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A comprehensive overview of industrial demand response status in Europe

M. Ranaboldo [a,*], M. Aragüés-Peñalba [a], E. Arica [b], A. Bade [c], E. Bullich-Massagué [a], A. Burgio [d], C. Caccamo [e], A. Caprara [a], D. Cimmino [d], B. Domenech [f], I. Donoso [g], G. Fragapane [b], P. González-Font-de-Rubinat [a], E. Jahnke [h], M. Juanpera [f], E. Manafi [f], J. Rövekamp [c], R. Tani [i]

[a] CITCEA-UPC, Universitat Politècnica de Catalunya – BarcelonaTech (UPC), Barcelona, Spain
[b] Industrial Ecosystems, SINTEF Manufacturing, Trondheim, Norway
[c] Business Science and Management Department, Albstadt-Sigmaringen University of Applied Sciences, Sigmaringen, Germany
[d] ENI Plenitude SpA Società Benefit, Milan, Italy
[e] Gas Technology, SINTEF Energy Research, Trondheim, Norway
[f] Design and Optimisation of Processes and Services (DOPS), Universitat Politècnica de Catalunya – BarcelonaTech (UPC), Barcelona, Spain
[g] SENER, Bilbao, Spain
[h] Institute for Industrial Production, Karlsruhe Institute of Technology, Karlsruhe, Germany
[i] We Plus S.p.A., Turin, Italy

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ABSTRACT

Industrial demand response (IDR) will play a crucial role in shaping future electricity systems, as it is a key element of a just energy transition and industrial development. The aim of this work is to provide an overview of the current status of IDR in a holistic perspective. First, the main benefits and potential of IDR are reviewed, together with the motivations and challenges for the industrial sector. Most recent advances in European markets and regulations with specific focus on IDR applications are explored. Then, the different resources which are currently available to help industries participate and implement IDR programmes are reviewed. In particular: 1) the (possible) tools for defining energy-aware scheduling and planning of the manufacturing systems are analysed; 2) The role of aggregators (i.e. intermediaries between industries and power markets) for facilitating explicit IDR is examined; 3) the importance of digitalisation to provide better IDR services from the manufacturing industry is highlighted, pointing out that digital twins, cyber-physical systems, Internet of Things sensors, robots, edge computing, artificial intelligence, and big data are promising technologies; and 4) most recent related research projects are reviewed. Finally, it is analysed and discussed how each of those resources can address the different challenges that are still preventing industries to apply IDR programmes.

Abbreviations	
ACER	European Union Agency for the Cooperation of Energy Regulators
aFRR	Automatic frequency restoration reserves
AI	Artificial intelligence
CPS	Cyber-physical systems
DR	Demand response
DSF	Demand-side flexibility
DSO	Distribution system operator
DSR	Demand-Side Response service
ENTSO-E	European Network of Transmission System Operators for Electricity
FCR	Frequency containment reserves
FSSP	Flow shop scheduling problem
ICT	Information and Communication Technology
IDR	Industrial demand response
IDRA	Industrial demand response aggregator
IEA	International Energy Agency
IoT	Internet of Things
IT	Information technology
JSSP	Job shop scheduling problem
LV	Low voltage
mFRR	Manual frequency restoration reserves
MV	Medium voltage
PMSP	Parallel machine scheduling problem
PPC	Production Planning and Control
R&D	Research and Development
RES	Renewable energy sources
RR	Replacement reserves

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* Corresponding author.
E-mail address: matteo.ranaboldo@upc.edu (M. Ranaboldo).

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(*continued*)

SMSP	Single machine scheduling problem
SO	System operator
TEC	Total electricity cost
TOU	Time of Use
TSO	Transmission system operator
UVAM	Mixed aggregate virtual units
VPP	Virtual power plant

1. Introduction

Flexibility is becoming a key element in electricity markets dominated by variable renewable energy sources (RES) [1]. Flexibility in power systems can be defined as "*the ability of power systems operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service requests signals, without inducing unplanned disruptions*" [2].

The International Energy Agency (IEA) recognizes that the lack of flexibility is one of the biggest hurdles in the face of a rapid deployment of renewables [3]. For instance, excessive variable RES generation, such as wind, currently has to be curtailed during off-peak periods [4]. In addition, flexibility has the potential to contribute to power system support during normal operation at the transmission and distribution level due to the provision of active and reactive power management at different time scales [5]. Furthermore, it can reduce the reinforcement costs necessary for grid planning [6]. The IEA's conservative scenario envisions that the need for flexibility in the European Union will grow by around 40 % by the end of this decade [7]. Indeed, the number of European Research projects focusing on this topic is rapidly increasing [8,9]. The business possibilities for companies in offering flexibility products are also becoming evident [10,11].

As shown in Fig. 1, the strategies to provide system flexibility can be grouped into: supply-side flexibility (e.g. new flexible power plants), demand-side flexibility (e.g. controllable/shiftable loads), grid-side flexibility (e.g., transmission expansion or improved market design), and storage-side flexibility (e.g. pumped hydro storage system and large-scale batteries) [12].

Flexibility has typically been harnessed on the supply side, for example, using hydro or thermal flexible power plants [15]. However, as observed in Fig. 2, flexibility on the supply side is decreasing with the increase of variable RES, resulting in a so-called "flexibility gap" [16]. Thus, there is a worldwide need to examine other ways to increase flexibility, such as demand-side flexibility (DSF) [17,18]. Flexibility on the demand side represents a promising solution to close the flexibility gap and is considered a competitive flexibility option with

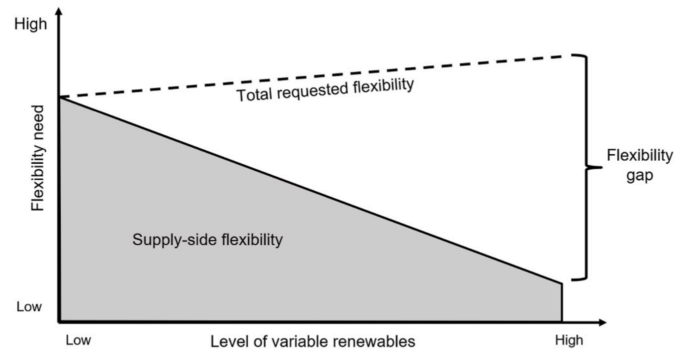

Fig. 2. – The emerging flexibility gap. Source: adapted from [16].

comparatively low marginal costs [19,20]. For instance, a recent study showed that DSF has the potential to reduce renewable energy curtailments by around 60 % in 2030 [21]. The primary benefit of DSF is its ability to response to changes in supply-demand balance and power quality problems with the support of end-users [22].

In detail, DSF refers to the set of strategies aiming at adapting the end-use electricity consumption [15,23] normally realized through the demand-side management, which includes energy efficiency and demand response programmes [24–27] (Fig. 1). Demand response (DR) is defined as "*changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*" [14]. The benefits and potential of DR has already been recognised by the authorities around the globe, e.g. in the "Clean energy for all Europeans'' bill by the European Union [28] or the IEA [29,30].

In this context, it has been recently highlighted that industrial demand response (IDR) may play a crucial role in shaping future electricity systems, as it is a key element of a just energy transition and industrial development [31]. In fact, a large share of the cost-effective DR potential lies in industry [32], and examples of the application of IDR mechanisms have been already published [32–35]. Some barriers are still preventing industries to apply DR programmes or strategies [36]. The services currently available on the market are fragmented: energy procurement solutions are generally limited to decision support and do not interact with markets; aggregators offer energy supply contracts, production flexibility optimisation and "traditional" trading, but these solutions build on the current market design and hardly integrate new potential flexibility markets. In addition, the solutions offered are not standardized in terms of interfaces, protocols, data models and communication processes between companies and aggregators. Several publicly funded research projects that focus on the development of open-source

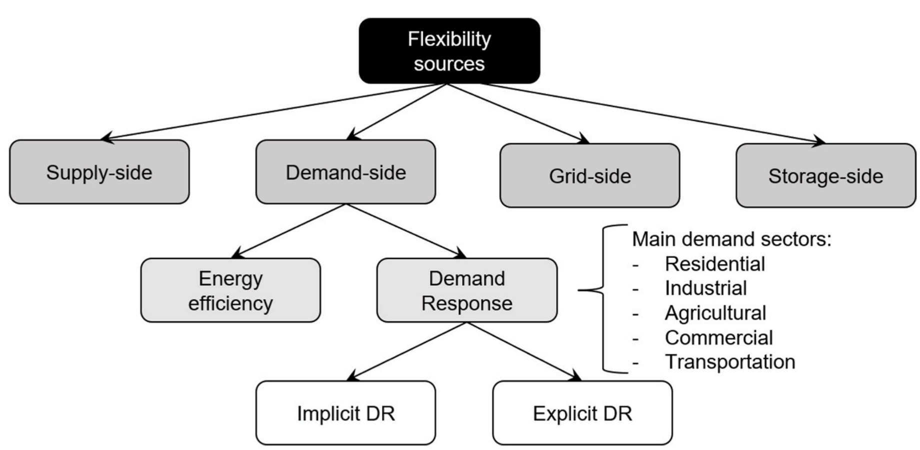

Fig. 1. – Demand response strategies within the general scheme of flexibility sources (own realisation based on [13,14]).

flexibility platform solutions for the standardisation of processes and protocols for flexibility use (e.g. the non-profit organisation USEF [37] and the OpenADR project [38]) make an important contribution to the standardisation of interfaces and communication within the flexibility value chain, but do not offer the necessary information technology (IT) solutions for connecting production machines and flexibility markets. On the other hand, flexibility in large-scale production represents a complex challenge for companies and must be accompanied by tools and measures to support strategic and operational decisions in order to accelerate implementation. Production processes have many different constraints and dependencies that need to be identified and considered in relation to product quality, deliveries and machine operating parameters [39]. The required data must be integrated, processed and analysed from a variety of heterogeneous legacy IT systems; control loops must be created to adjust energy consumption. Attempting to further utilize the flexibility gained would add another layer of complexity, as interaction with the external market must also be taken into account. Consequently, many industries have not yet or only partially tapped their potential for DR [20].

Currently, different resources are available to support the effective implementation of IDR, such as tools for defining energy-aware scheduling and planning of manufacturing systems [32,34,40], as well as aggregators [41,42] and the use of digital twins [43]. However, more research effort on DR programmes for commercial and industrial consumers is needed [14], further use case studies and reviews in the industrial sector to identify the common technical challenges of industrial demand flexibility [44], and to focus on standardisation and generalisation of the applied solutions.

