles of a steel factory with the real energy and power consumption. The consumer will be penalized for under and overconsumption. It is shown that electricity cost minimization leads up to 12% savings in high capacity operation and up to 52% in low capacity one. In another study [30] an optimization framework is presented to consider different load characteristics of a steel mill industry.

These characteristics include interdependency between industrial units, multiple days, size and number of cycles, sequential operation, and simultaneous management of energy and material flow. The optimization is also carried out under different tariffs and in each case the results lead to higher profits. As an example, the enhancement is 45% under inclining block rates and 10% under TOU pricing. This improvement is based on not only optimization of power usage, but also optimization of material usage and the quantity of final product in this study. Therefore, different optimum energy usage levels are attained based on changes in pricing scenarios. Increases in scheduling horizon will also lead to increase in total profit as it becomes more time flexible. On the basis of the results in this case, the improvement in TOU pricing is over 50%, under CPP is around 40%, under day-ahead pricing is over 20%, and under peak pricing is over 10%. In this study it is concluded that for industrial units a late CPP warning is often very costly and that's because the industry consumer doesn't tend to change its operation in a short notice. In another consideration in this study, the duration of batch cycles is considered as variables in the optimization problem that will lead to additional load flexibility and increase in profit. The numerical results show that the total energy consumption under fixed and variable batch cycles is 6.67 and 5.85 GWh, respectively. As a result, there is an increase in total profit as well.

3.2 Cement

The cement industry is one of the major consumers of energy, since it annually consumes over 350 trillion Btu of fuel and 10 billion kWh of electricity in the U.S. [31]. As the cement industry is energy intensive, demand management for this industry is not a new topic. A report conducted in the state of California (1977) about electricity pricing examined the effects of multi-level tariffs on cement plants. Two cement plants, one in England and one in France cut their daily peak demand by nearly half for higher price hours. In Mexico and Latin America, cement plants reduced their consumption during peak hours.

The electricity cost in a typical cement plant approximately consists 30% of its total cost [32]. A simple diagram presenting different processes in a typical cement plant is introduced in Figure 5. In this Figure, the most electricity intensive processes are bolded with a red line. In addition, Figure 6 roughly shows the share of electricity consumption of dominant processes in a cement plant for wet and dry process cases. A massive potential of DR in cement plants is found in the huge grinding mills; especially in non-continuous processes like quarrying operations, raw mills, clinker mills, and fuel mills. If considering not only electricity consumption but energy consumption in general, including other fuels, then kiln would be the dominant energy consumption process. Electrical loads which are related to the kiln system including drives, clinker cooler, material transport to and from the kiln, fans and filtration system cannot be stopped or shifted without loss of product or damage to the kiln. Therefore, the kiln is a process that has to work continuously without interruption, otherwise the production process would stop.

"See Fig. 5 at the end of the manuscript".

"See Fig. 6 at the end of the manuscript".

In [4], estimated installed capacity of all cement mills in Germany (up to the year 2011) is reported to be 314MW with an average exploitation level of about 80%. In addition, energy intensity of cement milling in this study is stated 0.1 MWh for every ton of cement produced. Normally, a typical mill would be sized for 20 hours/day of operation, while some of them are sized to work 16-18 hours/day in order to be more flexible to turn off during

higher prices. Regarding suitable DR programs for this industry, since the characteristics of every cement plant is particular, useful DR strategies vary from one site to another [4]. In general, cement plants potential for DR is to some extent reliant on the amount of present storage that can be employed in different processes. Plants with less amount of storage capacity do not have as much flexibility for shifting load. As an example, if cement mills or raw mills have smaller size compared to the kiln capacity, then the continuous operation of them during peak cement season may be needed to prevent lagging the entire cement making process; therefore, they cannot easily participate in DR programs [31]. In general, in a cement plant during the production process, only the kiln must keep running continuously; while if financially advantageous the operating time of raw mill, coal mill and cement mill can be adjusted as required. Based on Figure 6 these adjustable processes account for 60%-70% of the total electricity consumption of cement production.

Worth to mention that, although mills are suitable for DR purposes, but the mills performance are the most efficient for steady operation, so for efficient load shedding the financial incentives from the utility must outweigh the cost of stop and start of mills, both in wasted product and operator time if applicable [31].

As for some of the previous analytical statistics for cement plants participation in DR programs, in 1992, Lafarge's Whitehall, cement plant took part in some power system's interruptible programs and was able to reduce 20% cost of its electricity. A few years later, by acquiring its newly bought diesel generators in order to provide some of its demand onsite during a curtailment, power costs were reduced by over 40% compared to 1991 electricity costs. Another possibility for participation in DR programs is available for some cement plants that produce multiple types of cement. In these sites grinding varieties of cement with lower grinding energy requirements during peak hours is produced which leads to energy savings without decreasing product output [33].

In Indonesia (1997), a cement plant case study is reported with a high capacity of cement mills, that by proper scheduling, all of their finish grindings occurred during off-peak hours. The plant estimated savings of over one million dollars per year in energy costs [34]. In response to rolling blackouts in South Africa, a study regarding to the possibility of load shifting at cement plants was carried out, which investigated raw mill usage of a cement plant during several months and concluded that the raw mills could be scheduled to shut down during peak hours; This action would save 9 MW of on peak power without any reduction in daily plant output and would save approximately \$100,000 annually in energy costs [35].

According to the aforementioned potential of cement plants for DR and the studies in this area; characteristics of cement plants for DR is also evaluated in [31]. Factors analysed for this purpose include the characteristics of various equipment and processes, the operational constraints and the amount and type of energy sources. The ability to load shifting in these plants is mainly influenced by the automation level, scheduling and the storage abilities at each step. The technical possibility for Auto-DR implementation is also assessed and the results reveal that the program success is reliant on the level of controls and automation that exists at the site. Results also show that in the case some loads are not critically dependent on production, e.g., compressors, lighting or raw material stockpiling, Auto-DR would be beneficial. However, initial feedback from plant personnel indicated that cement plants may be hesitant to allow an outside source controlling the shutdown of their equipment, particularly in periods when they

have a high demand for their products. However, for critical loads like motors, a manual DR strategy would be more rational.

3.3 Refrigeration

Cooling and refrigeration is another major sector that has satisfying returns for DR implementation. In these processes for shifting and regulating the power consumption of cooling, thermal inertia is used like a buffer [4], [36]. Since industrial cooling and refrigeration warehouses usually have centralized control systems and energy efficiency measures, they have the potential for Auto-DR. In Auto-DR, Open ADR (Open Automated Demand Response) protocol is employed for continuously communicating signals over the internet in order to allow the facilities automating their DR [37].

Refrigerated warehouses are good candidates for DR implementation since they are large consumers of power especially during peak periods; based on a study [26] these loads account for nearly 16% of total consumption of food industry. Moreover, since these processes are not sensitive to short-term load curtailment, due to the inherent thermal inertia of loads, DR activities do not affect most of them. In addition, processes in this industry are simple and easy to understand [37]. Some applications of refrigerated warehouses provide storage in cold and frozen areas that are used for refrigeration of commodities and buildings services [38]. In addition, electric defrost is another major energy consumer in this industry. Figure 7, illustrates the dominant processes and the share of each process in total energy consumption of a typical refrigerated warehouse.

"See Fig. 7 at the end of the manuscript".

In [37], assessment of DR abilities of two refrigerated warehouses case studies and nine other facilities in Pacific Gas and Electric territory in U.S., is carried out. Based on a report in 2008, the total power demand of refrigerated warehouses in California was 360 MW and estimated DR potential for this industry was 45–90 MW. Although not all the consumers participated in these predicted DR programs and the real result showed much less than this amount. The strategies for increasing this level of participation is reported to be improving the market, applying Auto-DR instead of manual DR, and giving higher incentives to consumers for their participation.

