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# Demand-side management in industrial sector: A review of heavy industries

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ABSTRACT

The penetration of renewable energies is increasing in power systems all over the world. The volatility and intermittency of renewable energies pose real challenges to energy systems. To overcome the problem, demand-side flexibility is a practical solution in all demand sectors, including residential, commercial, agricultural, and industrial sectors. This paper provides a comprehensive review of industrial demand response opportunities in energy-intensive industries. Flexibility potentials are discussed from (1) viewpoints of power flexibility for cement manufacturing and aluminum smelting plants (2) viewpoints of joint power-heat flexibility for oil refinery industries. The flexibility potentials of industrial processes are classified based on their compatibility with time responses on long, mid, and short advance notices of different electricity market floors and ancillary service markets. Challenges and opportunities of industrial demand management are classified from viewpoints of power systems and industry owners. Software tools and solution methodologies of industrial energy models are surveyed for energy researchers. The studies show that cement manufacturing plants have great potentials in providing peak-shaving and valley-filling in crushers and cement mills with up to 10% and 16.9% reduction in energy consumption cost and power consumption, respectively. The aluminum smelting plants can provide up to 34.2% and 20.70% reduction in energy consumption cost and power consumption by turning down/off the variable voltage smelting pots.

## 1. Introduction

### 1.1. Background and motivation

In the last decade, the penetration of renewable energies, i.e. wind and solar, has increased considerably all over the world. For example, in the Danish sector of the Nordic Electricity Market, the share of wind energy increased from 44% in 2015 to 55% in 2020. This rate is scheduled to increase up to 60% in 2025. There is a similar pattern in the United States, Germany, and China which are investing heavily in renewable power generation [1]. Therefore, renewable energies are an essential and inevitable part of future power systems. Against thermal power, renewable power suffers from volatility and intermittency. Increasing the penetration of intermittent energy in future power systems, the stability and reliability of power systems are serious challenges. In this way, demand-side flexibility is a practical solution to hedge against uncertain renewable power. The energy consumptions of consumers, including residential, commercial, agricultural, and industrial sectors, have structural flexibilities that can meet the flexibility requirements of future power systems. To achieve the aim, the flexibility potentials should be extracted, aggregated, and finally integrated into the power system.

The flexibility potentials of the demand sectors are integrated into power systems to provide local and global system support. In the case of global support, the key aims can be stated as follows [2]:

1. Voltage compensation by reactive power management [3].
2. Power congestion management in weak lines of transmission and distribution networks [4].
3. Power loss reduction in transmission and distribution lines [5].
4. Power quality improvement in power grids, especially in critical buses [6].

Regarding the global power system support, the flexibility potentials fulfill the following underlying aims:

1. Providing power regulation during deficit and excess of renewable power generation [7].
2. Providing Power frequency control [8].
3. Preparing power reserves, including spinning, non-spinning, and supplemental reserves [9].
4. Increasing power system reliability and resiliency [10].
5. Reducing power system investment costs [11].

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**Acronyms**

| | |
|---|---|
| ADRA | Agricultural Demand Response Aggregator |
| CP | Clinker Production |
| CPP | Critical Peak Pricing |
| Cr | Crushing |
| CHP | Combined Heat and Power |
| DG | Distributed Generation |
| DR | Demand Response |
| DSM | Demand Side Management |
| FEMS | Factory Energy Management System |
| FG | Finish Grinding |
| FRP | Final Refining Process |
| GHG | Greenhouse Gas Emissions |
| HEMS | Home Energy Management Systems |
| HVAC | Heat Ventilation and Air Conditioning |
| IDR | Industrial Demand Response |
| KFP | Kiln Feed Preparation |
| ORI | Oil Refinery Industry |
| PEV | Plug-in Electric Vehicle |
| PLA | Parking Lot Aggregator |
| PRP | Primary Refining Process |
| RES | Renewable Energy Source |
| SRP | Secondary Refining Process |
| TOU | Time-of-Use |
| VSD | Variable Speed Drive |

6. Increasing the penetration of distributed renewable generation [12].
7. Providing peak-shaving, valley-filling, and power factor correction [13].

In order to achieve the abovementioned aims, three major steps should be taken as follows:

1. Extraction of power flexibility from different demand sectors
2. Aggregation of power flexibility with different sectors
3. Integration of demand flexibility into upstream networks

First of all, to extract flexibility potations of demand sectors, expert knowledge is required. The power flexibility of the industrial sector needs technical knowledge about the industrial processes and limitations [14]. In the agricultural sector, the power consumption of the irrigation system is optimized not only with the purpose of power flexibility but also to meet the crops' water needs and evapotranspiration requirements [15]. In the residential sector, the flexibility potentials of the heating systems are extracted from the thermal dynamics of buildings, heat carrier of the district heating, and heat storage; therefore, thermodynamic and building knowledge are required [16]. As a result, expert knowledge is required in each demand sector not only to extract the flexibility potentials technically but also to motivate the consumers socially to participate in demand response programs.

The segregated demand flexibilities fail to meet power system requirements. To overcome this problem, the flexibility potentials of a demand sector should be aggregated by a professional intermediary agent, called Demand Response Provider (DRP) or Demand Response Aggregator (DRA) [17]. At the upper level, the DRA/DRP coordinates the power flexibility of four demand sectors according to the power system requirements. Therefore, flexibility aggregation is essential between (1) different consumers of the same demand sector and (2) the four demand sectors.

Finally, the flexibility potentials are integrated into power systems to fulfill the abovementioned key aims. In this way, the flexibility requirements for frequency control are completely different from the flexibility of power system reserve in terms of response time, duration, and intensity. As an example, in an industrial cement factory, the power consumption of raw crushers can be turned off for a few hours to provide peak-shaving in critical hours [18]. In the metal smelting factories, the power consumption of variable-voltage smelting pots can be turned down in few seconds to provide a fast power regulation or frequency control [19]. Therefore, technical knowledge is required to find out which industrial process is reasonably fitted with the flexibility requirements of the supply side.

Based on the background, the main motivation of this study is to look for flexibility potentials in different industrial processes of heavy industries. Moreover, the study aims to find out the compatibility of industrial demand flexibility with the flexibility requirements of the power system. In this way, it should be answered "which industrial process is compatible with peak-shaving and which one is appropriate for real-time frequency control" and "how much demand flexibility can be expected from a heavy industry". This is the main motivation of this study to find out compelling answers for these questions through a comprehensive review of the literature.