Analysing literature, this research found different review papers focusing on IDR. In general, they tend to analyse specific aspects of IDR, such as the DR potential, the role of aggregators or focus on the barriers of IDR. Table 1 shows that many review papers focus on the barriers for IDR, which have been widely emphasised in literature [4,20,25,33,39,44,45]. Some papers highlight the DR potential. However, they are mostly focusing on a specific sector [25,44,46] or region [47], or describing the benefits [31]. Other papers highlight how specific aspects of digitalisations can support IDR, such as artificial intelligence [48], digital twins [43] or required control and communication infrastructure [4]. Few papers review the relevant regulations [25,33,45]. The most recent one only focuses on ancillary services [25]. Very few review papers analyse energy-aware scheduling models for enabling DR [44,46], being one of them focused on wastewater treatment plants [46]. Finally, only one review paper analyses the aggregator role for IDR [41], and no papers review recent research projects on the topic.

Such as shown in Table 1, there is a lack of papers that provide a comprehensive analysis of the manufacturing industry demand response, covering the multiple key aspects including IDR potential, markets, enabling technologies, research projects, and remaining challenges. Also, there is no study that highlights how current enabling technologies and research projects are interconnected and how they can contribute to addressing the challenges faced by the industry in implementing DR programs.

The aim of this review is to provide an overview of the current status of IDR methods in a novel holistic perspective. In particular, the main contributions derived are:

- Analysis of available resources for boosting DR from the manufacturing industry. To the best knowledge of the authors, no previous study has identified and addressed, simultaneously, existing energy-aware tools for planning production and scheduling operations at mid- and short-term, the aggregator role and its application for IDR, the advances in digitalisation in the industry for supporting IDR and existing research projects.
- Exploration of most recent advances in European markets and regulations with specific focus on IDR applications.
- Analysis of how existing technologies, such as energy-aware scheduling, aggregators, and digitalisation, together with research projects, can tackle existing DR challenges from the manufacturing industry and unlock its potential, under the current European context.

The rest of the document is organized as follows:

- Section 2 provides an overview of the context of IDR by identifying the types of IDR programmes, the IDR benefits and potential. The motivations and challenges for the industrial sector to engage IDR are also reviewed and analysed.
- Section 3 focuses on the markets and regulations for explicit DR.
- Sections 4 reviews the current status of energy-aware manufacturing planning and scheduling.
- Section 5 explains the role of demand response aggregators.
- Section 6 details the role of digitalisation in the industry.
- Section 7 shows recent research projects, highlighting how they can facilitate IDR implementation.
- Section 8 focuses on the discussion of drivers and barriers for IDR, and,
- Section 9 draws the conclusions of this study.

A graphical representation of the overall framework of this study is shown in Fig. 3.

This research focused on papers published in the last decade, referring to publications that report the most updated information in the

Table 1
– Most relevant review papers (2016–2022) in the field of industrial demand response and their focused topics.

Reference	Year	Topics' covered						
		Potential	Markets and regulation	Energy-aware scheduling	Digitalisation in the industry	Aggregators' role	Research projects	Barriers
Shoreh et al. [33]	2016		X					X
Paterakis et al. [4]	2017				X			X
Soder et al. [47]	2018	X						
Shafie-Khah et al. [45]	2019		X					X
Siddiquee et al. [39]	2020							X
Stede et al. [41]	2020					X		
Heffron et al. [31]	2020	X						
Kirchem et al. [49]	2020	X		X				
Ahmad et al. [48]	2021				X			
Leinauer et al. [20]	2022							X
Timplalexis et al. [25]	2022	X	X					X
Golmohamadi [44]	2022	X		X				X
Yu et al. [43]	2022				X			
Current work		X	X	X	X	X	X	X

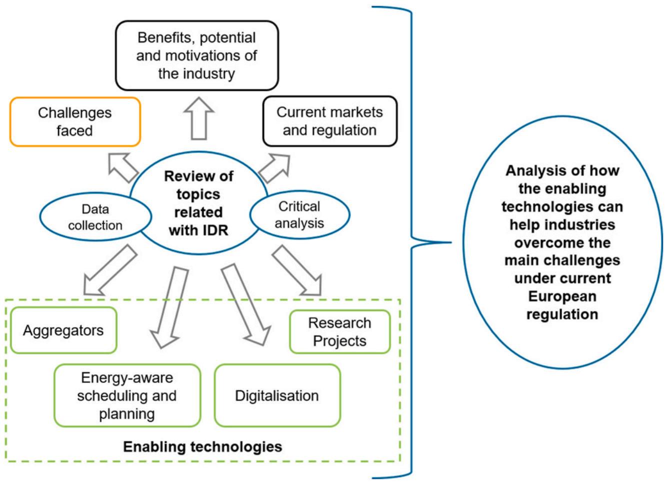

Fig. 3. – Overall framework of this review.

different topics. In case relevant information was found in previous papers, then older publications were included. As a result, more than 50 % of the cited references were published in 2020 or later, and less than 3 % of them were published before 2010.

It should be noted that the term "industry" may include a wide range of sectors, such as agriculture, manufacturing, transportation, information and communication, etc. [50]. The focus of this review is on the manufacturing sector, which represents the largest part of the industrial sector [25]; in this work, the word "industry" is generally used as a synonym of "manufacturing industry". This review is centred in Europe, where the authors are working and they have expertise. Even so, the discussion made here can be relevant also for other regions, as the challenges faced by IDR are very similar worldwide [39].

2. Background on industrial demand response

This Section provides an overview of the different types of DR programmes (Section 2.1), their benefits (Section 2.2) and potential of the IDR for the manufacturing industry (Section 2.3). Also, the motivations (Section 2.4) and challenges (Section 2.5) for the industrial sector are reviewed.

2.1. Types of programmes

DR programmes can be classified in two broad categories: implicit or explicit DR [4,12,14,51] (Fig. 1). The main difference is that in implicit (or price-based) DR programmes consumers voluntarily provide load reductions by responding to economic signals, e.g. time-varying electricity prices; while in explicit (or incentive-based) programmes, customers are offered payments in order to deliver a specific amount of load modification over a given time period. It should be noted that explicit DR programmes are typically regulated by the national (or regional) electric grids, which are in charge of the so-called "flexibility markets", i.e. energy markets that enable the buying and selling of flexible energy services in response to changing supply and demand conditions. Those markets and regulations are described and reviewed in Section 3.

The different DR programmes within those two categories can be classified as shown in Table 2, according to Refs. [4,14,52–54]. For each type of program, it is stated whether this program is already widely applied in industries (yes) and, if not, the feasibility of its application (possible or hardly).

Implicit DR programmes have been shown to be a very attractive option for industries to reduce their electricity bill [52]. In particular, Time-of-Use and Real-Time-Pricing are the most promising programmes. However, due to the complexity of many manufacturing

Table 2
– Overview of general DR categories and their industrial application.

Category	Type of program	Description	Industrial application
Implicit (price-based)	Time-of-use (TOU)	The electricity price for consumers depends on the time interval that the electricity is used. Typically, a day is divided into three intervals, named as peak interval, mid-peak interval and off-peak interval	Yes
	Critical peak pricing	This program is akin to TOU, except for the time when the reliability of the power system is jeopardized and then the normal peak price is replaced by a very higher price. This program is only employed for a couple of hours per year	Yes
	Real-time pricing	The electricity tariffs typically change hourly, reflecting the fluctuations in the price of wholesale electricity market. Typically, the consumers are notified on a day-ahead or hour-ahead basis. In the cases that the prices are not published on day-ahead basis, a price prediction module is needed for energy management of consumers	Yes
Explicit (incentive-based)	Direct load control	Utilities can remotely control some customers' appliances (e.g., air conditioners and water heaters) to shut down or cycle them, when needed (normally during peak demand or events)	Hardly
	Load Curtailment	Curtailable load programmes are addressed to medium and large consumers. Participants in these programmes receive incentives in order to turn off specific loads or even to interrupt their energy usage, responding to calls emitted by the utility	Possible
	Emergency demand reduction	In severe contingencies, the consumers are paid a considerable incentive for reducing their usage. These programmes may assist a power system to enhance its reliability.	Yes
	Demand side bidding, and ancillary services	These programmes are typically offered to large-scale consumers or aggregators (e.g. larger than 1 MW). During contingencies or peak demands, the consumers may bid to curtail part of their consumption at a certain bid price	Possible
	Capacity market	Customers receive incentive payments for providing load reductions as substitutes for system capacity	Possible

processes [44], the correct implementation of implicit DR programmes needs expert knowledge to be able to perform the more energy-intensive operations within low-price periods and, at the same time, fulfilling the production objectives of the company (for example, due dates with clients). In this sense, the correct information technology (IT) infrastructure (described in Section 6) and the correct optimisation tools for scheduling and planning (described in Section 4) are crucial.

Regarding explicit DR programmes, direct load control, in which utilities may directly control some appliances in the end-user premises, is mostly thought for small consumers, e.g. residential, with very limited industrial application. In addition, load curtailment (and emergency demand reduction) programmes for large industrial customers have been in place for more than 50 years [12,53], and can be considered a relatively mature form of DR. Participation in other services (such as demand bidding, ancillary services, and capacity markets) is the most complex, as it highly depends on regulations and on the capability of the industries to participate in the flexibility markets. In this sense an efficient production planning (Section 4), industrial aggregators (Section 5) and digitalisation (Section 6) play a crucial role. The current European flexibility markets and regulations for providing explicit DR services are reviewed in Section 3.

For both implicit and explicit DR programs, the following two actions are very common [55–57]: “load shedding” (or load curtailment), i.e. directly avoiding a certain amount of load, and “load shifting”, i.e. a certain amount of load is moved from one period to other periods. Load shifting includes actions such as “peak clipping”, i.e. reduction in the peak load demand, and “valley filling”, i.e. increasing load at off-peak (or very low price) periods [58].

2.2. Benefits

DR strategies are gaining attention in power system operations, driven by the increasing interest in implementing the smart grid concept [4,59], as they have some clear advantages. DR has shown to be an effective solution to reduce peak load and defer the cost of extending or reinforcing the network infrastructure [60]. It also enables an active participation of the demand side in grid operations (e.g. to manage the variability from renewable generation), which results in improving the efficiency, reliability, and safety of the power system [12].

The overall benefits of DR have been widely highlighted and can be grouped in the following categories [4,31,57,60–62]:

1) Facilitating the integration of intermittent renewable generation
2) Benefits for the system
3) Benefits for the market

Examples of each category are reported in Table 3.