One of the case studies (Amy's Kitchen's Santa Rosa facility) includes several bulky cooling rooms, freezers, blast freezers and a spiral freezer. Altogether, the facility's electrical end-use applications have an average aggregate baseline demand of approximately 1,600 kW with a peak demand of 1,900 kW, of which nearly 12% was accounted for by the spiral freezer alone. Besides to these cooling loads, these amounts of power usage consist multiple heating, ventilation, air-conditioning (HVAC) and lighting loads. There was an upgrade in control systems in this plant for the purpose of Auto-DR. By participating in Auto-DR programs the facility attained about 580 kW, approximately 36% load curtailment and achieved \$139,200 as incentive payments based on projected load curtailment, and potential additional incentives for future events, and showed a payback period of less than one year.

A cold storage food distribution centre is another case study in this report. Total power demand in this site ranges from between 700 to 900 kW that the freezer accounts for 30 and 40% of this amount. Based on the stable loads like freezer and HVAC systems in this site, it was estimated that this site is well-suited for an open Auto-DR. The results showed that on average the load reduction was approximately 25% (more than 200 kW); and in some other special cases, the load reduction was as much as 330 kW (41% of the baseline). In this load reduction, turning off the air

handlers in the freezer had the largest impact, but adjusting the set-point on the HVAC system led to a load reduction of around 25 kW.

Other nine industrial refrigerated warehouses as case studies participated in Critical Peak Pricing (CPP) program for load sheds and load shifts. The power consumption of these facilities was ranged from 150 kW to 1.3 MW. Most of the sites showed a typical load reduction of about 20-40%. At most of the facilities the type of DR was a load shifting rather than a load shedding. However, over the entire 24-hour period, most sites had an energy consumption of lower than or equal to their base loads. This reveals that DR in refrigerated warehouses is not at the cost of energy efficiency.

In [39], an efficient and modern cold storage warehouse is considered as a case study. This site is integrated with a wind generation system. The purpose of this study is the assessment of the effects of DR implementation on the amount of wind energy usage. A precise correlation has been observed between electricity price reductions and demand shifting to low price times on one hand and the amount of consumer's consumption from wind generated energy on the other hand. In addition, the seasonal effects on the real-time prices, and the application of a regular email information service by power supplier are also reviewed and investigated in this study.

It is concluded that this refrigeration warehouse has an extremely flexible load profile shape. In order to analyse the potential for DR, the electricity consumption profile of this medium voltage consumer was investigated for one year.

In [40], an experimental study uses a bottom-up approach based on interviews to analyse DR opportunities for refrigeration systems in Mannheim, Germany. The interviews were held among chosen plant operators, research institutes, equipment manufacturers, industrial associations and the statistical offices and administrations. The information for refrigeration loads in this study is not only related to the industrial sector, but also to the residential and commercial sectors. Estimation of the theoretical and the attainable potential for DR participation is achieved to be about 4.2 and 2.8 GW, respectively. This is almost 4–6% of the peak demand in Germany.

Different operation modes of refrigeration systems and the limitations on regulation are also analysed. Some strategies for load shifting like pre-cooling and post-cooling are proposed in these systems. Another solution for limitless time-based shifts in the operation of the facility is that of taking advantage of the thermal inertia of cooling systems. Other effective actions to have a flexible capacity include the optimization of the efficiency of cooling facilities and their insulation, as well as their regulation.

This report also reviews some barriers that prevent the rapid approval of load management policies for cooling and refrigeration systems. Some of these barriers include lack of knowledge and technical experience, an inadequate motivation for participation since the inadequate rate of return and organizational barriers, severity to comply with legal cooling needs, liability concerns regarding product preservation and probable damage to refrigeration devices.

Another major application of cooling systems is considered in the meat industry. In [41] the flexibility potential of consumers in this industry for DR program participation by interrupting the electricity of cooling systems is analysed. A case study that is a factory for producing cured ham in Spain is selected for validating and analysing the effectiveness of the presented solutions. For a typical meat production plant, freezing lines, preserving lines, air conditioning lines and drying lines are four basic types of circuits for cooling lines.

These cooling systems take advantage of the thermal inertia to keep both temperature and humidity within satisfactory ranges. A remarkable curtailment of the peak power, over 50% of the total plant power, is achieved. This reduction is easily achieved without disturbing the quality of the final product. By applying DR programs in this site, an amount of 43,114 kWh could be saved annually. As analysed, such energy savings would lead up to a 13.8% reduction in the process cost, or 0.6% in the total cost of the plant.

Although this amount of savings is not a strong incentive for customers to apply DR, a reduction of 60% in the electricity demand of the process which is nearly 7% of the total electricity demand of the plant can be obtained. This power demand reduction could lead to significant savings if offered as a DR in operation markets.

In the order of simulation results, some methodologies are applied and the results are as follows. Power peak reductions are assessed to be about 23% of the total demand of the factory. This means that savings of 338 kWh can be achieved for one, or a reduction of 3.6% in the consumption of the process and 1.2% in the total electricity consumption of the factory on a working day. This amount of load reduction will lead to a total potential of 52.6% when applied to the whole plant. This means that the mentioned cooling system represents 37% of total power consumption (or 31% of total cooling).

Moreover, in the case of assuming real electricity prices, as well as CO₂ emission factors annual savings of 396 ton of CO₂ and 4.9% in the total cost of electricity are projected.

In [42], case studies, such as refrigeration system and chiller systems, combined with ice reservoirs, are used to analyse the performance of a proposed three-level hierarchical structure controller. The system includes a set of aggregators and a controller at the grid operator level. Based on a contract agreement, each aggregator is asked by the top-level controller to follow a specified power during an activation time. Similarly, the aggregator is given a permission to send power references to the consumers. An optimal controller is considered at the top-level which receives cost and revenue profiles. Based on this information, the optimal power distribution is proposed.

3.4 Other industries

In [43], a case study for DSM is presented for oxygen manufacturing facilities. The oxygen generation facilities in this study are assumed to consist of an oxygen generation plant, an energy storage system, a solar and a schedulable energy generation system. These facilities are needed for processes like steel and glass manufacturing and wastewater management. In this study, an objective function is determined in order to minimize the total energy costs of the mentioned units. The objective function consists of the cost of electricity, the cost of raw materials for electricity generation and start-up and shut-down costs of schedulable energy generation systems. The approach, which is based on day-ahead electricity prices, determines the planning for schedulable tasks and distributed energy resources in order to shift demand from peak times to off-peak times. The results for total energy costs for fixed price equals to \$10842 and for hourly electricity price is \$10594.6. Moreover, total energy costs for hourly electricity prices with only ESS and with both ESS and EGS are \$10028 and \$8695.4 respectively.

In [4], the chloralkali process, which is a famous technique for chloride manufacturing, is selected for DR. Chloride is made through an electrolytic process including chloralkali dilution. The amount of chloride which was produced by this process in Germany accounts for nearly 5.1 million ton in 2005. This process has energy intensity of 2.85MWh for every ton of chloride produced. It is estimated that this process has the potential of about 660 MW

capacity (which accounts for up to 40% of the total capacity) for positive tertiary reserve capacity in Germany. But in real cases, due to the high cost of lost loads, only a minor amount of actual scheduling and physical dispatch takes place for positive reserve energy. In addition, as this process is expensive in terms of capital investment, thus it is usually operated at its full capacity for the purpose of maximum returns. Utilization levels are normally between 80% and 90%. The load of the chloralkali process can be reduced by up to 40% for maximum 2 hours. While shifting load is rarely possible in this process, since as mentioned the utilization level is high in this process.