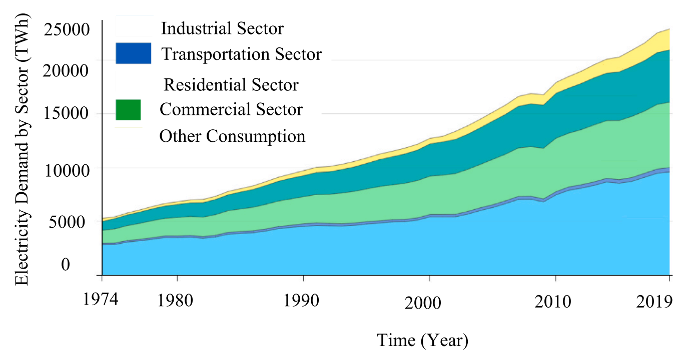


**Fig. 1. Electricity demand in different sectors in the world from 1974 to 2019** [1].

**Table 1**
Total flexibility potentials of demand sectors in the world in 2018 (NA: Not Available). [1].

| Demand Sector | Total Electricity Demand in 2018 (TWh) | Total Flexibility Potential in 2018 (TWh) | Percentage of Demand Flexibility (%) |
|---|---|---|---|
| Industrial | 9362 | 847 | 9.04 |
| Residential | 6008 | 3071 | 51.11 |
| Commercial | 4799 | NA | NA |
| Transportation | 390 | 51 | 13.07 |
| Other | 1757 | NA | NA |

## 1.2. Literature review

In recent years, many research studies have been carried out to review the Demand Response (DR) opportunities in four demand sectors. i. e. residential, commercial, agricultural, and industrial. To have a general insight into the flexibility potentials of the demand sectors, Fig. 1 depicts the total electricity demand in the world from 1974 to 2019. Besides, Table 1 presents the percentage of total available flexibility potentials in 2018. Based on the table data, the residential buildings exhibit great flexibility potentials around 51.11%. In contrast, the flexibility potential of the industrial sector is relatively low, approximately 9.04%. It shows that further studies should be conducted in the industrial sector to extract flexibility opportunities for industrial processes.

In the residential sector, flexibility potentials of thermostatically controlled appliances, e.g. refrigerators [20], water heaters [21], and heat pumps [22], are extensively studied. Besides, the flexibility opportunities of some appliances, e.g. vacuum cleaners [23], hairdryers [24], washing machines [25], Plug-in Electric Vehicles (PEV) [26], are investigated. Reference [27] reviews the latest information and communication technologies that support residential DR systems. A general overview of price-based residential DR programs is provided in Ref. [28]. This paper concludes that a price signal is an efficient tool for residential DR programs. Reference [29] conducted a literature review on central, distributed, and hybrid control of heating and cooling networks, especially for residential buildings. A comprehensive review of computational tools for the design, analysis and management of residential DR programs is presented in Ref. [30]. Renewable-based heat pumps and district heating have attracted much attention in the residential sector. In Ref. [31], a model predictive heat controller is proposed for residential heat pumps to optimize the energy consumption of the heating system in response to power availability in electricity markets with high penetration of renewable power. A mixing loop controller is suggested not only to extract flexibility potentials of the residential heating system but also to facilitate the integration of renewables into district heating [16].

Regarding the commercial sector, the DR programs can be implemented in a retail store or a large commercial building. Heat Ventilation and Air Conditioning (HVAC), lighting systems, and supermarket refrigerators are the main subject of commercial DR programs. Besides, the commercial parking lot is not only a practical solution to overcome the increased penetration of PEVs but also paves the way to make a profit from parked PEVs in commercial buildings. In recent years, a Parking Lot Aggregator (PLA) is suggested to integrate flexibility potentials of PEVs parked in shopping centers into power systems with high penetration of renewable power [32]. Besides, the commercial sector is proposed as a parking lot microgrid to provide peak-shaving and valley-filling for the electricity markets with power shortages [33]. Reference [34] reviews DR opportunities in a retail store to investigate retail stores' preferences of DR programs and stakeholders' engagement. Reference [35] provides a thorough review of DR programs in commercial and institutional buildings. This paper draws a strategy map as a pathway for achieving better building energy performance. In Ref. [36], a hybrid robust-stochastic approach is proposed to extract flexibility potentials of PEVs in presence of intermittent wind power generation. An optimal day-ahead charging framework is suggested for PEVs to provide power flexibility for electricity markets [37]. In addition to the power flexibility, the profit of PEV owners and power system operators are also optimized simultaneously.

**Table 2**
Histogram of review papers in the DR literature in four demand sectors (References in square brackets).

| | | | | |
|---|---|---|---|---|
| 20 | [62] | | | |
| **19** | [63] | | | |
| **18** | [64] | | | |
| **17** | [65] | | | |
| **16** | [66] | | | |
| **15** | [67] | | | |
| **14** | [68] | | | |
| **13** | [69] | | | |
| **12** | [70] | | | |
| **11** | [71] | [48] | | |
| **10** | [72] | [49] | | |
| **9** | [73] | [50] | | |
| **8** | [74] | [51] | | |
| **7** | [75] | [76] | | |
| **6** | [77] | [73] | [15] | |
| **5** | [78] | [79] | [80] | |
| **4** | [81] | [52] | [82] | [83] |
| **3** | [84] | [85] | [43] | [86] |
| **2** | [28] | [87] | [39] | [51] |
| **1** | [27] | [46] | [38] | [52] |
| | Residential Flexibility | Industrial Flexibility | Agricultural Flexibility | Commercial Flexibility |

In the case of the agricultural sector, the main research studies aim to optimize the water-energy nexus. In 2013 and 2015, comprehensive review studies were conducted by the US Department of Energy to investigate the opportunities/challenges of demand-side flexibility in farms [38,39]. The results showed that irrigation pumps have great potential to provide flexibility for power systems. In the next years, some scoping studies surveyed the issue in open-air farms [40] and greenhouses [41,42]. In continue, a review study proposed a restructuring in the agricultural industry to provide a great deal of flexibility for power grids [43]. The main concentration of the study is to facilitate the integration of renewable energies, e.g. wind and solar, in agricultural electricity consumption, especially irrigation systems. Recently, an Agricultural Demand Response Aggregator (ADRA) is proposed to integrate the flexibility potentials of the irrigation systems into three trading floors of the Danish Electricity Market [44]. In Ref. [13], a farm greenhouse is suggested with on-site solar sites and thermal generation units to provide peak-shaving for power systems when the highest crop evapotranspiration coincides with the peak demand of the power system.

In contrast to the three sectors, heavy industries are energy-intensive consumers which consist of different industrial sub-processes. In the residential, commercial, and agricultural sectors, the aggregation of a significant number of responsive demands provides considerable flexibility for the power system. In heavy industries, due to energy-intensive processes, the flexibility potentials of a factory may be equal to or higher than a significant number of responsive commercial, residential or agricultural demands. In manufacturing plants, some industrial processes are interdependent critically and may not be allowed to interrupt. In some others, the industrial processes can be interrupted on advance notice; the "advance notice" is critical to prevent serious damage to the costly equipment. For this reason, the Industrial Demand Response (IDR) programs are quite complex and need knowledge experts.