These benefits can become even more important when referring to large consumers DR mechanisms [63]. The industry is clearly one of such large consumers, as it uses more delivered energy than any other end-use sector, accounting for 38 % of the total global final energy use in 2021 [64], and more than 40 % of the globally consumed electricity [65]. Also, around 29 % of total CO_2 emissions come from this sector [66]. For that reason, IDR has been identified as one of the most promising solutions when it comes to exploiting DSF [15], as it holds unique potentials for system stability [31]. Compared with other flexibility measures, industrial demand-side management has been shown to be one of the most cost-effective and easiest strategies to implement [13,32].

2.3. Potential from the manufacturing industry

Potential assessment is a key step for promoting DR and for maximizing its benefits [24]. In most industrialized countries, the manufacturing industry promises the biggest potential for providing DSF [31] compared to other sectors such as residential or agricultural.

Table 3
– Summary of benefits of demand response. Adapted from [4].

Benefit category	Examples
Facilitating the integration of intermittent generation	- DR can increase in the demand in periods in which there is excessive wind/solar power generation - DR can reduce significantly variable RES plants curtailments - The reliability of the response of an aggregation of a significant/large number of loads is greater than the one of a small number of large generators
Benefits for the system	- DR can contribute to a reduced forecasted peak demand, thus limiting or postponing network investment - DR programmes may preventively contribute to confront an upward deviation of demand - Distribution substation congestion and losses can be mitigated by DR activities at the distribution level - The distributed nature and the spatial diversity of demand can be exploited in order to eliminate congestions
Benefits for the market	- Lower and more stable electricity prices - Control of market power - Economic benefits for the consumers

Table 4 summarises the contribution of the most relevant papers in assessing the potential of IDR according to encountered literature.

When referring to DR potential, literature generally distinguishes between the theoretical, technical, economic and achievable potentials [27,55,67]. Following the definitions of ref. [27,55]: the theoretical potential comprises all facilities and devices of the consumers suitable for DR, the technical DR potential considers technical restrictions, the economic potential is the part of the technical DR that can be operated in a cost-efficient way; finally, the achievable DR potential considers the level of acceptance of load interventions by the consumers.

The potential clearly depends on the industrial sector and the flexibilities each industry has. In general, energy-intensive industrial sectors, such as metals (in particular steel and aluminium), pulp and paper, cement, glass and chemicals, are among the most promising sectors when it comes to exploiting demand flexibility [25,31,55,70]. The following main flexibility enabling processes have been identified within those sectors [39,44,71,68]: melting by electrolysis (aluminium), electric arc furnaces (steel and glass), raw material and cement mills (cement), mechanical pulp processing (pulp and paper), and Chlor-alkali electrolysis (chemicals). Due to their technical requirements several processes such as steel production using electric arc furnaces, cement milling and aluminium electrolysis are only suitable for load shedding, while others such as chlor-alkali electrolysis and mechanical refining of wood pulp can be shifted [4,68]. The biggest flexibility can be generally achieved in industries where the production has a thermal inertia or a buffer capacity in the production [47]. The main reason is that there must not be any negative effects on the production of the end product, e.g. reduced product quality or increased waste, when a company changes its production pattern to provide flexibility [31].

Regarding the quantification of the flexibility potential, various DR potential assessment methods have been proposed in literature, generally focusing on estimating how much the peak load can be reduced; in fact, peak load reduction is the most important contribution of DR as it allows for reducing the need for expensive peaking plants [24]. Ref. [55] assessed the DR potential for load reduction by shedding or shifting in Europe, which varies strongly between countries. Browuer [56] estimated the IDR potential of specific industry sectors in Western Europe, while Kwon et al. [69] and Anjo et al. [70] quantify the overall DR potential for Denmark and Portugal respectively (but not specifically quantifying the industrial one). Germany is the country whose industrial DR potential has been evaluated in more detail by different studies, using both methodological [57] and modelling [19,68] approaches. All

Table 4
– Relevant papers contributing to defining and estimating IDR potential.

Reference	Year	Region of interest	Industrial sector(s)	Topics covered				
				Definition of DR Potential	Identification of flexible processes	Proposal of a DR Potential assessment method	Quantification of Flexibility potential	Quantification of Economic benefits from IDR
Grein and Pehnt [67]	2011	Germany	Refrigeration systems	X				
Paulus and Borggrefe [68]	2011	Germany	chlor-alkali, paper, cement, steel, aluminium		X[a]		X (Technical/ Economic)	X
Gils [55]	2014	Europe	Overall industry	X		X	X (Theoretical/ Technical)[b]	
Kwon et al. [69]	2014	Denmark	Overall industry			X (modelling approach)	X (Technical)	
Gils et al. [19]	2016	Germany	Overall industry			X (modelling approach)	X (Economic)	X
Brouwer et al. [56]	2016	Western Europe	chlor-alkali, paper, cement, steel, aluminium				X (Technical/ Economic)	
Summerbell et al. [52]	2017	United Kingdom	cement					X
Soder et al. [47]	2018	Northern Europe	Overall industry		X		X (Technical)	
Anjo et al. [70]	2018	Portugal	Overall industry				X (Theoretical/ Technical)[b]	
Muller and Most [57]	2018	Germany	chlor-alkali, paper, cement, steel, aluminium			X	X (Technical)	
Dranka and Ferreira [27]	2019	Not specified	Overall industry	X		X		
Heffron et al. [31]	2020	worldwide	Overall industry		X			
Lee et al. [51]	2020	Not specified	Cement			X		
Pierri et al. [71]	2020	Germany	Pulp and paper		X (mechanical pulp processing)	X		
Siddiquee et al. [39]	2021	Not specified	Overall industry		X[c]			
Golmohamadi [44]	2022	Not specified	cement, aluminium and oil refinery		X		X	
SmartEn [72]	2022	Europe	Overall industry					X
Timplalexis et al. [25]	2022	Not specified	Steel, aluminium, cement		X			

[a] Identified flexible processes: Chloralkali electrolysis, Mechanical refining of wood pulp, Aluminum electrolysis, electric arc furnace, cement mills.
[b] Even if the authors mention that theoretical DR potential is assessed, a set of technical restrictions are also considered, thus the DR potential assessed in Refs. [55, 70] should be interpreted as the 'Technical Potential' (according to definitions followed in this work).
[c] Identification of the following manufacturing sectors with the highest DR potential (and their respective enabling processes in brackets): aluminium (smelting), steel (electric arc furnaces, electric motors, cooling appliances), cement (grinders, motors, pumps), food (refrigeration units, pumps), glass (electric furnace), and pulp and paper (refining).

those studies agree that load reduction potential is higher than load increase potential. Even if the estimated potential varies due to different methods and assumption, the results of those research studies are overall consistent indicating average IDR technical potentials between 4 and 5 % of peak load reduction in Germany that could be realized in the short term [41]. The obtained values are in line with the results of Soder et al. [47], who found load reduction potentials of 4.7–7.1 % of peak load after reviewing the potentials for IDR in seven Northern European countries.

2.4. Motivations for the industry

There are several motivations to incentivize companies to participate industrial DR programmes. These motivations can be in the form of financial incentives (i.e., additional revenues or cost savings), and social and community obligations [36]. By reducing the energy usage during peak demand periods, high energy prices and penalties can be avoided, leading to significant cost savings. For instance, SmartEn [72] estimated a potential direct saving of 0.01 €/kWh in European industries in 2030 just by applying load curtailments, while Summerbell et al. [52] estimated cost savings of around 5–9 % by load shifting in a cement factory (Table 4). Participating in industrial DR programmes can also be incorporated into business models to provide additional revenues for participating companies [73]. Regarding "social and community obligations", companies are motivated to participate in industrial DR programmes to reduce the stress on the grid during high demand peak periods and prevent the power outages, contributing to increase the reliability of the electrical grid [44]. Further, studies show that participating in DR programmes can help reducing greenhouse gas emissions and promote the integration of renewable and sustainable energy sources [36].

2.5. Challenges

IDR is a complex task and need knowledge experts, as it requires changes in production patterns as frequently as changes in grid demand, triggered by price signals [44,74]. To efficiently provide DR services, industrial companies must be equipped with an automated decision system that considers the technical constraints of the processes and the alternative energy sources available [4].

Despite the motivations mentioned in Section 2.4, industrial companies may face fundamental challenges and barriers when considering to apply and enter in an IDR program. These may include technological challenges such as lack of sufficient knowledge and IT infrastructure to participate in IDR, economic challenges such as uncertain return on the investments required, regulatory barriers in the market, and organisational challenges while implementing and operating the new systems. Main categories, examples of challenges and barriers are listed in Table 5. To facilitate greater participation by industrial companies in DR programmes, these challenges should be highlighted and addressed. Sections 4 to 7 review different resources available to overcome such challenges.

However, at the base remains the fundamental need (and barrier) for easy adoption of the required IT solutions by the industry. To overcome this, a comprehensive data strategy for industrial flexibility should aim to develop data models, algorithms, process models and workflows and provide solutions that are either industry agnostic or offer a high degree of adaptability for industries that fall into the same categories.

Table 5
– Challenges faced by the industrial sector in entering and operating in an IDR program.

Challenge general category	Challenges to start applying and entering an IDR program	Challenges when operating in an IDR program	References
Economic	- Unclear evaluations and implications of DR benefits[a] - Uncertainty in DR project contracts[b] - High costs and capital requirements (in digitalisation and machinery update) to participate DR	- Price forecast uncertainties - Customer concern on non-performance penalty - Low power cost savings through DR - Difficulty in pricing the potential explicit DR service to be provided	[20,25,39,44,75]
Market	- Market complexity - Low market maturity - Heterogeneous DR market products in different countries	- Lack of appropriate market mechanism and standard practice	[33,44,76]
Regulation	- Policy lacking in defining the requirements of participation - Program requirements and restrictive legal permits for inclusion to energy programmes.	- Contradictory legal incentive and regulations - Lack of privacy and data security issues in legal framework - Ever-changing regulation hampers medium-term planning.	[4,20,39,45]
Technological	- High IT requirements and investments - Lack of technical knowledge required for participating in electricity markets	- Difficulty of collecting and processing market data, energy consumption data, etc. - Lack of interoperability and computational capacity	[4,20,33,45,77]
Organisational	- lack of corresponding investments for energy management at the top management level - Lack of internal resources	- Lack of load control approaches - Neglect of the interaction between power system operation and industrial process operation.	[20,33,44,78]
Sociotechnical	- Trust, openness, clarity between parties	- Lack of acceptance among employees - Lack of skills	[20,44,62,79]

[a] Paradox: Everyone will benefit from future price cuts, but not everyone has to be flexible for this to happen.