The studies like these (oxygen and chloride manufacturing industries) show that industries including electrochemical processes have a fairly satisfactory potential for DR. Studies must be continued also to include other types of electrochemical processes. Another study that analysed the potential of a chemical industry is presented in [44]. In this study, major operational sequences of an oil refinery industry are identified and an optimization based load control framework is used to integrate its different operation sequences. Industrial load control is achieved under different pricing schemes like day-ahead, time-of-use, peak pricing, inclining block rates, and critical peak pricing to compare the results and select the best approach. At every pricing scenario, the optimal scheduling cost is lower than the base case. On average, optimal load control is capable of reducing the cost by over 14%.

In [45], the offered solutions for DR, including power quality and energy efficiency enhancements, are applicable for energy intensive industries, e.g., textile, leather, and glass. In addition, they can also be implemented in other small and medium sized industries. Moreover, assessments for the possibility of energy audits and peak demand reductions are also carried out for these industries in this study.

Another significant large consumer industry that proved to be a promising industry for DR implementations is data centres. In fact, data centres are not only large loads, but also they can provide a huge potential flexibility like expensive large-scale storage systems if suitable incentives offered to them [46]. In 2011, they consumed roughly 1.5% of the total electricity in the world, and as for their capacity, in some cases individual data centres can be as large as 50 MW, or more [47], [48], [49]. Moreover, the amount of their energy consumption is even growing, by nearly 10-12% annually [47], [48], [50]. Data centres are almost completely automated and monitored, therefore, controlling and adjusting their load is possible simply without additional costs. As a case study in [48] and [51], the flexibility of four data centres is examined under different management approaches. Results revealed that by only temperature adjustment and some other building management approaches and without changing in IT workload handling, the load curtailment of 5% was possible in 5 minutes and the load curtailment of 10% was possible in 15 minutes; while if workload management approaches are considered, it can be even more flexible, without additional time needed for the load curtailment.

The literature related to data centres' DR is scattered across multiple areas and is studied from different points of view [52]. In [52], [46], [53], [54], [55], [56], [57], [58] DR is analysed for industrial data centres.

With regard to data centres, selecting an efficient DR program is somehow difficult, because data centres have commonly significant market power. In [46], a novel pricing method based on predictions is presented which is an attractive market structure in conditions when market power is an issue. The results indicate that it performs better than traditional supply function bidding mechanism. The potential of data centre DR is also quantified through a comparison with a typical large-scale storage system.

In [52], a survey is carried out to analyse the opportunities and challenges in data centres' DR. In this study two case studies are presented in order to evaluate the effect of data centre DR as a means to voltage violation frequency reduction and optimizing operation and cost. Results indicate that the voltage violation rates decrease as data centre power demand becomes more flexible. As an example, a 20 MW data centre with 20% power demand flexibility is equivalent to 0.67MWh of optimally-placed storage in the distribution network. Based on economic criteria, by comparing the energy storage cost of typical lithium-ion batteries and flywheels respectively with a DR supplied by a 30 MW data centre it is concluded that this would have the value of \$500,000 and \$5,000,000 respectively. Thus, each data centre represents millions of dollars' worth of installed storage capacity if utilized in DR programs. As for case study 2, the potential of DR from the data centre is obtained based on a non-convex optimization framework, as a means of helping load serving entity reduce the costs of supplying demand in the presence of a large-scale renewable installation. Two data centre cases, one with a constrained baseline usage and another with an optimized usage, are simulated. Results show that data centres can provide the same service for the load serving entity as a large scale storage installation. An optimized 7 MWh large-scale storage is comparable to a 30 MW data centre, even more valuable here than in case study 1.

In [53], workload shifting and the use of local power generation are involved in two DR schemes in order to reduce a data centre's peak loads and energy expenditure. To this aim, a stochastic optimization method is presented for minimizing its energy consumption and a robust optimization problem is solved in order to provide minimal worst-case guarantees. Uncertainties related to the time of coincident peak and corresponding warnings, workload demand and renewable generation are also modelled. The results showed 35%–40% reductions in energy costs, and 10%–15% reductions in emissions by applying the algorithms. In general, [54], [55] and [56] have analysed data centre participation in regulation and ancillary service markets. Finally, some other studies [57], [58], analysed the uncertain and complex nature of adding local resources like energy storage systems, renewable energy resources, and backup generators on-site; as data centres often are equipped with some of these facilities.

For a few studies in the field of industrial DR the information and calculations are presented in general and not for any specific type of industry. In [59], the scheduling plan of an industrial load is presented which is based on day-ahead scheduling and real-time operation algorithm. The proposed scheduling is based on the consideration of the electricity price and the labour costs at the same time. The policy is to shift the operation time from the contingency to the off-peak time. The considered system includes agents for managing distributed generation resources, energy storage systems, smart loads, and a micro-grid central controller to observe and control the entire system. In [60], a mathematical formulation is addressed to optimize the problem of day-ahead load shifting in a smart grid consisting of various types of industrial, residential and commercial loads. To solve the problem, a heuristic-based Evolutionary Algorithm is introduced. The results show a 10% reduction in the operating cost.

In [61], a variety of DR approaches, e.g., energy cost savings, peak load reductions and peak load shifts, are selected and employed to increase the success of the project. In these programs the entire ranges of the tariff, ranging from the existing fixed tariff structures to fairly new dynamic ones including price based signals are considered.

Another area of focus in reported studies in literature is to evaluate and then rank different industries or different processes in an individual industry for DR purposes. In order to achieve a bottom-up approach, various information

resources, algorithms, and measurements are used in [62]. This approach is used to enhance a new database which shows the potential DR resources in the industrial area in the U.S. Indeed, the industrial sector is highly heterogeneous. Over 300,000 production plants through almost 400 industrial subsectors are classified by four-digit Standard Industrial Classification (SIC) system in U.S. In order to distinguish the top 30 industrial subsectors some principles are utilized to filter the available data. The principles are applied in a cascading and parallel method. Table 4 shows some of the selected top industries with a high potential for DR. In this Table energy intensive processes for the selected industries are also introduced.

"See Table 6 at the end of the manuscript".

In [2], top industries are evaluated to determine their absolute flexibility as a function of their average demand. Although any single load may not meet the requirements for one particular DR program, all of the loads are capable of participating as part of a large network to assist in the management of the power system. The recognized DR programs are curtailment programs, frequency response, distribution and high voltage transmission relief, primary frequency response, emergency load shedding, renewable integration, and voltage control and support. The study found that there was an excess of 12 GW of DR available in a list of selected industrial facilities in the U.S.

In [4], by technical and economical process assessment, high potential processes for DR are recognized. The strategy of the proposed top-down approach for process selection is based on the processes overall potential and specific costs for energy.

A system is studied in [5] that utilizes the offline and quasi-dynamic operation limitations of the plant in order to dynamically rank loads and workstations within an industrial site as candidates for demand reduction. Then suitable workstations are selected on the basis of mathematical optimization methods and fuzzy systems. The proposed approach can also be employed in combination with other options like an on-site generation or storage solutions.

In [63], various types of loads were found to be suitable for shedding and shifting loads, e.g., conveyors, pump systems, process cooling, motors, aerators, and compressed air. In addition, the long-term objective of this report is to prepare checklists for potential Auto-DR schemes to develop an implementation plan for other DR programs suitable for future industries. Auto-DR is a totally automatic DR system that uses client and server structural design and its aim is to substitute manual labour and half-automated DR. The idea is to use signals among utilities and customer's equipment based on communication technology standards. Auto-DR was firstly utilized in the commercial sector, especially for HVAC and lighting. In 2007, this technology was employed for industrial facilities [63], [64].