In the literature, some scoping studies have reviewed the IDR potentials. First of all, the US Department of Energy provided a general overview of IDR opportunities in 2008 [45]. The study suggested a strategic roadmap for IDR programs in the US. In 2016, cement manufacturing and metal smelting industries are investigated in the review study [46]. In 2018, a scoping study was carried out in the UK to increase energy efficiency in the industrial sector [47]. Metal, food, and drink industries are the main scopes of this study. Demand response opportunities in the energy systems and industrial processes of wastewater plants are reviewed in the study [48]. A comprehensive review is carried out on the demand response of internet data centers [49]. In this study, load models, load regulation operations, and economic aspects of demand-side flexibility are surveyed. Technical characteristics of demand response opportunities for industrial parks are reviewed [50]. The study addresses different technical aspects of demand flexibility in a multi-energy sector, including gas and power networks simultaneously. Recent advances in the demand response opportunities of industrial and commercial sectors as well as the limitations and barriers are reviewed in the study [51]. A broad overview of industrial demand response technologies is provided in the United States to describe standards and end uses of industrial demand flexibility [52].

In addition to the review studies, many research studies are carried out to investigate flexibility potentials in light and heavy industries, including cement plants, metal/steel/aluminum smelting factories, textile industries, glass furnaces, oil refinery plants, pulp and paper mills, and food industries. In Ref. [53], a hygro-thermal model is presented to estimate demand response opportunities of refrigerated display cabinets in food industries. Industrial demand side management is conducted in cement manufacturing plants to reduce the electricity

**Table 3**
The bibliographic features of review studies in the four demand sectors from 2010 to 2020 with key contribution(s).

| No. | | Reference | First Author | Year | Journal | Main Contribution(s) |
|---|---|---|---|---|---|---|
| 1 | Residential | [27] | H.T. Haider | 2016 | Renewable and Sustainable Energy Reviews | Information and communication technologies in residential DR programs |
| 2 | | [28] | XingYan | 2018 | Renewable and Sustainable Energy Reviews | Survey of price-based DR programs in the residential sector |
| 3 | | [69] | J.V. Canteli | 2019 | Applied Energy | Algorithms of reinforcement learning for residential DR programs |
| 4 | | [70] | P. Kohlhepp | 2019 | Renewable and Sustainable Energy Reviews | Integration of residential HVAC as flexible demand into power systems |
| 5 | | [71] | P. Rajendhar | 2019 | IET Generation, Transmission & Distribution | Interaction of HEMS, smart grids, and renewable generation |
| 6 | | [72] | H.Sharee | 2018 | IEEE Access | Review of HEMS with various DR programs, smart technologies, and load controllers |
| 7 | | [73] | Lennart Söder | 2018 | Renewable and Sustainable Energy Reviews | Estimate flexibility potentials in Northern European countries |
| 8 | | [74] | M. H. J. Weck | 2016 | International Journal of Energy Research | Review barriers of residential DR programs in the Netherlands |
| 9 | | [75] | B. Priya Esther | 2016 | Renewable and Sustainable Energy Reviews | Review of architecture, approaches, optimization models, and methods of residential DR |
| 10 | | [77] | Aftab Khan | 2015 | Renewable and Sustainable Energy Reviews | Review HEMS with various DR architectures and models |
| 11 | | [78] | M. Murator | 2014 | Renewable and Sustainable Energy Reviews | Review techno-economic challenges of residential DR in modern electricity markets |
| 12 | | [81] | S. Gyamfi | 2013 | Renewable and Sustainable Energy Reviews | Review of challenges in voluntary demand reduction in the residential sector |
| 13 | | [84] | Geoff Kelly | 2012 | Renewable and Sustainable Energy Reviews | Review of energy efficiency in household appliances |
| 14 | Industrial | [46] | M. H.Shoreh | 2016 | Electric Power Systems Research | A comprehensive review of DR opportunities in the industrial sector |
| 15 | | [48] | D. Kirchem | 2020 | Applied Energy | Review of DR programs in energy systems and industrial processes |
| 16 | | [49] | Min Chen | 2020 | Renewable and Sustainable Energy Reviews | Review of DR opportunities in data centers |
| 17 | | [73] | L. Söder | 2018 | Renewable and Sustainable Energy Reviews | Estimate flexibility of responsive industries in Northern European countries |
| 18 | | [50] | Z. Chen | 2019 | Modern Power Systems and Clean Energy | Review of integrated flexibility potentials in industrial parks |
| 19 | | [51] | M.Shafiekhah | 2019 | IEEE Transactions on Industrial Informatics | Survey of most recent advances on industrial and commercial DR |
| 20 | | [76] | T. L. Vasques | 2019 | Energy Efficiency | Literature review of energy efficiency and DR opportunities of data centers |
| 21 | | [79] | Qin Wang | 2017 | IEEE Transactions on Industrial Informatics | In-depth review of flexible ramping products in industrial processes |
| 22 | | [52] | Sila Kiliccote | 2015 | WIREs, Energy and Environment | Overview of DR technologies in the United States |
| 23 | | [85] | Kaile Zhou | 2015 | Renewable and Sustainable Energy Reviews | A comprehensive review of DR programs in China's power industry |
| 24 | | [87] | Tom Maes | 2011 | Renewable and Sustainable Energy Reviews | Literature on industrial energy management, industrial symbiosis, and eco-industrial parks |
| 25 | Agricultural | [38] | Daniel Olsen | 2015 | Lawrence Berkeley National Laboratory | DR opportunities for automated irrigation systems in California |
| 26 | | [39] | Daniel Olsen | 2013 | Lawrence Berkeley National Laboratory | Review of water-energy nexus in agricultural farms of California |
| 27 | | [43] | Aghajanzadeh | 2019 | Journal of Cleaner Production | Agricultural DR programs to decarbonize power grids and facilitate RES |
| 28 | | [15] | Golmohamadi | 2020 | Technology and Economics of Smart Grids and Sustainable Energy | Review of challenges, barriers, opportunities of DR programs in the agricultural sector |
| 29 | | [80] | Amir Vadiee | 2012 | Renewable and Sustainable Energy Reviews | Review of energy management in horticultural applications and closed greenhouse |
| 30 | | [82] | V. Skoulou | 2011 | Renewable and Sustainable Energy Reviews | Assessment of the sustainability and integrated management of energy crops in Greece |
| 31 | Commercial | [51] | M. Shafiekhah | 2019 | IEEE Transactions on Industrial Informatics | Review of the interaction of commercial DR and electricity markets |
| 32 | | [52] | Sila Kiliccote | 2015 | WIREs, Energy and Environment | Overview of DR technologies, standards and end uses, in the U.S. commercial sector |
| 33 | | [83] | Siiri Söyrinki | 2018 | Sustainability | Application of DR in a grocery store with refrigeration and photovoltaics panels. |
| 34 | | [86] | Tariq Samad | 2016 | Proceedings of the IEEE | Review of motivation for DR in commercial buildings |