[b] This is mainly due to the following issues: 1) Electricity retailers do not offer these services in a transparent and open way. 2) The independent demand aggregator is not yet well established or developed in some countries.

3. Flexibility markets and regulations

As introduced in Section 2, explicit DR programmes are typically regulated by national (or regional) electric grid authorities responsible for overseeing the so-called “flexibility markets”. Thus, the participation of the industry in such programmes highly depends on how those markets are designed and regulated. This section provides an overview of current flexibility markets and regulations that can be found in Europe. Section 3.1 focuses on the existing flexibility market types and the electricity markets that can be relevant for IDR. Section 3.2 presents the policies and regulations of those markets. Finally, section 3.3 presents the harmonisation process that is taking place in Europe to unify the electricity markets and their regulation to facilitate the exploitation of flexibility and DR.

3.1. Flexibility markets

Flexibility markets are a type of energy market that enables the buying and selling of flexible energy services in response to changing supply and demand conditions. The traded product, energy flexibility, can help balance the electricity grid and it is key to optimize and enhance the integration of RES.

The main market participants are system operators (SOs), whether transmission SOs (TSOs), distribution SOs (DSOs) or other regional operators, aggregators (if any), and users, owners of flexibility-enabled devices, such as generators, consumers and prosumers [80]. SOs are responsible for ensuring the technical reliability of the system, being in charge of maintaining the frequency, resolving the technical constraints and the infrastructure maintenance. Within the flexibility markets, SOs manage and settle the ancillary service markets. Although each country has its SOs, in Europe, the association for cooperation of TSOs ENTSO-E is responsible of the secure operation of Europe’s electricity system. Besides, market operators or - as referred in Europe - NEMOs (Nominated Electricity Market Operators) are responsible for the economic management of the wholesale day-ahead and intraday markets.

Within the European flexibility markets, the research in this study primarily identifies the conventional balancing service markets. These include frequency containment reserves (FCR), automatic and manual frequency restoration reserves (aFRR and mFRR, respectively), and replacement reserves (RR). However, other flexibility products can be found in some European countries. It is the case in Spain, where within the ancillary services, a promising demand-side response (DSR) balancing service stands out, and a voltage control and capacity market non-frequency services are being developed. In the case of Germany, there also exists a service for interruptible loads, reactive power for voltage control, and a cold start capabilities service, among others [81]. All these flexibility markets, also known as ancillary services, aim to provide support to the grid. However, each has a specific purpose and is accompanied by a different list of requirements, which are also country-dependent. A standard classification is according to their physical characteristics, used in Refs. [33,44,82,83]. This differentiates three types of services, regulation, spinning and non-spinning reserves, and replacement reserves. Regulation, the fastest and most profitable ancillary service, maintains grid frequency in near real-time. Spinning reserve provides immediate capacity during power system contingencies, while non-spinning reserve requires slightly more time. Replacement reserve restores the operational state after contingencies. Each type varies in activation time, duration, information and communication technologies (ICT) requirements and service settlement. Table 6 summarises the main flexibility markets in Europe and provides a short description of each service.

In addition to flexibility markets, there are other energy markets that are relevant to industrial flexibility marketing (implicit DSR). These are the wholesale day-ahead and intraday markets. The day-ahead spot markets provide a straightforward way to market production flexibility. Products are hourly energy delivery, and auctions close the day before

Table 6
Description of the European ancillary services.

Service name	Short description
FCR	Stabilise frequency deviation after a disruptive event (regulation). Controlled solely by the grid frequency: activation is carried out by decentralized, local devices of the technical units. High technical and qualitative requirements since it must act in near real-time.
aFRR	Restores frequency after deviation to target frequency. Automatic activation. Fast replacement of the primary reserve, with lower technical requirements than FCR.
mFRR	Restores frequency after deviation to target frequency. Manual activation. Fast replacement of secondary reserve, to make aFRR available again for short-term interventions, and preventive use for more significant frequency deviations. Lower technical requirements than aFRR.
RR	Replacement of secondary and tertiary reserves, to make aFRR and mFRR available again for further deviations in the grid frequency. Comparable to mFRR, but even lower technical requirements and slower activations times.

delivery at noon, allowing time for scheduling electricity consumption (implicit DR). Prices are volatile and dependent on external factors, but can be leveraged through dynamic electricity tariffs, enabling load shifting between high- and low-price hours. Intraday auctions, also held the day before, offer tradeable half-hourly and quarter-hourly products. Continuous intraday trading, which contains the same products as the intraday auction, permits bidding up to 5–30 min before electricity delivery, capitalising on volatile prices for potential profit. Spontaneous trading opportunities arise, allowing short-term adjustments to planned electricity supply schedules.

3.2. Flexibility regulations

Regulation for flexibility markets refers to policies and rules set by governing bodies to facilitate the trading of flexible resources, such as energy or capacity. These regulations can include rules for the scheduling and dispatch of DR resources, pricing mechanisms, and requirements for the measurement and verification of DR performance. The rules for operation in balancing power markets are typically set by the governing body responsible for overseeing the electricity market in a given region or country. In many cases, this may be a regulatory body or a SO that is responsible for ensuring the safe, reliable, and efficient operation of the electricity grid. The participation in any of the balancing services, the technical and operational capability to provide the service must first be demonstrated to the managing SO. Likewise, a participation application must be submitted and several telemetry and communication requirements, among others, must be validated. Generally, all these requirements can be found described in the TSO of the country online sites.

In the same way, the characteristics that define each of the balancing services are also published on the official sites of the managing SO. It is essential that industries or final consumers who want to provide a DR service take them into account, since some of them may be indispensable in their decision-making, whether for reasons of technical or economic feasibility. One of them is the full activation time or responsiveness, which defines the maximum reaction time in which you must be able to deploy the flexibility offered, either a reduction or increase in consumption. Other important parameters are validity period, which defines the time window in which the accepted flexibility must be deliverable, and the minimum amount of power offered or bid, which for many end-users becomes a limitation since traditionally this minimum has always been very high (e.g. 1 MW).

Table 7 presents the main balancing ancillary services in Europe, showing the most relevant characteristics of each of these services. The

Table 7
Balancing services in Europe and their requirements and characteristics.

	Country	Full activation time [min]	Validity period [min]	Minimum amount of power	Minimum duration [min]
FCR	EU	0.5	240	1 MW	National responsibility
aFRR	EU[a](PICASSO)	5	15	1 MWh	–
	Germany[b]	5	240	1 MW	–
	Italy[c]	0.3	n.a.	10 MW	–
	Norway	5	60	1 MW	–
	Spain[d]	0.5	15	1 MW	0.33
mFRR	EU (MARI)	12.5	15	0 or 1[e]	5
	Germany	12.5	240	1 MW	5
	Italy	15	120	1 or 10 MW[f]	–
	Norway[g]	12.5	60; 15	1; 10	5
	Spain	15	120	1 MW	120
RR[h]	EU (TERRE)	30	15–60	0 or 1	15
	Germany	n.a.	n.a.	n.a.	n.a.
	Italy	120	480	1 or 10 MW[i]	–
	Norway	n.a.	n.a.	n.a.	n.a.
	Spain	30	15–60	1 MW	15
DSR[j]	Spain	15	180	1 MW	–

[a] The European platforms (PICASSO, MARI and TERRE) only cover **energy markets**.
[b] In Germany, only the **capacity markets** for **balancing power** are listed for **aFRR** and **mFRR**, the energy markets are connected to the European platforms PICASSO and MARI from 2022.
[c] In Italy, only the **energy markets** are listed for aFRR and mFRR. RR is connected to the European platform TERRE.
[d] In Spain, only the **energy markets** are listed for aFRR and mFRR. RR is connected to the European platform TERRE.
[e] 0 MW for fully divisible bids, 1 MW otherwise as the minimum amount of energy bids for **mFRR** or **RR**.
[f] 1 MW is valid for mixed aggregate virtual units (UVAM) pilot projects only, started in 2018. They may include consumption, production (including RES), and energy storage units (including the vehicle-to-grid).
[g] Norway is currently in a harmonisation process with Sweden, Finland and Denmark in the so-called **Nordic Balancing Model**, that will change the future regulations for the capacity and energy market. In the table is given the current situation (**status: 2022–12**) for the **national Norwegian capacity** and **energy market** for **mFRR**.
[h] Only **energy markets**.
[i] 1 MW is valid for UVAM pilot projects only.
[j] Activations can only be made from Monday to Friday from 8 a.m. to midnight (October to March), and from 6 p.m. to midnight (April to September), with a duration of 3 h per day.

services of few specific countries of the European union (i.e. Spain, Germany and Norway) are also shown in Table 7 in order to highlight the current lack of uniformity in market regulation.

As it can be deduced from Table 7, not any service can be easily provided, and will depend to a large extent on the industrial process of the factories, their degree of automation and their responsiveness.

3.3. Evolution of European harmonisation

To further strengthen the stability of the grid system and the European electricity interconnection between the countries, a guideline for electricity balancing (EBGL) and market regulations (CACM) have been developed by the ENTSO-E and its national TSOs in cooperation with the European agency ACER. These guidelines describe and establish common principles for the procurement and the settlement of different ancillary services and functional cross-border electricity market operations. The European harmonisation shall enable stable cross-border exchange of balancing energy and capacity, connect balancing markets and power exchanges, and streamline the integration of new generation, storage, and demand-side load management technologies.

In the last few years have been built for the most relevant ancillary services the platforms FCR Cooperation (FCR), PICASSO (aFRR), MARI (mFRR) and TERRE (RR). The platforms have been designed to transfer the national auctions for the procurement of balancing energy into a European auction (FCR is an exception, as the auction only covers the capacity market). TERRE platform for RR provision is not yet active, but it offers lower entry barriers compared to the other markets. MARI platform has been operational since October 2022, allowing bid submissions of energy provision for the following day. PICASSO has been operational since June 2022. It is structured similarly to MARI, but since aFRR requires fast energy delivery, it is currently unattractive for most energy-intensive companies. Finally, FCR Cooperation only accepts symmetrical bidding and requires high technical requirements, limiting the participation of many companies.