3.5 Multi-energy systems

Different energy sectors have a long history in showing interactions in terms of operation and planning. These interactions are especially increasing within the last decades and even are more crucial in industries. As an example, electricity, heat/cooling and gas networks interoperate in many cases through various distributed technologies such as CHP (combined heat and power), electric heat pumps, air conditioning devices, CCHP (combined cooling, heating and power) [65], [66]. Likewise, by expanding the application of EV (electric vehicles), bio-fuels and hydrogen-based transport, interactions among electricity systems, fuel chains, and transport sector are increased as a

consequence [67]. One of the benefits of interactions among the energy carriers is that the conversion efficiency of primary energy sources is increased; also the energy system will become more flexible and optimal operation is achieved, and at the same time the consumer's participation through market interactions is facilitated as well.

The mentioned systems are known as MESs (multi energy systems), multi energy carriers or smart energy hubs in the literature. An energy hub by definition is an integrated system of units like combined heating, cooling and power systems or heat storage, that facilitates the conversion and storage of multiple energy carriers such as electricity and natural gas. For example, a hub is capable of providing its required thermal load within multiple sources like the heat from the microturbine, or from the district heating network, or by means of a furnace. This possibility of flexible operation is even increased if storing energy would also be prepared. This whole flexible system will facilitate the hub's operation in a changing situation to variable prices or loads in a smart grid [68].

A survey of the related literature of these systems is presented in [69]. While there are various studies that include a variety of topics in this regard, the studies regarding the integration of these systems with DR is evaluated in only a few studies. In [70], a novel method is presented for exploitation of flexibility in a system with multiple interconnected plant components. Economic evaluations are assessed by taking into account different energy shifting strategies.

A multi energy consumption VPP (virtual power plant) model that is integrated with DR resources is presented in [71]. In this model, EVs, heat pumps, and electrolyzers are combined in order to participate in spinning reserve. The results specified increased efficiency and added benefits to the whole power system from technical and economical point of views. Reduction in operational costs and emissions, and integration of additional volumes of renewable energy sources was another positive effect of the proposed model. In [72], [73] the integration of these multi energy systems with DR was applied for the residential sector and buildings. In [72] a predictive strategy control model is introduced for the intelligent control of a micro-CHP system in integration with DR. Simulation results showed the proposed system lowers variable costs for households by about 1%-14%. The cost reductions were highest for real-time pricing scheme. In [73], a methodology is presented in order to quantify the flexibility which is proposed by thermal storage of building stock in combination with heat pumps, to power systems with significant penetration of wind power. A model is presented in order to assimilate the building stock thermal behaviour as equivalent energy storage in the electricity market. The model allows the coupling to a detailed dynamic thermal model of buildings for the evaluation of the respective operational limitations as well.

Industrial units often have more potential for MES. As usually two or more types of energy carriers are existed and utilized in industries. In addition, heat consumptions are huge in industries, therefore a good potential for CCHP or CHP systems are primarily found in industrial sites. Moreover, they are often previously equipped with on-site facilities like micro-turbines that simplify applying these systems without additional costs.

By applying MES in industrial sites, coupling between different energy carriers enables customers to participate in the DR programs not only by means of load shifting, but also by switching the source of their consumed energy [74], [75]. In the previously defined smart energy hubs, customers are able to participate in DR programs by converting one type of energy, like the natural gas to another type, like the electricity by using some converter devices such as micro turbine or gas furnace. Therefore, from the power utilities' viewpoint, the electrical

consumption is reduced. However, from the customers' viewpoint, the electricity consumption is not changed, but the source of supplying electricity is switched to another energy carrier like natural gas [74], [75]. Therefore, this type of participation in DR programs is especially beneficial in some industries that do not tend to shift or curtail their consumption, due to the correlation of processes in their supply chain. In [74] and [75], the customers connecting to a smart energy hub aim to maximize their daily payoff, which is defined as the difference between their satisfaction level from consuming electricity and thermal power and the total energy payment to the utility companies. Results showed that by applying DR programs, the customers' payoff is increased by about 30%, and the peak load in the electricity network is decreased by approximately 40%.

In another study [68], an economic evaluation method for energy hubs with conversion, thermal storage, and DR possibility is proposed. The presented method is based on Monte Carlo simulation that calculates an optimal dispatch of the hub for different pricing schemes and the input and output energy carriers. By comparing configurations' results with a storage and/or DSM, the added value of the related investments is evaluated as well.

3.6 Remarks

Overall, some industries, such as refrigeration systems, cement, aluminium and steel, and data centres have shown high potential for DR participation if compared to other industries. Refrigeration systems are attractive for DR implementation in terms of relative similarity of the processes and simplicity of their technology. Also, aluminium industry has a fairly simple production process and, therefore, it facilitates implementing DR programs. Compared to aluminium industry, cement and steel manufacturing have more complex and intertwined processes, however they are also suitable for DR due to their massive energy consumption. On this basis, there is a reasonably valuable potential for implementing DR in these industries. Cement plants potential for DR is to some extent reliant on the amount of existing material storage at the site. Plants with less amount of storage capacity do not have as much flexibility for DR.

Data centres that are laboratories for testing applications, already consist of automated controls; therefore, they have the potential for DR and should be an area of significant attention. Reliability has an extremely high value for enterprise type data centres, but greater opportunities for Auto-DR can be found in a large number of data centres. Moreover, because of the lack of efficient large-scale energy storages, development of market programs to extract flexibility from data centres for DR participation is crucial.

4. Barriers to Industrial Demand Response

As stated in previous sections, some of the mentioned barriers will hinder widespread applying of DR programs especially in the industry sector. In this section a thorough classification of these barriers are presented. As illustrated in Fig. 8 these barriers are categorized into three groups, which are discussed in details in [76]. A summary of each of the barriers is explained as follows.

"See Fig. 8 at the end of the manuscript".

4.1 Financial Barriers

Financial barriers that hinder the use of DR in industrial facilities are as follows.

4.1.1 Lack of widespread utilization of time-based rates

Most of the customers are on retail tariffs, while time-based rates can show the timely electricity cost variations and the financial benefits of DR [77]. It is shown that time-based rates can expedite the implementation of DR programs. As a successful example in this regard, U.S. department of energy (DOE) issued funds to some customers such as Oklahoma Gas and Electric, and Sioux Valley Energy, for implementing time-based rates. Such experiences prove that time-based rates can have significant effects on reducing demands in peak hours [78].

4.1.2 Lack of persuasive incentives

Based on the type of industrial customers, DR programs may fail to provide acceptable financial incentives to persuade customers to participate. In some cases, the cost of disrupting production can be very high in comparison to the DR incentives. Furthermore, manufacturers may not accept the risk of negative impacts of DR on the quality of production to earn some incentives [76].

4.1.3 Lack of exact evaluations for DR benefits

For industrial consumers valuing the benefits of DR, and determining how to account the achieved profits contains complexity. Often it is vague and there is not a clear agreement upon consisting components of a cost/benefit analysis for DR programs. As an example, one of the major benefits of applying DR is the amount of reduction in wholesale price electricity costs. Although, it is not concluded yet that for how long it should be accounted, only over the short term or to consider it as a mid- to long-term benefit [79].

There are also some uncertainties and issues regarding the calculations of the value of avoided generating capacity costs. This avoided cost is considered as one of the benefits of DR and there is a disagreement upon the price of this avoided capacity.

If some of the values of DR programs is ignored or underestimated, this may lead to lower incentives and as a consequence lower participation from industrial consumers' side.