consumption cost and carbon emission by 4.2% and 4%, respectively [54]. In aluminum smelting plants, a hierarchical model predictive control is suggested for smelting pots to provide ancillary services for the power system [55]. The flexibility potentials of two energy-intensive industries, including chloralkali process and wood pulp production, are evaluated in Ref. [56]. Pulp and paper mills with electric boilers can provide primary frequency reserve for power systems. The simulation results show that the pulp and paper industry not only provides frequency response to the supply side but also reduces the energy consumption cost between 7.4% in summer and 2.3% in winter [57]. Dynamic optimization is addressed in the study [58] to make a balance between natural gas and power consumption of glass furnaces under electricity price fluctuations. Oil refinery plants are investigated to extract joint heat-power flexibilities of refinery processes, steam boilers, and Combined Heat and Power (CHP) units [59]. In Ref. [60], mathematical formulations are presented for cement, steel, and aluminum factories to integrate industrial power flexibilities into the energy and ancillary service markets. In the literature, some studies investigated the flexibility opportunities of industries in response to dynamic electricity prices. In fact, time-varying electricity price is one of the most important approaches to study the behavior of flexible demands in response to dynamic electricity prices [61].

To give the readers a general insight into the scoping studies in the four demand sectors, Table 2 illustrates some distinguished review studies in the last decade, from 2011 to 2020. As the table reveals, most scoping studies have concentrated on the residential sector. The number of review studies on the industrial, agricultural, and commercial sectors is relatively lower than the residential ones. Therefore, more review studies should be conducted in the industrial sector to clarify the technical challenges of industrial demand flexibility.

**Table 4**
Characteristics of review papers in the industrial DR literature with main objectives, challenges, and opportunities.

| Reference | Opportunities/Challenges | Main Target Industry(s) | Surveyed Industries |
|---|---|---|---|
| [46] | Challenges:<br>(1) Financial barriers.<br>(1-1) Lack of persuasive incentives.<br>(1–2) Lack of exact evaluations for DR benefits.<br>(2) Regulatory barriers.<br>(2–1) Utility reconstruction issues.<br>(2-2) Program requirements and aggregation.<br>(2–3) Measurement and verification variety.<br>(2–4) Limitations on market regulations.<br>(2–5) Inclusion in energy efficiency programs.<br>(3) Knowledge-based barriers.<br>(3–1) Lack of knowledge and resource availability.<br>(3–2) Interoperability and open standards limitations.<br>(3-3) Administrative burden. | (1) Cement Manufacturing Plants<br>(2) Metal: aluminum and steel<br>(3) Refrigeration | (1) Oxygen Manufacturing<br>(2) Chloride Manufacturing<br>(3) Oil refinery industry<br>(4) Data centers |
| [51] | Challenges:<br>(1) Market Barriers.<br>(1-1) Collecting and processing data.<br>(1–2) Hidden costs and market power.<br>(1–3) Increase the standardization:<br>(2) Barriers of Social and customer behavior.<br>(2–1) Trust level among parties.<br>(2-2) Widespread adoption of DR programs.<br>(3) Technological barrier.<br>(3–1) Sensing, computing, and communication.<br>(3–2) Technological skills.<br>(4) Regulatory barriers.<br>(4–1) Lack of regulation for DR.<br>(4–2) Various regulations in different countries. | (1) Aluminum Smelting Factory<br>(2) Steel Manufacturing Plant<br>(3) Cement plant<br>(4) Pulp and paper mill | |
| [50] | Opportunities:<br>(1) Inhibiting demand.<br>(2) Adjusting the load curve.<br>(3) Allowing operators to control the load directly.<br>(4) Improving customer satisfaction.<br>(5) Guiding customer behaviors depending on the price.<br>Challenges:<br>(1) Market mechanism is not perfect.<br>(2) Industrial DR is not used widely yet. | Industrial Multi-Energy Systems | Industrial Parks/ Zones |
| [48] | Challenges:<br>(1) Neglect of the interaction between power system operation and industrial process operation.<br>(2) Abstraction from critical physical process constraints. affecting the DR potential.<br>Opportunities:<br>(1) Energy-water nexus as a great source of industrial DR.<br>(2) Integration of water-energy flexibility to power system. | Wastewater treatment plants | (1) Steel plant<br>(2) Refinery industrial plant<br>(3) Biscuit production<br>(4) Vehicle cockpit<br>(5) Manufacturing<br>(6) Paper industry<br>(7) Colliery process<br>(8) Chlor-alkali plant<br>(9) Air-separation process<br>(10) Pulp and paper mill |
| [76] | Challenges:<br>(1) Regulation and market maturity.<br>(2) Risk management.<br>(3) Market complexity.<br>(4) Load control approaches. | (1) Computing Data Centers including:<br>(1-1) Small-scale Data Centers<br>(1–2) Medium-scale Data Centers<br>(1–3) Hyper-scale Data Centers | Components of datacenters:<br>(1) Computing unit<br>(2) Lighting<br>(3) UPS<br>(4) Cooling system |
| [49] | Challenges:<br>(1) Suitable load models of the internet data center for power system operations.<br>(2) Expansion of load regulation potential for internet data center.<br>(3) Design of targeted DR mechanisms for spatial-coupling loads.<br>Opportunities:<br>(1) Have a potential of temporal and spatial load regulation.<br>(2) Significant impact on the cost savings.<br>(3) Improved efficiency in energy systems. | Internet Data Centers | Components of datacenters:<br>(1) IT equipment<br>Components of datacenters:<br>(2) Cooling system<br>(3) Auxiliary energy systems |
| [73] | Challenges:<br>(1) Industrial DR imposes a challenge as industrial processes need to be run continuously.<br>Opportunity:<br>(1) The industry's flexibility is higher in heavy industries, e.g. cement and metal.<br>(2) The biggest flexibility can be achieved in industries where the production has thermal inertia or a buffer capacity in the production. | Industries in North European countries | (1) Iron foundry<br>(2) Cement manufacturer<br>(3) Pulp and paper industry<br>(4) Arc furnaces and rolling mills<br>(5) Chemical industry<br>(6) Wood processing plants |
| [85] | Challenges:<br>(1) Customer understanding and participation.<br>(2) Advanced metering infrastructure (AMI) and ICT.<br>(3) Pricing mechanisms and optimal scheduling.<br>(4) Big data analytics-based decision support.<br>(5) Government regulations and market policies. | China's power industry | (1) Hydroelectric power<br>(2) Thermal power<br>(3) Nuclear power<br>(4) Wind power |
| [87] | Challenges:<br>(1) Technical and spatial, e.g. lack of matching | (1) Industrial Park<br>(1-1) Green industry parks | (1) Food and beverage<br>(2) Textiles |