Capacity reserves are not yet tendered via the platforms but through national TSOs, although there is already European cooperation to harmonise capacity markets in the form of two regional projects: ALPACA, constituted by TSOs from Central Europe, and the Nordic Capacity Market for the Scandinavian countries. Both focus on aFRR, but in the future, mFRR capacity will also be included. Other ancillary services are intended to be harmonized. A draft regulatory framework for DR harmonisation was published by ACER in December 2022 [84]. Besides harmonisation, other possibilities to facilitate industry participation in explicit DR programmes could include decreasing the minimum bid size and technical assistance to manufacturers on ICT requirements, such as data acquisition and communication [85].

4. Energy-aware manufacturing scheduling and planning

For participating in DR programmes, industries should efficiently schedule and plan their manufacturing proces s, taking into account energy consumptions and costs. This Section focuses on literature describing the overall framework for production planning and control (Section 4.1), and the available models and algorithms to design optimized production plans that can enable industries to participate in implicit and explicit DR programmes (Section 4.2).

4.1. Energy oriented production planning framework

Most scientific studies distinguish the classical Production Planning and Control (PPC) frameworks into long term (strategic), mid term (tactical), and short term (operational) PPC levels with associated tasks, decisions, roles, and input-output relationships [86–90]. (i) The long term (strategic) planning level determines the aggregated production and inventory levels, and rough-cut capacity plans (e.g., the size of workforce) in aggregated volumes over monthly/yearly time frames. The input for this level includes for example aggregated demand forecasts for product groups, business and sales plans, aggregated resource capacities (e.g., workforce, machines, inventories). (ii) The mid-term (tactical) planning and scheduling level incorporates the quantity and timing decisions over daily/weekly time frames, such as production lot sizing and inventory levels for end products and components, capacity requirements plan, and basic plant schedule for orders and processes. The input consists of more detailed information about actual orders, forecasts, inventories and capacity levels. (iii) The short term (operational) scheduling and control level (minutes/hourly/daily) deals with the most detailed decisions for scheduling and dispatching the specific production orders to specific production units/resources, and continuous monitoring and controlling of the production execution.

As the energy resource has been becoming a critical element of costs and constraints in production, energy-oriented PPC adds important input-output relationships into optimisation of production plans in terms of costs, quality, and service levels. At the long term strategic PPC level, energy contracts with energy suppliers and rough-cut energy procurement (both internal and external) plans should be considered. Fig. 4 illustrates the connection and matching of production planning and scheduling functions with energy management functions and modules for energy-oriented production planning, such as energy-supply oriented order planning and scheduling [91], and energy-cost oriented scheduling of production loads and energy storage (e.g. battery) usage in line with day-to-day energy prices [92]. At the short term operational PPC level, energy-oriented production execution and control requires flexible load adaptation, adjustment of process starts and interruptions, to generate flexible and efficient energy consumptions [93].

4.2. Optimisation models and algorithms

This section focusses on the operational level, where the impact of short-term variations in the context (electricity prices, renewables generation, demand, etc.) can have a huge impact on production scheduling. Various studies have presented insights into either production scheduling or DR management in literature [94–97]. However, the number of papers that have emphasised scheduling and DR management together is low. This section of the survey deals with flexible production planning and control systems that combine energy flexibility considering the manufacturing constraints with a focus on DR management. The main idea of a scheduling problem is to allocate the shared resources to different tasks in a way that the defined objective criterion, like makespan, tardiness, etc., would be optimized. Scheduling problems can be categorised into four classes: single machine scheduling problem (SMSP), parallel machine scheduling problem (PMSP), flow shop scheduling problem (FSSP), and job shop scheduling problem (JSSP).

SMSP is a type of scheduling problem where the jobs need to be

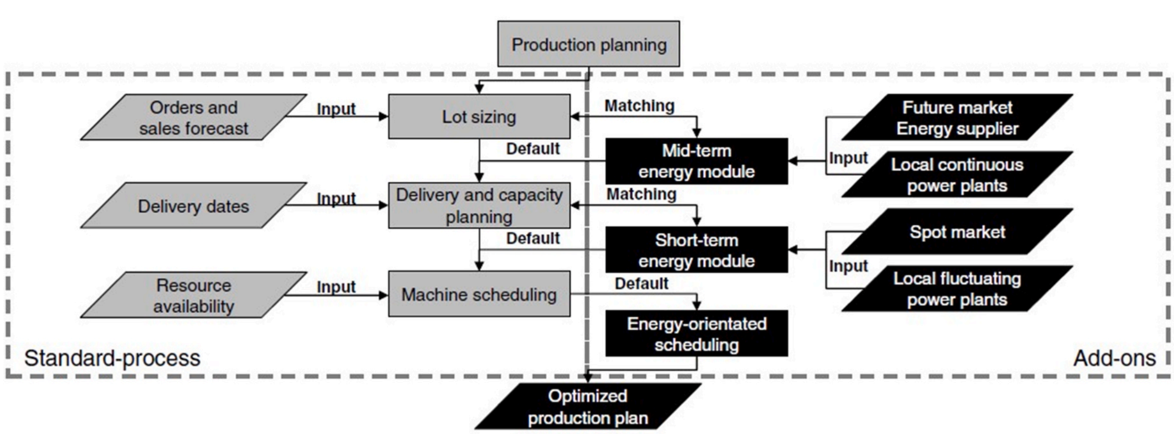

Fig. 4. Extended energy-oriented tactical-level production planning process. Source: [91].

scheduled on a single machine [98,99]. PMSP is to schedule jobs processed on a bank of the same function machines in parallel [100–102], which can be considered as the generalisation of the SMSP. In FSSPs, all jobs have to undergo the same series of operations and follow the same route [103,104]. In JSSPs, each job contains a series of operations whose sequence is predetermined [105–109]; the difference with FSSP is that jobs in a JSSP do not necessarily follow the same route.

5The papers analysed for each of the four types of scheduling problems are summarized in Table 8 and described in the following paragraphs. For each type of problem, firstly the papers that implemented implicit DR are addressed and then the papers that implemented explicit DR are reviewed. Also, this research classified the papers according to the solving method used, which can be exact or heuristic, i.e. intuitively designed procedures to find a good suboptimal solution with low computational requirements [110,111], depending on the complexity of the problem addressed.

Starting with the SMSP, Che et al. [112] formulated a mathematical model to minimize both maximum tardiness and total energy Consumption in a SMSP with a power-down mechanism. Aghelinejad et al. [98] investigated a SMSP under TOU tariffs, where machines' speed is scalable and their EC differs from job to job. They also considered three different modes, including the processing-state, idle-state, and off-state, for the machines, which affects their EC. Wu et al. [99] examined SMSP considering release dates under TOU electricity tariffs by proposing time-indexed and period-based mathematical models and a two-stage based on tabu search to minimize the total electricity cost (TEC).

Regarding PMSP, which can be considered as a generalisation of the SMSP, Abikarram et al. [100] presented a mathematical optimisation model for a PMSP under consideration of both demand charges and consumption charges. Saberi-Aliabad et al. [101] proposed a mathematical model and a fix and relax heuristic for unrelated PMSP to minimize TEC under TOU tariffs. Zhang et al. [102] evaluated a two-stage PMSP where one stage contains speed-scaling machines and the other one is compromised of unrelated parallel machines. They formulated a mathematical model and designed a tabu search-greedy insertion hybrid to minimize TEC under TOU tariffs. Papers focusing on flow-shop and job-shop problems could address both implicit or explicit DR (while the SMSP and the PMSP only focus on implicit), thus they are classified like that in the following.

Regarding the FSSP for implicit DR, Zhang et al. [113] considered both the TEC and the total carbon emissions; They proposed a mathematical model for the energy-aware FSSP. Ramin et al. [40] developed a methodology to schedule the day-ahead operations, which incorporates market-related aspects and critical manufacturing constraints. A 2-stage stochastic model for an energy-cost-aware FSSP was developed by Fazli Khalaf and Wang [103], where the production system is supplied by grid and energy storage. The model aims to maximize the total profit of renewable fed into the grid and to minimize TEC under real-time energy prices. Biel et al. [114] designed a two-stage decision support tool to handle the uncertainty attached to wind speeds and wind power generation, where they decide about the schedule and energy supply in the first stage and take real-time adjustment action to adapt the energy supply decisions according to the actual wind power. Sofana Reka and Ramesh [123] formulated a DR day-ahead pricing scheme for a refinery plant as a stochastic model to minimize a two-stage cost function. Luo et al. [117] dealt with a FSSP considering the electric power cost based on TOU tariffs and production efficiency as the objectives. They proposed a multi-objective ant colony optimisation (MOACO) to tackle this problem. Zhang et al. [104] introduced a method for energy-efficient FSSPs to deal with the delivery time and electricity cost under TOU electricity tariffs. They considered three modes for the machine tools, namely set-up, stand-by, and processing, and tried to shift more energy-consuming activities to the off-peak periods. Duan et al. [118] introduced the moth-flame optimisation algorithm to improve the non-dominated sorting genetic algorithm II (NSGA-II). Considering makespan and carbon emissions as objective functions, they combined NSGA–II with moth-flame optimisation algorithm to schedule heterogeneous processes in a production system. Summerbell et al. [52] introduced a load-shifting method based on available inventory storage, to minimize either CO2 emissions or electricity costs.

Regarding the FSSP for explicit DR, Xenos et al. [120] introduced a solution to tackle the reliability issues faced by the TSO, where they find the optimal schedule, called baseline power consumption, for non-dispatchable programs in each time period. Then, they considered this baseline as an input to find the solution based on the dispatchable program. Zhang et al. [121] proposed a two-stage optimisation methodology to obtain an incentive-based DR load-scheduling to face the challenges and uncertainties of a real-world DR implementation and improve user satisfaction.

Regarding the JSSP for implicit DR, Corominas et al. [115] studied just-in-time JSSP, where they formulated a mathematical model and designed a graph-based heuristic to solve the scheduling problem by finding the shortest path. Park and Ham [116] used two different mathematical approaches to minimize total energy cost and makespan simultaneously. Roth et al. [92] investigated a mathematical model to solve the discrete problem of energy storage and production scheduling, where they studied a nitrogen production plant that generates electricity through photovoltaics, purchases electricity based on a day-ahead pricing scheme, and stores the electricity through a Lithium-ion battery. The mathematical formulation is not suitable to mimic the dynamic EC due to the solver's intractability and scalability. Few studies used discrete-event simulation to consider more details, like power states (including startup and shutdown), in their model. Gong et al. [119] utilized discrete-event simulation to build a digital twin of the energy- and labor-aware flexible JSSP. Considering real-time energy prices, and varying labor wages over shifts, they developed a non-dominated sorting genetic algorithm-III to minimize different objectives, including total workload, maximal workload, total energy cost, makespan, and total labor cost.