As a successful example, in order to address the cost-effectiveness of wholesale DR, FERC legislated a rule in 2011 in order to help on the compensation of DR in organized ISO/RTO energy and ancillary service markets. This rule agrees that when a DR resource was able to balance supply and demand as an alternative to a generation resource in ISO/RTO energy market, and when that dispatch was cost-effective, the DR activity must be compensated for the service at the locational marginal price (LMP). This rule led to a significant increase in DR participation. By applying this rule for only 6 months, financial energy reduction increased by 800 percent [80].

4.2 Regulatory Barriers

Potential regulatory barriers to DR described in this section.

4.2.1 Utility reconstruction issues

One of the benefits of DR is that by applying these programs properly, the need for construction of new infrastructure and new assets is reduced. Since regulated utilities often obtain financial returns based on the need for new infrastructure this may have bad impacts on their tendency for DR programs [81]. In addition, utilities earn much of their revenue through selling electricity to customers. While DR program will reduce electricity consumption during peak periods, especially for shedding power that the amount of power is not compensated in off-peak periods; thus overall electricity sales decline. Thus, the utility business model should concurrently consist of utility and customer interests, otherwise reduced electricity sales would impact utility revenues.

4.2.2 Program requirements and aggregation

As mentioned in section 2, some potential industries lose their tendency to participate to ancillary services due to numerous market and operational regulations, like minimum size requirements, certification or operational limitations, or aggregation rules that prohibit small industrial consumers from participating in these programs [82]. In some cases, third-party aggregators are forbidden from enrolling DR providers due to utility disapproval or regulatory concerns about consumer effects and benefits [82]. The utilities often tend to retain the authority to dispatch load resources itself, therefore they will not voluntarily allow aggregators to persuade their customers to participate. Indeed, in order to participate, aggregators need to regularly negotiate with each distribution utility or respond to several utility competitive bids.

In some states in U.S. like California some suggestions are proposed for reducing these regulations and allowing various type of industrial consumers to participating without additional entities. As an example, Automated DR is a solution in this regard that is used to send businesses DR signals and automatically implement load reductions through control systems [83].

4.2.3 Measurement and verification variety

Lack of unified standard measurements and verification procedures for DR would have an inverse effect on these programs and inhibit the consumers' participation. Currently measurement and verification procedures for DR vary widely across utilities, and ISOs/RTOs. Without standard DR procedures, its benefits assessment and evaluations is not easily possible.

4.2.4 Limitations on market regulations

As mentioned in section 2, electricity market structures, both wholesale and retail, often focus on the supply side and this may limit DR participation in certain markets. This is due to the fact that the regulations and rules of power systems date back to the time when generators were the only resources in the power market. For instance, RTO/ISO tariffs usually define minimum run times (or bidding parameters) for generators, while do not normally establish maximum run times (or bidding parameters), which could lead to greater DR participation [84]. However, for industrial consumers this would have some plus points, as industries usually tend to know the duration of the program, especially large industrial customers that may require changing their operational plans.

But this barrier must be removed in order to encourage more participation. In some cases, the full value of DR programs may not be captured for a typical industry unless it would be capable of participating in different markets including capacity, energy, and ancillary services [85].

4.2.5 Inclusion in energy efficiency programs

DR should be considered as a separate activity from that established for energy efficiency programs. In this way, utilities are encouraged to increase and enrich their offers and financial rewards for DR programs as a way of encouraging more participation.

4.3 Knowledge-based barriers

Industrial managers often require clear information about various types of DR programs and the cost/benefit analysis, and the effect that these programs would have on their industrial processes and production. The typical knowledge-based barriers are as follows:

4.3.1 Lack of knowledge and resource availability

Lack of knowledge and understanding of utility incentives and the way of applying these programs on one hand; and inadequate on-site technical expertise on the other hand, can lead to low participation. This type of information and knowledge even is more crucial for industrial customers, and manufacture energy managers. Improved knowledge on DR programs is one way of increasing customer awareness and participation in existing programs. Joint education campaigns by utilities, regulators, and grid operators are beneficial in this regard; in addition, the rules for participant industries must be clear and easy to follow as well. While DR may offer opportunities to reduce energy costs, it can be a time consuming and somehow complex process for exact economic evaluations of its impact in industries. One of the uncertainties is the duration and frequency of DR which is usually not exact and needs to be predicted for the purpose of economic evaluations.

4.3.2 Interoperability and open standards limitations

For proper operation of a DR program, various types of devices and systems from different technologies must accurately interoperate. Several interoperability standards have been recognized such as SEP 2.0 [86] Open ADR [87] and Green Button [88] and they are adopted in the market. Though open standards are required more than before in order to align communication between various devices. Indeed, a standard and interoperable platform is required for the successful implementation of DR programs. This platform facilitates communication between DR devices, participating industries, utilities, ISOs/RTOs, and wholesale markets. It is able to provide industries with real-time prices and makes the possibility of Automated DR [89]. These open standards make any changes in systems possible with a low-cost option for software upgrades in Auto DR technologies. Indeed, without open standards, any changes in an existing standard would be expensive and complex for implementation.

As good examples of some associations in U.S. that started to publish roadmaps and strategies in regards to these technical protocols and standards, are first the National Institute of Standards and Technology (NIST); and second is DOE's Lawrence Berkeley National Laboratory that started to address the related issues and also is testing and

developing standards and roadmaps for DR interoperability, wired and wireless communications, communication architectures, devices, and monitoring and control technologies [90].

4.3.3 Administrative burden

As previously stated, participating in a DR program is time-consuming and needs experts to evaluate and acknowledged the programs properly. This would be an issue for some participants especially for small industries. In this regard, entities like aggregators or Curtailment Service Providers will be a help to mitigate the labor burden. These mediate entities are specialized to work with ISOs/RTOs to reorganize DR participation requirements. For instance, EnerNOC, is an example of the mentioned entities that manages the customer orders in regards to participation in all respects; its objective is to ensure that the industries receive the highest financial compensation as for their participation. There is no cost for participation, and as a reward for their participation, industries can have access to on-demand energy data through “Demand SMART”, which is EnerNOC’s comprehensive DR application [91]. However, when utilizing an aggregator, the industrial customer should still spend time for managing of its participation in DR. Indeed, some customers have stated that they do not tend to participate in DR programs due to extra needed paperwork and other labour involved, along with other troublesome requirements.

5. Conclusions

Industrial consumers have traditionally provided various DR opportunities for power systems in different regions of the world, but their potential has not been thoroughly appreciated yet. Although these consumers are technically capable of reducing their loads quickly and reliably, regulatory concerns do not allow the consumers carrying out most of their possibilities; moreover, industrial consumers are not motivated enough with the available DR programs. In other words, the flexible industrial consumers’ participation in electricity markets needs to be enhanced by means of new DR programs that exploit the whole potential of consumers. These DR programs should provide both consumers and the regulators with suitable tools and methods to effectively demonstrate the technical and economic benefits of such flexibility for all the involved actors. These tools should include risk in cost saving analysis for a specific investment. This is more critical today, since the industries already applied energy management systems.

On this basis, a prerequisite for the successful exploitation of whole potential flexibility of industrial consumers is that the electricity markets’ design should be able to appropriately allow them benefiting from this flexibility.

Unluckily, market and reliability rules were established when merely generators were available resources to the system operator. Therefore, these rules often impede load response, especially in those reliability services that are fast, critical, and expensive.

On this basis, without any effort to solve these problems, DR remains the major underutilized reliability resource available in the power system. Therefore, DR implementation should be increased by removing obstacles, being more expertize in load management and promoting advancement in control and communication systems. Implementation of the Auto-DR technology might be a solution for some large industrial facilities such as data centres. Overall, the technical potential of DR should be obtained by advancing DR participation level and increasing the awareness of industries to an appropriate level.