(continued on next page)

**Table 4** (*continued*)

| Reference | Opportunities/Challenges | Main Target Industry(s) | Surveyed Industries |
|---|---|---|---|
| | energy profiles.<br>(2) Financial, e.g, capital accessibility and preconditions of companies and third parties.<br>(3) Organizational, e.g. lack of information about potential companies, energy consumption.<br>(4) Social, e.g. trust, openness, clarity between parties, reciprocal relations.<br>(5) Legal, permits (energy production, linking to distribution net, environmental permits, spatial permits, safety issues) | (1–2) Integrated eco-industry parks | (3) Wearing apparel leather<br>(4) Wood and cork<br>(5) Pulp and paper<br>(6) Chemical products<br>(7) Plastic products<br>(8) Non-metallic mineral<br>(9) Basic metals<br>(10) Manufacture of machinery<br>(11) Manufacture of furniture<br>(12) Manufacture of motor vehicles |
| [79] | Challenges:<br>(1) Market design: the emergence of renewable power and storage devices.<br>(2) Model improvement and validation: despite robust optimization and stochastic programming, some recent advances on this topic include data-driven are needed.<br>(3) Implementation issues: implementation of flexibility management is a complex action in industries practically. | General flexible ramping products | |

The main contributions of the review studies are stated in Table 3 for the four demand sectors. Based on the table, the most scoping studies in the residential sector have concentrated on Home Energy Management Systems (HEMS) and heating systems, e.g. Heat Ventilation and Air Conditioning (HVAC). In the industrial sector, the flexibility opportunities of industrial processes are discussed in different industrial plants. In the agricultural sector, most scoping studies survey demand response opportunities of water-energy systems, e.g. water irrigation pumps. Regarding the commercial sector, supermarket refrigerators and commercial buildings are heeded.

Table 4 surveys the main characteristics of some distinguished review papers in the industrial sector. In this table, the main opportunities and challenges of industrial DR programs are illustrated. Besides, the target industries are stated.

### *1.3. Paper contributions and organization*

Based on the literature review and to the best of the authors' knowledge, none of the scoping studies provided a comprehensive review of the demand response potentials for joint heat-power flexibility, e.g. oil refinery plants. Besides, the compatibility of flexibility potentials of industrial processes of heavy industries with different electricity market floors is not discussed. None of the studies elaborated on the time response of industrial processes in response to long, mid and short advance notices of flexibility requests. Also, the simulation software, objective functions, and optimization solutions are not classified. To narrow these gaps, this paper reviews industrial demand-side flexibility in energy-intensive industries from the viewpoints of (1) power flexibility in cement manufactories and aluminum smelting and (2) joint power-heat flexibility in oil refinery plants. The flexibility potentials of the industries are classified based on their compatibility with the response time of electricity market floors. Afterward, the main challenges and opportunities of industrial demand flexibilities are classified. The main software tools, mathematical models, and metaheuristic approaches are surveyed to provide a general insight for the researchers. Finally, bibliographic data are stated to show the role of industrial energy management in the past and today's research environment. To sum up, the main contributions of the study can be stated as follows:

1. Investigation of power and joint heat-power flexibility potentials in industrial processes of heavy industries, including cement manufacturing, aluminum smelting, and oil refinery plants.
2. Classification of the industrial demand flexibility with long, mid, and short advance notices of demand response programs in the normal operation of electricity markets and contingency modes.
3. Surveying the simulation software, optimization algorithms, challenges, and opportunities of industrial energy management.

Fig. 2 sketches the graphical abstract of the raised issues. Besides, Fig. 3 describes the different steps of the current study. Based on the graphs, in sections 2, 3, and 4, the flexibility potentials of three energy-intensive industries are elaborated. In section 5, the main electricity market floors and ancillary services are stated in normal and contingency operational modes. Section 6 classifies the key challenges and opportunities of energy management in heavy industries. Section 7 explains the diversity of software tools, mathematical programming, and nature-inspired optimization solutions. In section 8, the bibliographic information of industrial energy management is stated. Finally, section 9 concludes the scoping study.

## 2. Cement manufacturing plants

Cement manufacturing plants are comprised of several industrial processes that transform raw material, including limestone, clay, and shale, into cement powder. Generally, the industrial process of a cement plant can be divided into four main industrial sub-processes as follows [88]:

(1) Crushing (Cr)
(2) Kiln Feed Preparation (KFP)
(3) Clinker Production (CP)
(4) Finish Grinding (FG)

Crushing is the first industrial sub-process that crushes the limestone and pre homogenize the raw materials [89]. The raw material, e.g. limestone, clay, shale, is transferred by large dump trucks and/or conveyors. The crushers are normally comprised of primary and secondary crushers. The energy intensity of the crushers varies between 5 and 20 kWh/ton of feedstock [18]. Due to stockpiling of the production in the silos, the crushers are normally operated during off-peak hours (low electricity prices). Therefore, the crushers are exploited for a few hours a day, and the silos' stockpile supplies the KFP. It is worthy to note that as the size of limestone silos increases, the flexibility potential of the crushers increases.

The output of crushing, i.e. homogenized raw materials, supplies the kiln feed preparation. The KFP includes raw mills to grind and blend the raw materials to prepare them for clinker production (CP) [90]. Similar to the crushers, the KFP mills have great potential to operate during off-peak hours. The Cr and KFP are interruptible processes whose electricity consumption can be shifted to off-peak hours (low price hours) not only to provide peak-shaving and/or valley-filling for the power system but also to reduce the electricity consumption cost of the factory. Stockpiling of the raw mix in the KFP silos plays a key role in the flexibility potentials of the KFP. Consequently, it can supply the feedstock of the CP without causing an interruption in the whole procedure.