Regarding the JSSP for explicit DR, Sinha and Chaturvedi [122] introduced a graphical methodology based on pinch analysis to minimize EC and carbon emission in the production system in order to satisfy future demand.

Table 8
– Classification of the references regarding the Optimisation models and algorithms for energy-aware planning and scheduling related with IDR.

Type of DR	Solving algorithm	Type of scheduling problem			
		Single-machine	Parallel machine	Flow shop	Job shop
Implicit DR	Exact	[98,112],[a]	[100]	[40,103,113,114]	[115,116]
	heuristic	[99]	[101,102]	[52,104,117,118],[a]	[92,119]
Explicit DR	Exact			[120]	
	heuristic			[121]	[122]

[a] Implicit DR based on CO2 emission (not electricity price).

5. Industrial demand response aggregator

An industrial demand response aggregator (IDRA) is a retailer, a balancing responsible party or a third-party company that groups distinct industrial clients in power systems [124]. Acting as an intermediary, the IDRA helps them commercialize their generation capacity and flexibility on the demand side. In general, the aggregation is not only limited to traditional industrial loads but can encompass all the other energy systems within the industry, such as energy storage system, wind or solar energy, and other distributed generation units. The IDRA provides their clients with recommendations or control signals for generation units and load profiles, to act as a virtual power plant (VPP) and actively participate in the wholesale, spot, and ancillary service markets. This way, the aggregation process creates economic value not only for their industrial customers, but also the power system in general. In this sense, there are many attempts to design new market rules so that the number of so-called independent aggregators can expand over time [125,126]. Also, different studies have been carried out to optimize industrial aggregators' operation [127–129]. The following sections describe the most relevant values created by IDRA (Section 5.1) and the current examples of successful IDRA commercial projects (Section 5.2).

5.1. Value created

An IDRA can play various roles in the process of marketing distributed energy resource flexibilities on the demand side [41,130,131]; between these roles, it can be mentioned:

1. **Identification of flexibility potentials**: IDRA can help industrial clients identify flexibility potentials in DR within their organisation whereas industrial clients can benefit from the IDRA's know-how on electricity markets. Typically, the IDRA provides the first impetus of this process, looking for new customers within a specific sector. However, identifying the potential for flexibility is not a major hurdle as quite often clients already have suitable energy management systems in place, so the industrial processes and energy requirements are already known.
2. **Realisation of flexibility potentials**: IDRA carries out all the activities between the identification of the potential and the activation and marketing of the distributed resource (e.g., personnel training, installation of ICT infrastructures and certified energy boxes, prequalification procedures for electricity markets, coordination issues with TSOs). In this process, the role of the IDRA has central importance since the barriers are mainly organisational than technical. A relationship of trust between the IDRA and the client is necessary so that the latter seriously considers the implementation of its potential for flexibility and enables the IDRA to control its industrial processes.
3. **Automation**: IDRA can disseminate the knowledge and implement automation of the provision of flexibility from industrial processes at the client site (e.g., sending of control signals, automated and integrated resource planning). The degree and depth of the automatic activation depend on the market where the flexibility is offered therefore a close collaboration between the IDRA and the client is necessary since the former knows the electricity markets while the latter knows the technical structures.
4. **Participation in electricity markets, services & provision of related information.** IDRA provides industrial clients with information such as electricity prices and minimum bids, and it leaves the use of this information to their clients; alternatively, the IDRA participates in these markets on their behalf. In the latter case, the IDRA helps the clients to overcome the cost barrier (e.g., certified ICT infrastructure, complex optimisation models, backup capacity, personnel updating, 24-h trading desk) for market participation, offering them the possibility of spreading these costs among many.
5. **Provision of risk management products and suitable contracts:** IDRA can provide the industrial client with risk management products as well as suitable contracts for the industrial client (e.g., standard exchange-traded contracts, non-standard contracts) to overcome the uncertainty barrier of electricity prices (e.g., insurance against short-term spot market price risks, the guarantee of minimum revenues) and changes in the regulatory framework.
6. **Bundling of services**: the IDRA can provide the industrial client with a suite of services (e.g., participation in intraday and day-ahead markets, balancing and ancillary services markets, electricity, and gas markets) instead of just one. Creating a suite of services allows the IDRA to reduce the cost of activating new customers since it is easier to sell a service to a customer when a business relationship already exists for another service. At the same time, purchasing a suite of services ensures the industrial client better management of his portfolio on markets, especially if the client owns both gas-powered and electricity-powered industrial processes.
7. **Provision of incentives to customers**: to encourage customers to actively participate in DR, the IDRA can offer free products (e.g., smart meters), free services (e.g., preliminary energy audit, estimation of expected economic benefits), and economic incentives such as discounts on electricity rates.

Overall, IDRAs main objective is to assess and realize flexibility potentials considering holistically the energy flows of their customers, acknowledging the real-life constraints of each application. If flexibility is marketed successfully, without hindering the industrial production processes, this approach can be beneficial both in terms of costs and emissions reduction compared to unidirectional relations with conventional retailers.

5.2. Applications

IDRAs can provide a wide range of energy services to their customers, with recorded cases of companies covering most of the value-creating roles identified in the previous section. Kerscher and Arboleya [132] propose such classification, indicating IDRAs operating in various geographical locations across Europe. Within the recorded commercial enterprises, the projects summarized in Table 9 have been identified. The Spanish company Bamboo Energy, for example, investigated for the frozen bakery company Europastry [133] the possibility of enabling the flexibility of their industrial refrigerator to participate in flexibility markets, with capacity of up to 0.5 MW. Others profitable recorded applications of IDRA include more holistic approaches to help industrial clients market their flexibility while increasing their self-consumption. This is the case of the collaboration between the German aggregator Next-Kraftwerke and the manufacturer and distributor of high-end printable products Peleman Industries [134]. The IDRA provided market access for the site's 2 MWh energy storage system by including it in its FCR fleet within a VPP, providing balancing services using up to 80 % of the battery's capacity. Also in Germany, the company Entelios AG, published several successful implementations across various industrial customers. For TRIMET Aluminium [135], it aggregated the load curtailment of an electrolysis furnace to up to 25 % of its nominal capacity as a virtual battery of a VPP. This allows TRIMET to market their flexibility, providing grid reserves. For BASF's Schwarzheide site [136], it provided electricity trading services taking advantage of one of the firm's combined cycle production plants with the volatility of intraday energy prices. Finally, another example can be found in Britain, where the company Fl exitricity performed as an IDRA aiding the multi-temperature warehousing Norish [137] leveraging the flexibility of a cooling plant to offer short-term operating reserve energy to the grid.

6. Digitalisation of the industry

Digital technologies are transforming production, processing, and delivery across industries. The optimisation enabled by digitalisation is projected to lead to energy savings of at least 10–20 % [138]. Also, the importance of digitalisation to provide better DR services has been recently highlighted [29,139,140]. Digitalisation enhances operational efficiency, adaptability, and resilience in manufacturing processes, allowing for adjustments in energy sources and prices and developing strategies to mitigate the impact of disruptions. When compared to the industrial sector, the energy sector has adopted digital technologies early on and the integration of sustainable energy systems with digital technologies will drastically alter energy generation, distribution, and consumption [141]. As part of the Industry 4.0 era, the integration of physical and digital infrastructure in the energy sector will result in the digitisation of power plants. Big data analytics, industrial simulation, and sensor-based condition monitoring offer massive opportunities for

Table 9
– Examples of successful IDRA commercial projects.

IDRA	Country	Industrial Sector	IDRA Activity	Industrial flexible equipment	Estimated flexibility
Bamboo Energy	Spain	Food industry	Identified flexibility and provided market access	Refrigerator	0.5 MW
Next-Kraftwerke	Germany	Printable Products Manufacturing	Aggregated ESS into VPP for FCR	Energy storage	2 MW and 1.6 MWh of capacity
Flextricity	England	Multi-temperature warehousing	Identified flexibility and provided market access	Cooling plant	0.9 MW
Entelios	Germany	Metallurgical (Aluminum)	Aggregated as virtual battery for DR in VPP	Electrolysis furnace	n.a.
Entelios	Germany	Chemical	Marketed flexibility of self-production plant	Combined cycle power plant	n.a.

infrastructure management, grid reliability, and efficient production planning, leading to improved power generation, transmission, and distribution [142]. Additionally, new digital technologies such as blockchain-based peer-to-peer electricity trade, smart charging, and cloud DR systems can support the integration of renewable energy resources like residential solar panels and energy storage [143]. However, the energy-focused digitalisation of industry is still lagging behind. Generally, the current digital technologies affecting the industry can be grouped under the concept of Industry 4.0 [144–146]:

I. Cyber-physical systems (CPS) - A collection of technologies that connect physical assets and computational capabilities to monitor and control physical systems.
II. Internet of things (IoT) Sensors - Embedded sensor technology for monitoring physical assets.
III. Big data and analytics - Collection and analysis of large amounts of data.
IV. Edge computing - Distributed IT architecture in which client data is processed at the periphery of the network, as close to the originating source as possible improve ability for real-time business insights, equipment maintenance predictions or other actionable information.
V. Cloud technology - Application of cloud computing in products, enhancing their capabilities and related services.
VI. Artificial intelligence (AI) - Systems that think like humans and rationally using six main disciplines, including natural language processing, knowledge representation, automated reasoning, machine learning, computer vision, and robotics.
VII. Automation and industrial robots - Machinery and equipment that automate operational processes, including Collaborative Robotics, which allows humans and machines to work in a shared learning environment.
VIII. Digital twin - Technologies that mirror the physical world in a virtual environment, with the aim of simplifying and making the design, creation, testing, and live operation of systems more affordable.
IX. Visualisation technology - A set of innovative computer technology applications that create an interactive world, allowing the user to control virtual objects and the whole virtual scene in real-time.
X. Additive manufacturing - The process of building objects by joining materials in successive layers using 3D model data, unlocking design options and offering potential for mass customisation.
XI. Blockchain - A database that creates a tamper-proof and distributed digital ledger of transactions, with timestamps of blocks maintained by every participating node.