With a further development of the generation capacity of renewable energy resources, DR is a key factor to determine the future power balance in cooperation with the development of energy storage systems and other new technologies and to enhance the power system infrastructure.

Acknowledgments

João P. S. Catalão thanks the support of FEDER funds through COMPETE and Portuguese funds through FCT, under FCOMP-01-0124-FEDER-020282 (PTDC/EEA-EEL/118519/2010) and UID/CEC/50021/2013, and also thanks the support of the EU 7th Framework Programme FP7/2007-2013 under grant agreement no. 309048.

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Figure captions

Fig. 1. Necessity for implementation of industrial DR.

Fig. 2. Time and duration of ancillary services' response.

Fig. 3. Electricity consumption of aluminium production Processes [28].

Fig. 4. The steel industry supply chain.

Fig. 5. Supply chain of a typical cement plant.

Fig. 6. Energy consumption of typical wet and dry cement plants based on processes.

Fig. 7. Energy consumption of a typical refrigerated warehouse.

Fig. 8. Industrial DR barriers.

Table captions

Table 1. A summary of survey papers in the field of DR

Table 2. Categories of the scope of DR surveys in the literature

Table 3. Different classifications determined for Ancillary Services in the literature

Table 4. Characteristics of DR programs for ancillary services [92]

Table 5. DR participation based on type of industry

Table 6. Dominant industries with high potential for DR [2], [62]

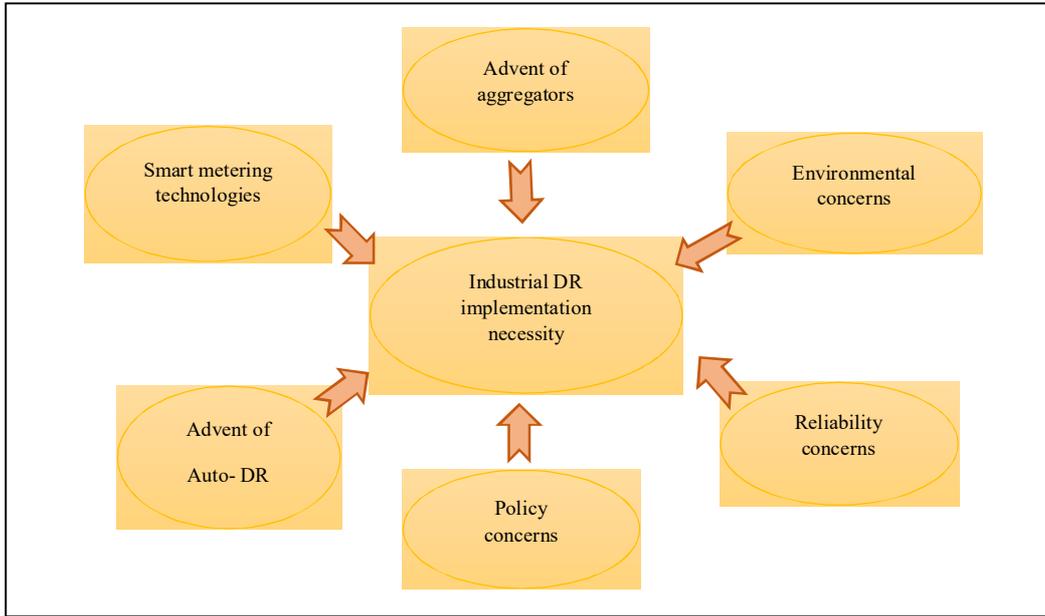


Fig. 1. Necessity for implementation of industrial DR.

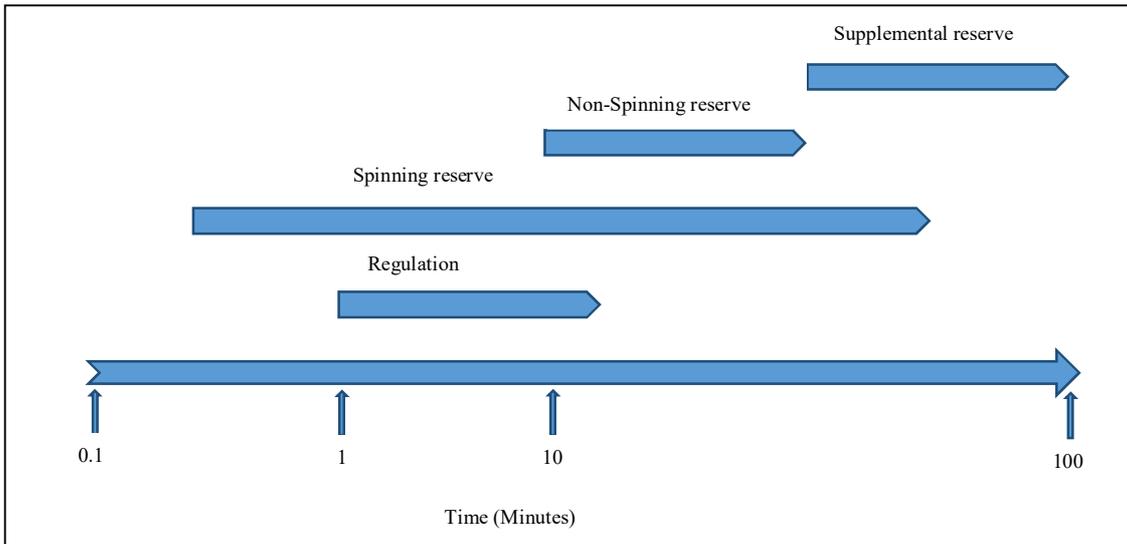


Fig. 2. Time and duration of ancillary services' response.

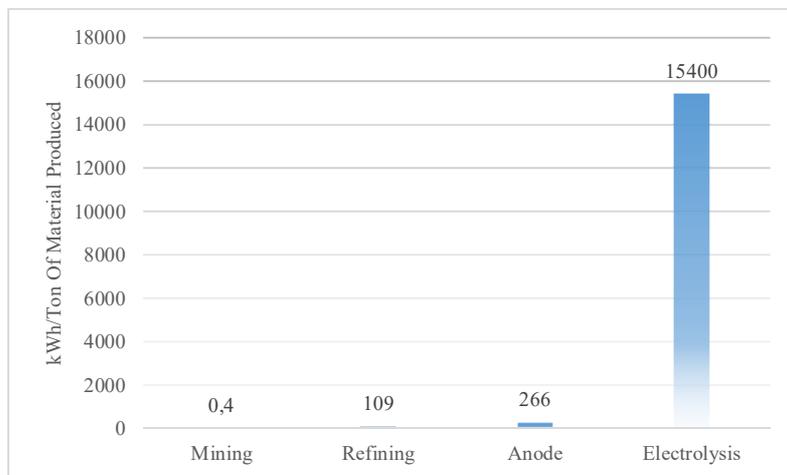


Fig. 3. Electricity consumption of aluminium production processes [28].