The CP includes a preheater tower and kiln which are operated uninterruptedly receiving feedstock from the KFP [91]. In this way, two

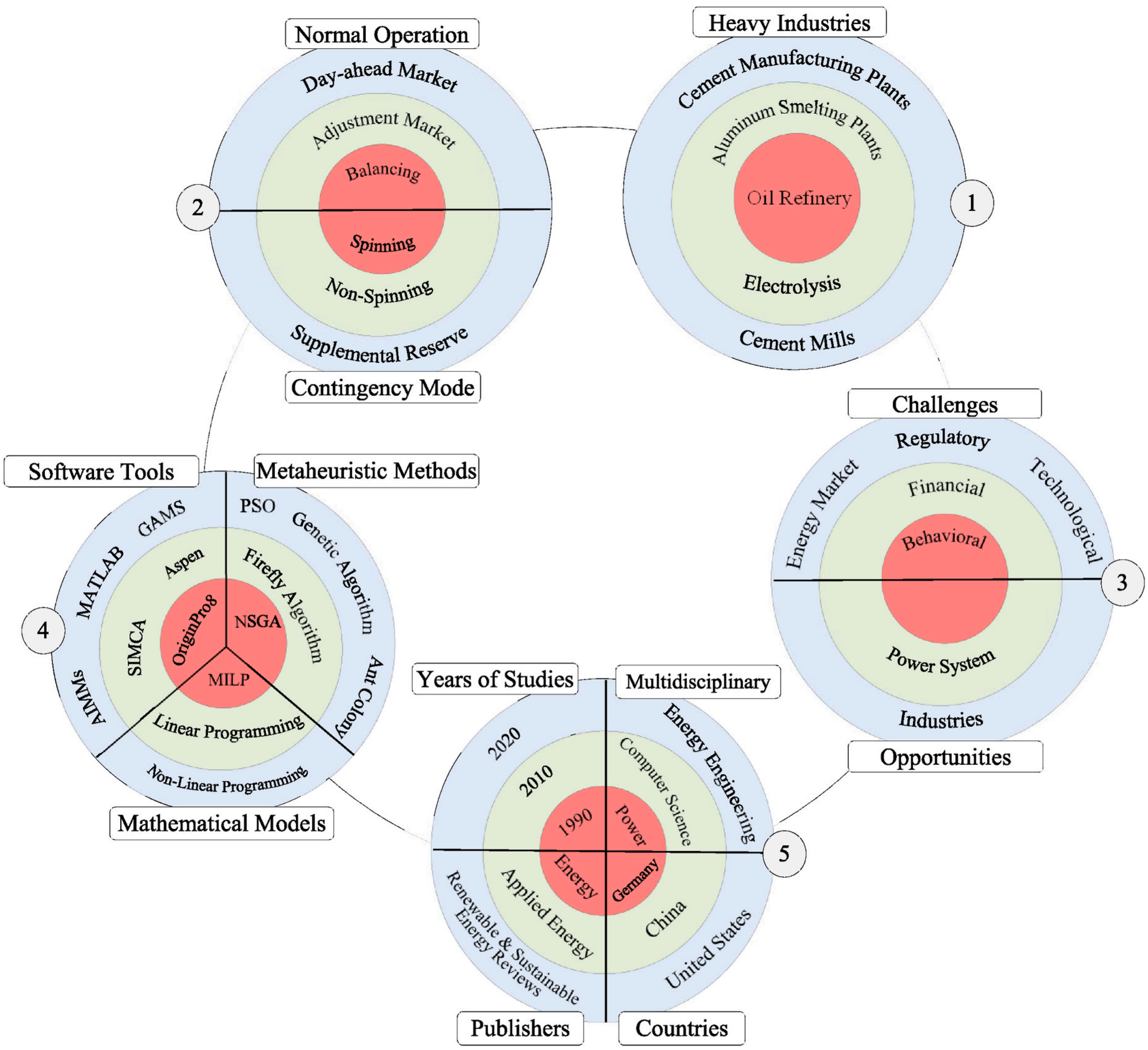


**Fig. 2.** Graphical abstract of the suggested methodology of industrial flexibility in the current study.

points should be stated. Firstly, the CP is normally a continuous duty process without long interruption. The reason is that an unscheduled interruption may impose a high cost on the kiln's envelope and equipment. Besides, the kiln is mainly supplied by fossil fuels, e.g. coal and natural gas. Therefore, the flexibility potential of the CP is relatively low.

The output material of the CP is hot clinker. The clinker is cooled down in the clinker cooler and then is imported to the FG [92]. The FG includes cement mills to transform the clinker into cement powder. Although the cement mill is an interruptible industrial process, the flexibility potential of the FG is lower than the crushers and KFP at least for two reasons. Firstly, the previous process, i.e. the CP, is a critical process without any interruption. Therefore, the FG must be operated to prevent over-stockpiling of the clinker. Besides, the FG is the final process in which the cement production is loaded by trucks, ships, etc. As a result, it is under pressure to meet the consumers' delivery constraints. The flexibility potentials of the industrial processes of the cement plants can be surveyed as follow:

(1) Turning on/off the interruptible industrial processes [93].
(2) Turning up/down the smart variable speed mills [19].

The former refers to a scheduled interruption in the crushers, and mills of KFP, and FG. In this way, the whole process is turned off/on in response to the DR requests. Therefore, great flexibility potential is unlocked for the power system. In contrast, the latter reflects a minor increase/decrease in the power consumption of smart mills run by Variable Speed Drive (VSD) [94]. The VSD makes it possible to turn up/down the power consumption of mills on short advance notice without any interruption in the industrial process. While the former provides demand flexibility for power systems on long advance notice, e. g. the day-ahead markets [14], the latter provides up-/down-power regulation on short notice, e.g. real-time markets [19], especially in electricity markets with high penetration of Renewable Energy Source (RES).

Fig. 4 describes the schematic diagram of the industrial processes of the modern cement industry. Based on the graph, the cement plant is comprised of four main subprocesses with storage for the feedstocks. The processes can be turned off/on in response to power availability on the supply side. Moreover, the processes can be turned up/down on short notice to provide down-/up-regulations for the power systems. In this way, the storages play a key role in providing power flexibility to the electricity market. The energy management system of the cement factory includes storage stock management and production line management. The energy management system aims to control the production lines as well as the silos not only to provide demand flexibility for the power system but also to reduce the electricity consumption cost of the factory. Note that the daily production of cement is a key factor to meet