The digitalisation of the industry will impact the DR by a) identifying, monitoring and controlling energy-intensive processes b) enabling flexible and robust manufacturing, and c) enabling dynamic negotiation with aggregators and autonomous adaptation.

a) Digitalisation for identifying, monitoring and controlling energy-intensive processes

The latest advancements in digital technology provide new approaches to tackle energy efficiency challenges and reach new heights, from enhancing regulation and policy to improving data analysis and stakeholder connections throughout the entire energy sector, from generation to consumption. For instance, the use of IoT sensors, digital twins, and big data analytics can identify energy-intensive processes and facilitate DR measures [43]. The combination of such data with the Edge Computing technology can support on creating an intelligent environment where the resources are made smart with the ability of self-sensing, self-analytics and self-optimisation [146]. Analysing data can also help identify inefficiencies and reduce energy demand through improved energy efficiency [147]. Maximizing energy efficiency is crucial for a comprehensive energy policy strategy.

b) Digitalisation for manufacturing flexibility

Manufacturing flexibility is a multi-dimensional concept and there is no general consensus on its definition. Nonetheless, the concept of manufacturing flexibility aims to employ strategies and methods to quickly and efficiently respond to changes in production demands, disruptions in the supply chain, and market conditions in the face of uncertainty [148]. The field devices on the shop floor generate large amounts of data can be useful, in an IoT-Edge computing architecture, for maintenance planning and prognostics and health management [149]. In the context of DR, manufacturing flexibility is crucial because it allows manufacturers to respond to changes in energy demand and supply in real-time, reducing energy costs and ensuring grid stability. In DR programmes, energy consumption can be managed by adjusting production processes, shifting energy use to off-peak hours, and using alternative energy sources. These changes can be facilitated by a flexible manufacturing system that can respond quickly to changes in energy demand and supply. Thereby, digital technologies such as CPS can help to balance production systems and share capacity to enable manufacturing flexibility [150,151]. Moreover, In the process industry, energy-intensive production is common. Industry 4.0 technologies have shown that these processes can become more flexible by integrating autonomous material handling solutions, connecting machines and workstations throughout the production system to create decentralized production systems [152].

c) Digitalisation of manufacturing systems for dynamic negotiation with agents and autonomous adaptation

Central control architectures are still dominating manufacturing systems, hindering rapid adaptations to changes. The advancement of digitalisation and AI is driving the decentralisation of decision-making. Decentralized control is a vital component of Industry 4.0, enabling dynamic adaptation and improved performance through decentralized decision-making. The digitalisation and decentralisation of decision-making in manufacturing systems allows for dynamic negotiation with agents such as aggregators that offer both manufacturing and energy flexibility, enabling autonomous adaptation to agreed terms. As manufacturing systems become more autonomous, the potential for offering and responding to DR increases significantly. Although many studies advocate the use of decentralized multi-agent systems for DR, there has been limited real-world adoption [128]. For example, Lu et al. [153] utilized agent-based deep reinforcement learning to determine the optimal energy management schedule for discrete manufacturing systems and minimize electricity costs while improving grid stability. However, the study does not provide implementation details for the hardware layer. Additionally, Davarzani et al. [154] introduced a decentralized multi-agent system framework to achieve flexible price-based DR at the local distribution level of the grid. Summarizing, Table 10 shows the technologies under the umbrella of industry 4.0 that can support positively the DR in an industrial setting.

7. Research projects

To achieve the realisation of the DR as a means to cover the flexibility gap, research projects have been undertaken in order to improve tools such as digitalisation or aggregation, as well as providing guidelines in the definition of regulation. This section summarises some relevant projects but other studies considering real-use cases can also be found in literature [35]. The main characteristics of the research projects reviewed in this study are summarized in Table 11.

Once demonstrated grid operators can enable stakeholders to participate in energy markets in Integrid project [174], and understanding the DR as a service to support the electrical grids, challenges such as the interaction between distribution and transmission networks (and their respective operators, DSO-TSO) and regulatory framework requirements have been addressed in Refs. [175,176]. These projects have developed tools and methods to provide grid services such as voltage regulation, load balancing, congestion management or islanded operation and have mainly considered residential and commercial sectors. While the industrial sector is also considered, how industries can provide DR have not been addressed.

In [5], different decision supporting tools have been developed to increase energy efficiency as well as for reduction of the energy cost by including the energy vector in production planning algorithms. While [177] focussed on implicit DR program, explicit DR has been explored in Ref. [178], analysing its potential in Germany. Currently, implicit and explicit DR is being addressed in Ref. [180]. For this purpose, tools such as digital twins, energy-aware production planning and aggregation platforms are being developed. The solutions will be tested in five pilot cases around Europe. A similar project is also undergoing that will study how to redesign and optimize production processes with the progressive inclusion of renewable energies in order to help industries providing emerging DR flexibility services to the grid [181].

8. Discussion

In this Section, it is analysed how the different resources (or enabling technologies) reviewed in this work i.e. energy-aware scheduling and planning, aggregators, digitalisation and research projects, can help industries to address the main challenges in implementing DR programs, i.e. economic, market, regulation, technological, organisational and sociotechnical (section 2.5). Some promising future research lines are pointed out at the end of Section. A summary of the analysis carried out is shown in Table 12. Based on Table 12, the relation between the enabling technologies with each challenge is also shown graphically in Fig. 5.

Currently available energy-aware scheduling and planning tools can significantly support industry participation in both implicit and explicit DR programmes: planning optimisation models permit a detailed evaluation of DR benefits (economic challenge), help generating DR offers (market challenge), provide a better understanding of relationship between production planning and energy management (organisational challenge), and increase transparency, technical knowledge and acceptance among employees (sociotechnical challenge). Furthermore, heuristic models can be used to obtain good solutions with limited computational requirements (technological challenge).

Aggregators (IDRA) help industries to commercialize their flexibilities on the demand side. As shown in Section 3, the regulation in different countries is still demanding a high minimum quantity of power to enter in the market, which does not allow small industries to access the market alone. Aggregators may enable those industries participating in the market as a cluster, thus cumulating their flexibilities (market challenge). IDRA can also provide relevant information regarding regulations, electricity prices, minimum bids, etc. (regulatory challenge), help in the collection and process of market data (technological challenge), and help industries in identifying their flexibility potentials in DR within their organisation (sociotechnical challenge). In addition, participating as a cluster can reduce the cost for entering and improve the economic benefits of DR (economic challenge).

Digitalisation drives the emergence of a highly interconnected system, blurring the line between traditional energy suppliers and consumers. This leads to increased opportunities for local energy trade and grid services. While digitalisation plays a crucial role, the electrification of energy services and the growth of decentralized power sources, which would occur regardless of digital technologies, are equally important drivers. The combination of digitalisation and energy technologies can facilitate the expansion of DR in energy consumption. Specifically, the digitalisation of the industry enables the identification, monitoring, and control of energy-intensive processes, flexible manufacturing, and dynamic negotiation with aggregators. CPS support production planning

Table 10
– Digital technologies supporting DR in an industrial setting.

Digital technologies	Digitalisation for identifying, monitoring and controlling energy-intensive processes	Digitalisation for manufacturing flexibility	Digitalisation of manufacturing systems for dynamic negotiation with aggregators and autonomous adaptation
CPS	[155,156]	[150,151,157]	[128]
IoT sensor	[158]	[159,160]	
Big data and analytics	[161,162]	[159]	
Edge computing	[146]	[149]	
Cloud technologies		[163]	[32,164]
AI	[165]	[166]	[48,153]
Robots		[152,167]	
Digital twin	[43,147]	[168,169]	
Visualisation technology	[170]	[171]	
Additive manufacturing		[172]	
Blockchain			[173]

Table 11
– Research projects that support IDR.

Project	Status	Sector	Services provided	Energy-aware scheduling	Aggregation	Digitalisation	Challenges	Market regulation
InteGrid (H2020) [174]	Finished (Oct 2020)	grid-side perspective (MV-LV) residential sector	Voltage control Operational planning DR for TSO	Not applicable	Yes	Yes	Demonstrate DSO can enable stakeholders to participate in energy markets	Yes
INTERRFACE (H2020) [175]	Finished (Dec 2022)	residential	Load Balancing Voltage control (LV) Congestion management	Not applicable	Yes	Yes	TSO-DSO interaction regulatory	Yes
Coordinet (H2020) [176]	Finished (Jun 2022)	residential commercial industrial (only from grid-side perspective)	Load Balancing Congestion management Island operation Voltage control	Not applicable	Yes	Yes	TSO-DSO interaction	Yes
CoPro (H2020) [177]	Finished (Jun 2020)	Industrial	Energy cost reduction	Yes	Yes	yes	Improve energy and resource efficiency Design energy price-based production scheduling	No
SynErgie [178,179]	Finished (Nov 2019–Oct 2022)	Industrial (energy intensive industry)	Day ahead Energy markets Balancing	Yes	No	yes	Flexibilize energy intensive process	Yes
FLEX4FACT (Horizon Europe) [180]	On-going (Jun-2022 to Nov-2025)	Industrial (energy intensive industry)	CO2 emissions reduction Self-consumption Energy cost reduction Balancing	Yes	Yes	Yes	Exploit manufacturing flexibilities Provide DR services	No
FLEXIndustries (Horizon Europe) [181]	On-going (Jun-2022 to May-2026)	Industrial (energy intensive industry)	CO2 emissions reduction Energy cost reduction Self-consumption Energy and process management Balancing	Yes	No	Yes	Flexibilize energy intensive processes Manage emerging DR mechanisms	No

Table 12
– Challenges addressed by the different resources described in this review.