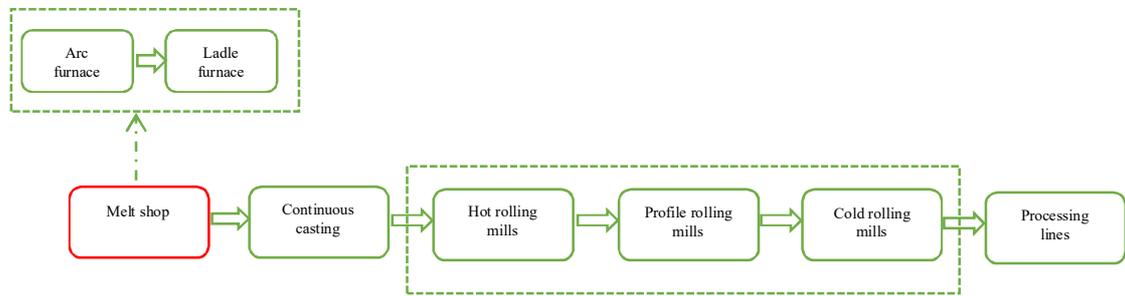


Fig. 4. The steel industry supply chain.

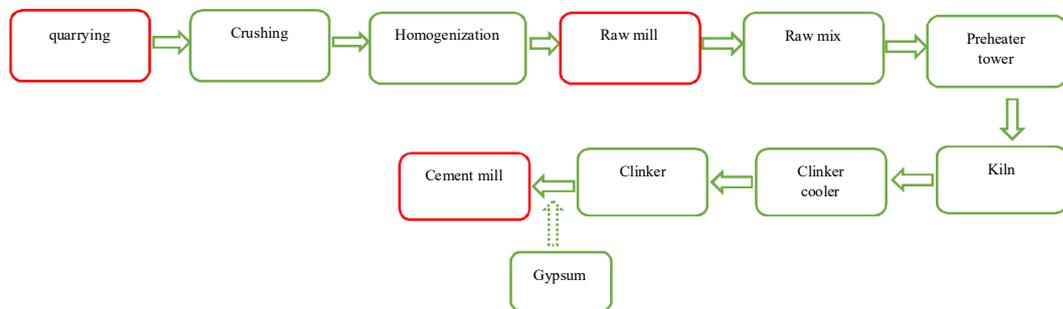


Fig. 5. -Supply chain of a typical cement plant.

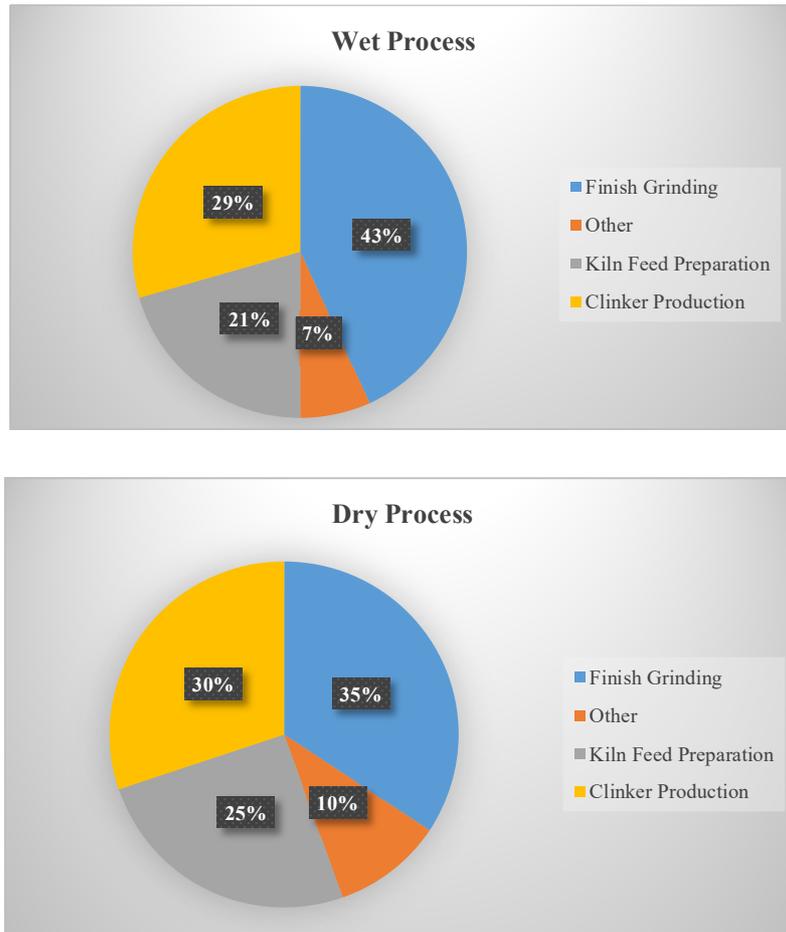


Fig. 6. Energy consumption of typical wet and dry cement plants based on processes.

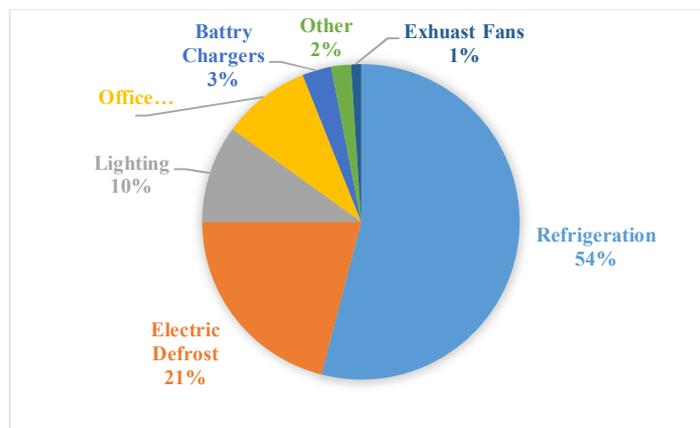


Fig. 7. Energy consumption of a typical refrigerated warehouse.