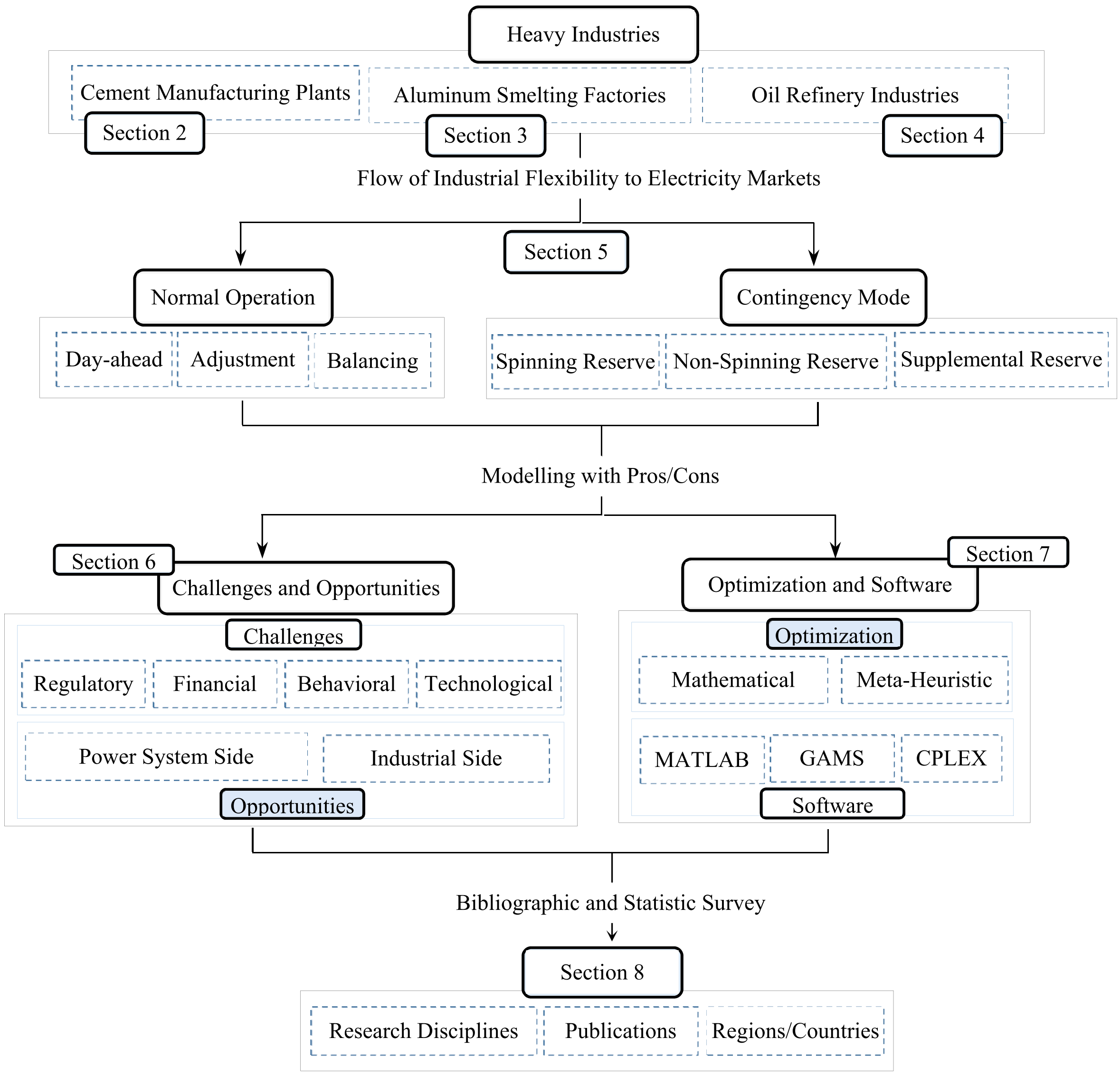


**Fig. 3.** Diagram of the suggested steps in the current study.

the consumers' delivery preferences.

Table 5 illustrates the energy intensities of four industrial processes of the cement plants. Moreover, the flexibility potentials are surveyed. Based on the table, the KFP and FG have high flexibility potentials both in terms of energy intensity and time response to advance notices. The crusher can respond to long, mid, and short notices effectively. The CP is an uninterruptible subprocess due to technical limitations. In the CP, the majority of energy is consumed by the kiln which is the heart of cement plants. The temperature of the kiln must meet a standard bound. Unexpected temperature deviations can cause heavy financial loss to the kiln's envelope and insulation. For this reason, the flexibility potential of the CP is relatively low.

In the literature on the cement plants, the principal aims of demand-side management can be stated as follows:

(1) Peak-shaving and/or valley-filling for power systems [54].
(2) Reduction of energy consumption cost [96].
(3) Facilitation of RES integration into power systems [97].
(4) Providing up-/down-power regulation in near real-time [98].
(5) Reduction of carbon footprint [99].

In [54], a new production scheduling is developed to minimize electricity consumption costs and electricity-derived $CO_2$ emissions in the UK. The study proposes a rescheduling of the production plan without loss of overall production. The research study [18] is conducted to provide peak power shaving for Iran Electricity Market. The study uses robust optimization to determine the optimized flexibility operations of cement plants in the worst-case realization of the uncertain electricity price. Besides, feedstock storage is offered as a workable solution to turn off the interruptible processes when a power shortage occurs. In Ref. [19], three-stage stochastic programming is suggested to unlock the flexibility potentials of the cement industry hierarchically in three trading floors of the Danish Electricity Market. The main aim of the study is to provide near real-time regulation for power systems with high penetration of renewable power. The research study [100] suggests a model predictive control to provide ancillary service and power regulation. This study proposes onsite energy storage as a practical solution to overcome the discrete power change of industrial processes. In Ref. [101], various strategies of energy consumption reduction are examined on cement plants. The study proposes industrial practices to increase energy efficiency in the industrial processes of the cement plants.

Table 6 surveys the main studies from 1976 to 2020 focusing on demand-side flexibility in the cement industries. Based on the table,