		Resources			
		Energy-aware scheduling and planning	Aggregators	Digitalisation	Research projects
Challenge general category	**Economic**	Efficient Scheduling and planning tools can provide a better evaluation of DR benefits	Participating as a cluster can reduce the cost for entering and improve the economic benefits of DR	CPS can support production planning. AI, big data and cloud technologies can improve price forecasts	Tools and methods developed by R&D projects can reduce costs associated with participating in DR
	Market	Energy-aware scheduling and planning tools can help generating DR offers	IDRA can participate in the market instead of the industry directly	Automated manufacturing (supported by IoT, robots and additive manufacturing) and AI can enhance real-time response and thus possibly to generate real-time flexibility offers to the market	Research projects can help in defining adequate market procedures
	Regulation		IDRA can provide relevant information regarding regulations, electricity prices, minimum bids, etc.	Digitalisation can address data security issues in legal frameworks	Research projects can help in defining more efficient and standardized policies
	Technological	Heuristic models can obtain near optimal production plans with low computational requirements	IDRA can help in the collection and process of market data	Digitalisation technologies are becoming cheaper and more accessible also for Small and medium enterprises	Research projects can help in understanding industry needs and develop specific and user-friendly technologies for IDR
	Organisational	Better understanding of relationship between production planning and energy management		CPS and digital twins can help industries to identify the flexibilities of their processes	Lack of internal resources can be supplemented by R&D projects that bring external resources with low costs
	Sociotechnical	Planning tools can increase transparency, technical knowledge and acceptance among employees	IDRA can help industries identify flexibility potentials in DR within their organisation	IoT sensors, digital twins, and big data analytics can identify energy-intensive processes. Visualisation technology can enhance user-acceptance of DR	Research projects can disseminate latest advancements in technology and policies

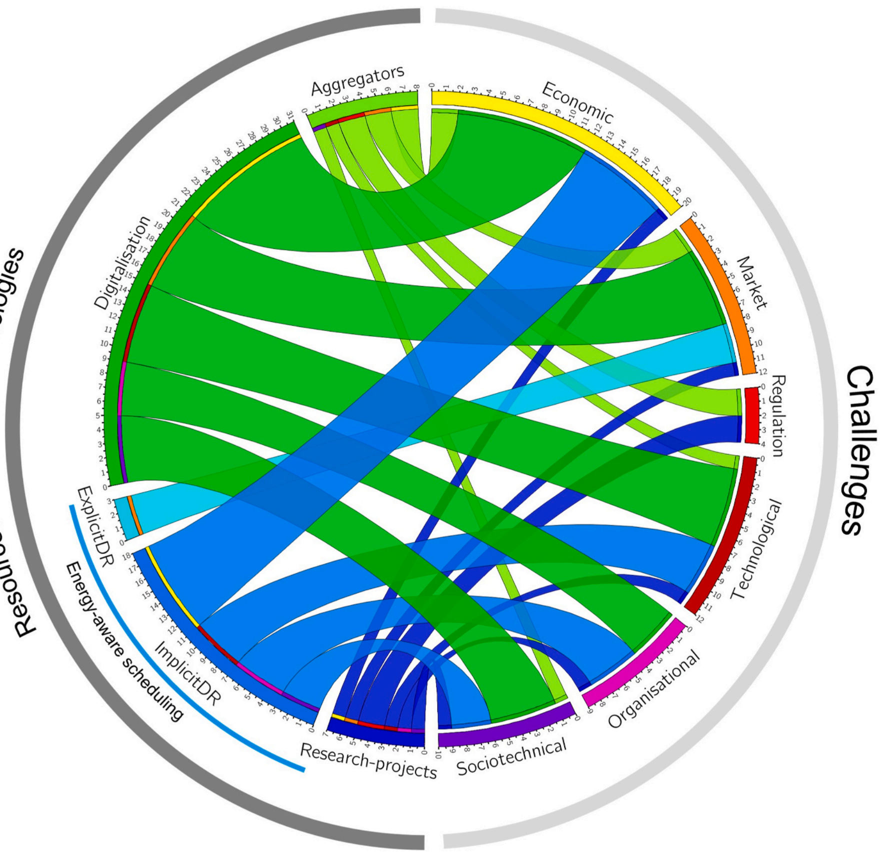

Fig. 5. – Chord diagram relating the enabling technologies described in this review (left) with the challenges for IDR (right). The size of each enabling technology depends on the number of papers analysed in this review for that specific technology. The portion of those papers addressing a specific challenge is an own elaboration based on the review done.

and help industries identify process flexibilities, while AI, big data, cloud technologies, and automated manufacturing enhance price forecasts, optimisations, and real-time response. Additionally, digitalisation technologies are becoming more affordable and accessible to small and medium enterprises. In summary, digitalisation includes a bunch of transversal technologies that in different ways addresses all the main challenges categories (Table 12).

In particular, sharing and harmonising data models, algorithms, process models, workflows, can be a key element for the development of a "data universe" for industrial flexibility, following similar examples in other domains (e.g. OSDU for the oil and gas sector [182]), by leveraging experiences with use cases in different industrial sectors and linking relevant initiatives in the development of data spaces for energy applications (e.g. SAREF [183], OpenADR [38], EFI [184], USEF [37]). Research and innovations projects can help in this direction, supporting the understanding of industry needs and develop specific and user-friendly technologies for IDR, which can reduce costs associated with participating in such programmes (technological and economic challenges). Additionally, research projects can endorse industries lacking of internal R&D resources and enhance the dissemination of latest advancements in technology and policies (organisational and sociotechnical challenges).

The literature review carried out in this study can also help pointing out possible future research lines and developments. Regarding energy-aware planning and scheduling tools, the existing literature on scheduling problems primarily emphasizes implicit DR, particularly TOU and real-time pricing. In contrast, despite the fact that contracting with industries is common in distribution systems, scheduling problems incorporated with incentive-based explicit DR have received limited attention. Therefore, there is a massive potential for conducting research addressing scheduling problems combined with explicit DR. In addition, explicit DR can expose industries to the payment of a penalty if the load modification - over the given time period - is not respected. This risk is substantially different from the one that industries typically manage; and the potential revenues of explicit DR are often not deemed attractive enough by industries to take this step. Therefore, the supply of risk management products to industries could become the most relevant and arduous task of the aggregators (IDRAs), as well as the topic for future lines of research and development.

Moreover, the literature review revealed that digitalisation in an industrial context has primarily focused on identifying, monitoring, and controlling energy-intensive processes with its main goal is to enhance manufacturing flexibility and improve various key performance, including quality, productivity, throughput time, and resilience. However, in order to establish a dynamic system where IDR can operate, digitalisation needs to enable dynamic negotiations between industrial sites and aggregators, facilitating autonomous adaptation. To achieve this, future research should concentrate on enabling end-to-end data communication and modelling, allowing manufacturing make real-time decisions and adapt accordingly. Currently, manufacturing systems face challenges in dynamically reacting and considering all variables to make optimal decisions due to their high complexity. To fully unlock the potential and benefits of IDR, digitalisation, particularly through the utilisation of CPS, IoT sensors, big data and analytics, edge computing, cloud technology, AI, robots, digital twin, visualisation technology, additive manufacturing, and blockchain, can reduce complexity and support decision-making towards autonomous systems. Therefore, future developments and research in digitalisation should prioritize the integration of digital technologies, especially digital twin, to further decentralize decision-making processes, enabling autonomous negotiation and adaptation between aggregators and manufacturing.

It should be noted that the analysis carried out in this research focus on the current European context and regulation. The situation in other regions or possible changes in the regulation may affect the above discussion and the conclusions derived.

9. Conclusions

IDR is a very promising solution for exploiting demand-side flexibility [15]. As explained in Section 2, DR can bring significant benefits to the market, for the grid and for facilitating the integration of intermittent generation; also, due to their intensive electricity usage that causes the main demand peaks in the electricity system, industry has the biggest potential for providing DR in comparison with the residential or agricultural sectors, and the IDR potential has been already highlighted and quantified by many studies. This leads to a significant range of motivations for the industries to participate in DR programmes. The regulation has also been evolving recently in order to facilitate participation of the industries in such programmes (Section 3). Even those, some challenges are still preventing industries to apply DR programmes leading that the overall IDR potential is still highly unexploited (sub--Section 2.5).

This work has then reviewed the different resources (or enabling technologies) which are currently available to help industries participate and implement DR programmes, such as energy-aware scheduling and planning tools, aggregators, digitalisation and research programs. The main findings are summarized below:

- Energy-aware scheduling and planning tools of the manufacturing process can significantly support industry participation in both implicit and explicit DR programmes (Section 4).
- Aggregators, i.e. intermediaries between industries and power markets, demonstrated to play critical role in facilitating explicit IDR, raising awareness for the potentials of DR, as well as engaging key actors in industrial companies (Section 5).
- The importance of digitalisation to provide better DR services from the manufacturing industry has been highlighted in Section 6. In this sense, digital twins, Cyber-Physical Systems, Internet of Things sensors, Industrial Robots, edge computing, AI, and big data are promising technologies.
- The multiple research projects that have been publicly financed or are currently undergoing to support industries and standardize markets and regulations were analysed in Section 7.

As described in Section 8, a key finding of this study is that most of current challenges for the industries to enter in DR programmes and operate in the markets can be addressed by the resources reviewed in this research. Additional relevant results of the analysis carried out are the identification of remaining challenges and the highlight of future developments, which are reported below.

The remaining challenges could be related to the large gap between research and industrial application, namely the lack of data models, process models, and workflows that can be developed and tested for specific industries and then made available to other players in the same segment, as well as use cases from different sectors that can help generalise solutions and drive adoption beyond pilot implementations. The availability of such a framework could help companies reduce the initial investment required for initial data mining efforts and spend fewer resources adapting data streams to specific models in order to leverage existing tools developed based on such data models.

Additional support may come from dissemination activities (such as the review provided in this work), necessary to spread knowledge because sometimes industry or decision makers do not have access to the relevant information and are often unfamiliar with the tools available. In contrast, it should be noted that existing tools are generally focused on a specific subject (such as production planning or aggregators for entering in the DR market); the development of a holistic tool that can support industries in all the phases together would be highly recommended for removing remaining technological and social barriers. An example can be a platform that analyse energy consumptions, design production plans, generate and aggregate flexibility offers from different industries.

Finally, even if advancements in standardizing and simplifying have been recently done, regulations are still a barrier in many countries, preventing industries to participate in the markets. However, there is hope for having a harmonized European legislation soon. As this research focuses on the current European context, the study carried out should be extended in case significant regulation changes take place.

CRediT authorship contribution statement

M. Ranaboldo: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Supervision. **M. Aragüés-Peñalba:** Writing – review & editing. **E. Arica:** Investigation, Resources, Writing – original draft. **A. Bade:** Resources. **E. Bullich-Massagué:** Conceptualization, Writing – original draft, Supervision. **A. Burgio:** Investigation, Resources, Writing – original draft. **C. Caccamo:** Writing – review & editing. **A. Caprara:** Investigation, Resources, Writing – original draft. **D. Cimmino:** Investigation, Resources, Writing – original draft. **B. Domenech:** Writing – review & editing. **I. Donoso:** Investigation, Writing – review & editing. **G. Fragapane:** Investigation, Resources, Writing – original draft. **P. González-Font-de-Rubinat:** Investigation, Resources, Writing – original draft. **E. Jahnke:** Investigation, Resources, Writing – original draft. **M. Juanpera:** Writing – review & editing. **E. Manafi:** Investigation, Resources, Writing – original draft. **J. Rövekamp:** Resources. **R. Tani:** Investigation, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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