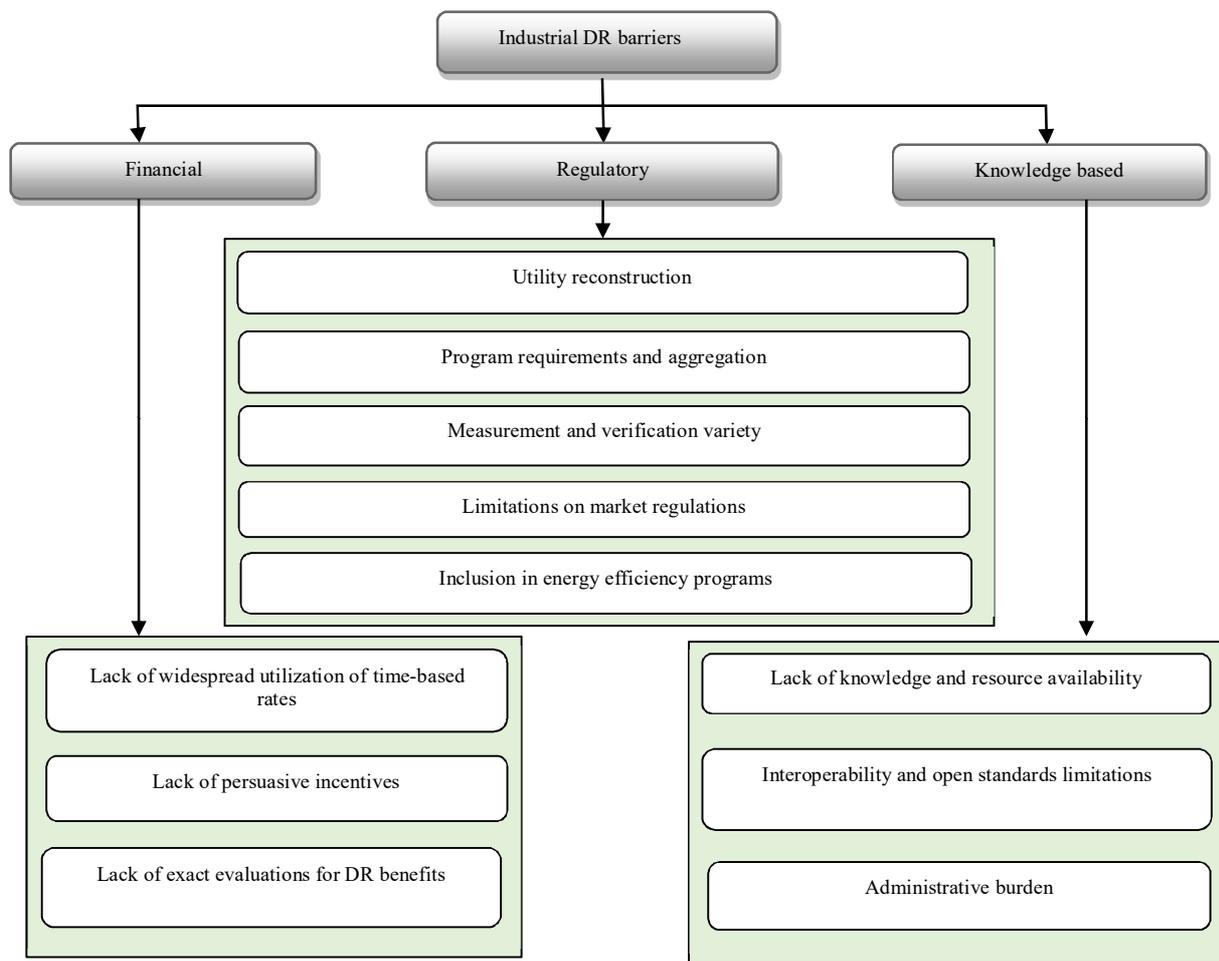


Fig. 8. Industrial DR barriers.

Table 1. A summary of survey papers in the field of DR

Ref.	Aims and classifications
[6]	<ul style="list-style-type: none"> Developing technologies related to DR, like smart metering, energy control and communication systems are described and some DR applications are described, including few real industrial case studies
[7]	<ul style="list-style-type: none"> A survey on major aspects of DR including programs, issues, approaches and future extensions Introducing the means and tariffs that the power utility takes to incentivize users to reschedule their energy usage patterns Analysis of the existing mathematical models and problems followed by the state-of-the-art approaches and solutions to address these issues
[8]	<ul style="list-style-type: none"> Classification of various DR schemes and programs according to their control mechanisms, the motivations offered to reduce the power consumption and the DR decision variables Categorization of various optimization models for the optimal control based on the target of the optimization procedure
[9]	<ul style="list-style-type: none"> Analysis of DR as a way to plan and schedule the operation of renewable energy resources A comprehensive cost/benefit evaluation of DR Several assessment methods in combination with impacts of DR on electricity prices
[10]	<ul style="list-style-type: none"> A review of DR including the existing applications and a possible implementation strategy in smart grid environments A discussion on the classification and status of DR programs in different U.S. electricity markets
[11]	<ul style="list-style-type: none"> Assessment of possible business models for energy efficiency and DR providers in different electricity market. The analysis covers three types of characteristics: Demand Side Management (DSM) transaction characteristics, renewable energy correlation and load control characteristics.
[12]	<ul style="list-style-type: none"> A survey and analysis of DR modelling approaches and their impact on operations and outcomes of home energy management systems
[13]	<ul style="list-style-type: none"> An outline of the impact of policy and regulation changes, electricity market enhancements and technical advancements on DR participation
Current paper	<ul style="list-style-type: none"> Investigating and introducing different types of high potential industries for DR programs A review and analysis of the contribution of ancillary services and their potential in industries An outline of the barriers that hinder a widespread utilization of industrial DR programs

Table 2. Categories of the scope of DR surveys in the literature

Category 1: Developing technologies and future extensions	Category 2: Programs and approaches, market participation	Category 3: Barriers and issues	Category 4: Mathematical models and optimization problems and scheduling
[6], [7], [13]	[7], [8], [10], [11], [12], [13], current paper	[7], current paper	[7], [8], [9]

Table 3. Different classifications determined for Ancillary Services in the literature

Different categorization	References
<ul style="list-style-type: none"> • Mechanisms of frequency control (primary, secondary and tertiary frequency regulation) • Voltage control • System backup and restoration 	[41]
<ul style="list-style-type: none"> • Frequency control: related to the balance in real time of energy • Voltage control: related to quality features in the supply apart from frequency, such as voltage regulation (also named reactive power service) • System backup and restoration: aimed at returning the system to normal operation status after experiencing a black-out. 	[93], [94]
<ul style="list-style-type: none"> • Scheduling, System Control and Dispatch Service • Reactive Supply and Voltage Control from Generation Sources Service • Regulation and Frequency Response Service • Energy Imbalance Service • Operating Reserve - Spinning Reserve Service • Supplemental Reserve Service 	[95]
<ul style="list-style-type: none"> • Regulation: continuously responses to short-term load fluctuations (consists of regulation up/down). • Spinning reserve: responses to unexpected increase or decrease in load • Non-spinning reserve: responses to unexpected, rapid and infrequent disruptions 	[32]
<ul style="list-style-type: none"> • Regulation (up and/or down) • Spinning reserve • Non-spinning reserve • Replacement reserve. 	[24]

Table 4. Characteristics of DR programs for ancillary services [92]

Ancillary service		Physical requirements			
Type of program	General characteristics	Reaction speed	Duration of reaction	Time to complete reaction	Dispatch frequency
Replacement reserve	Provided by resources with a slower response time that are replaced by contingency reserve resources	<30 minute	2 hours	-	Hours to days
Regulation	Response to random unexpected deviations in scheduled load (bidirectional, up and down)	~ 1minute	minutes	minutes	Continuous within specific bid period
Contingency (emergency): spinning and non-spinning	Rapid and immediate reaction in supply interruptions	Seconds to a few minutes	10 to 120 minutes	≤ 10 minutes	Hours to days

Table 5. DR participation based on type of industry

Industry	Process	References
Food	Electric defrost, refrigerated warehouses, cooling production and distribution	[3], [37], [96], [40], [97]
Metal industry: Steel manufacturing/ Aluminium production	Steel mill, electric arc furnace, oxygen generation facilities, crushing	[4], [29], [30], [98]
	Aluminium electrolysis, smelting	[3], [24], [32], [25], [4]
Production of chloride	Chloralkali process, electrolytic process	[4]
Cement manufacturing	Grinding mills, quarrying operations, raw mix grinding, fuel grinding, and clinker grinding, crushing	[3], [4], [31], [32]
Paper and wood pulp	Mechanical refining	[4]
Textile/leather	Wrapping, weaving	[45]
Glass manufacturing	Electric furnace, oxygen generation facilities	[45],[98]
Oil refinery	Catalytic cracking, crude oil processing	[44]

Table 6. Dominant industries with high potential for DR [2], [62]

Industry	Main manufacturing processes
Food and similar products: wet corn milling, sugar manufacturing	Packaging, chiller, refrigeration
Textile mill products, and apparel	Wrapping, weaving
Lumber and wood products, furniture and fixtures	Sawing, planing
Pulp, paper, and paperboard mills, converted paper product manufacturing	Chipper, dewatering press
Printing and publishing, chemicals and related products	Electrolysis, compressor, grinding
Petroleum refining and related industries: petrochemical manufacturing, industrial gas manufacturing	Catalytic cracking
Rubber and miscellaneous plastics and leather products: resin and synthetic rubber manufacturing	Mixing, milling
Stone, clay, glass, and concrete products	Electric furnace, crushing
Primary metal industries: iron and steel mills, alumina and aluminium production, foundries	Crushing and classifying
Transportation equipment: automobile manufacturing	Metal cutting, final assembly