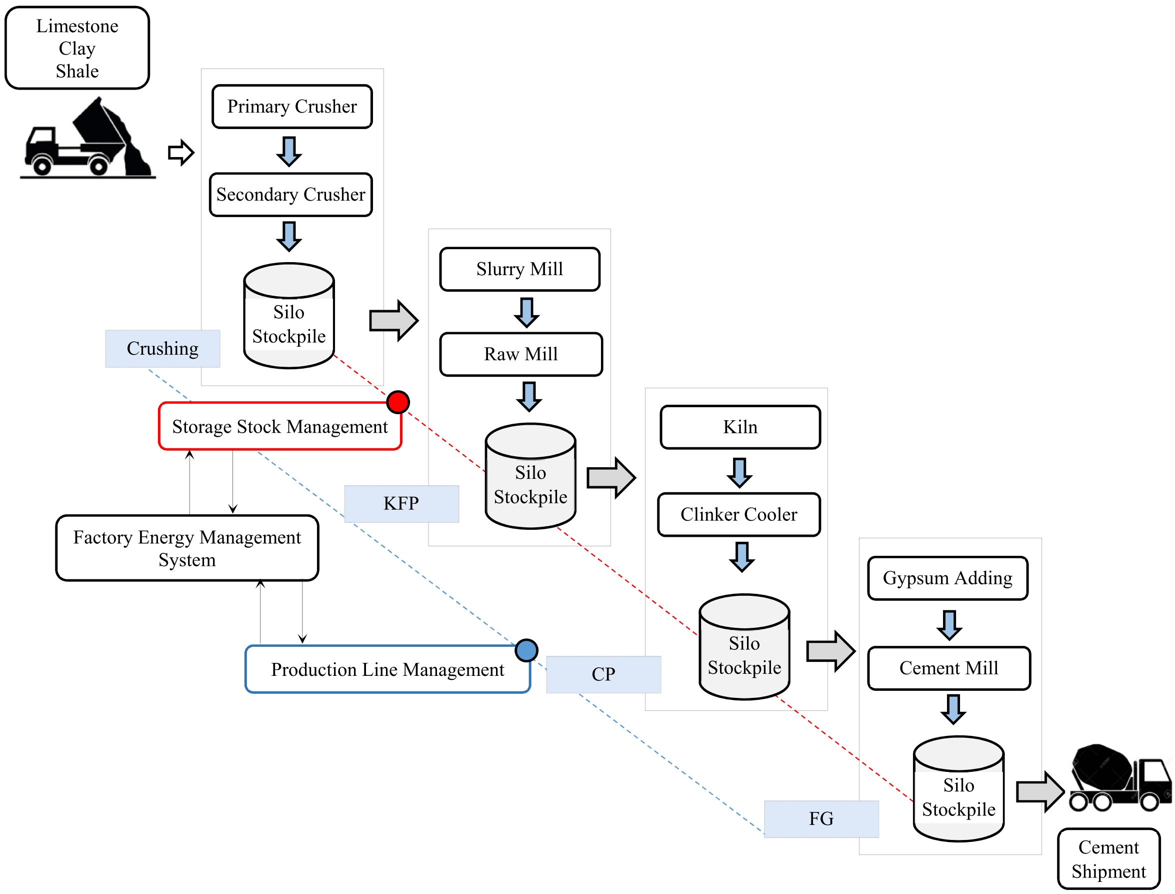


**Fig. 4.** Four industrial processes in a modern cement manufacturing plant from viewpoint of demand side management [18].

**Table 5**
Energy intensity, flexibility potentials, and electricity market compatibility for industrial processes of cement plants.

| Process | Energy Intensity [95] [a] | | Interruption | Flexibility Potential | | |
|---|---|---|---|---|---|---|
| | Electrical (kWh/ton) | Fuel (MBtu/ton) | | Long Notice | Mid Notice | Short Notice |
| C | 5–20 | ≈0 | Interruptible | High | High | High |
| KFP | 27–38 | ≈0 | Interruptible | High | High | High |
| CP | 39–45 | 4–6 | Uninterruptible | Low | Very Low | Very Low |
| FG | 52–57 | ≈0 | Interruptible | High | Medium | Medium |
| Total | 123–160 | 4–6 | | | | |

[a] The data is extracted to provide general insight into the energy intensity of different sub-processes in a modern cement plant. However, the data may vary based on different technologies and process types, e.g. wet or dry, etc.

some key features can be recognized. First of all, most studies use deterministic approaches to optimize energy management in the cement industry [102]. Increasing the penetration of renewable power, uncertain variables should be addressed to overcome the intermittency of the supply side. To overcome this problem, two non-deterministic approaches, including stochastic programming [19] and robust optimization [18], are suggested recently. In the electricity market, the power flexibilities of the cement industries are normally integrated into energy markets, e.g. the day-ahead market, on long advance notice [54]. In this way, few studies have investigated the role of cement industries in ancillary service and near real-time markets. Besides, most studies have concentrated on the demand-flexibility of crushing and cement mills. Except [18], barely any study can be seen to address the flexibility potentials of the whole industrial processes of the cement plants.

Table 7 quantifies the energy management plans in the cement industries. As the table reveals, different DR programs can cause a reduction in electricity consumption from 4% to 25%. On the other hand, the industries have reported a 6%–10% reduction in energy consumption costs. A comprehensive study on 84 aggregated cement plants in Iran shows that the cement plants can decrease the peak demand up to 37% in critical hours of power system operation [18].

## 3. Aluminum smelting industries

Aluminum smelting plants are one of the key energy-intensive industries. The energy intensity of aluminum plants is relatively between 13 and 14 kWh/kg Al [115]. Generally, in aluminum smelting plants, the aluminum oxide is turned into aluminum using chemical reduction [116]. The electrolysis takes place in smelting pots supplied by DC electric current. The smelting pots are operated in high currents, i.e. hundreds of thousand ampers, and a very low voltage, i.e. less than then volt. The smelting process takes place in several pots, the so-called potline. A potline may be comprised of tens of single pots. In large-scale smelting plants, more than one potline is operated. To manage the power consumption of the potlines, the input voltage of the pots is controlled [117]. Therefore, the direct current and power

**Table 6**
A survey of DR studies on cement plants with main contribution(s). "NA: Not Addressed, FOR: Forced Outage Rate, PSO: Particle Swarm Optimization, LP: Linear Programming, MILP: Mixed Integer Linear Programming".

| Ref. | Year | Principal Aim | Electricity Market | Uncertainty(s) | Mathematical Structure | Software | Main Contribution(s) |
|---|---|---|---|---|---|---|---|
| [101] | 1976 | Energy consumption reduction | NA | Deterministic | Experimental | NA | Practicable reductions in energy use. |
| [103] | 1986 | Energy consumption reduction | NA | Deterministic | Experimental | NA | Important energy waste sources are identified. |
| [104] | 2000 | Increasing energy efficiency | NA | Deterministic | Experimental | NA | Practical solution to potential energy saving. |
| [105] | 2010 | Increasing energy efficiency | NA | Deterministic | Experimental | NA | Implementation of Energy Conservation Supply Curves to identify cost-effective energy efficiency potentials. |
| [106] | 2012 | Increasing profit of industry | Day-ahead Real-time | Electricity price | Fuzzy model | NA | Optimization of operation of risk-taker/-averse industry in uncertain electricity market. |
| [107] | 2013 | Reducing operational cost | Wholesale market | (1) Electricity price (2) FOR of units | Stochastic Programming | GAMS/ CPLEX | Optimization of industry load profile with uncertain self-generation facilities. |
| [108] | 2015 | Peak shaving of power system | Retail market | Deterministic | PSO | NA | Proposing time-based DR according to behavioral classification of industries. |
| [102] | 2016 | Reducing operational cost | Day-ahead Reserve | Deterministic | LP | GAMS/ CPLEX | Modify power consumption in response to electricity price. |
| [54] | 2017 | Reducing operational cost | Wholesale Market | Deterministic | LP | NA | Rescheduling the milling to minimize operation cost. |
| [100] | 2018 | Provide regulation and ancillary service to power system | Day-ahead Real-time | Deterministic | MILP | CPLEX | Providing regulation and load following by adjusting power consumption. |
| [19] | 2019 | Overcome RES intermittency | Day-ahead Adjustment Balancing | Electricity price | Stochastic programming | GAMS MATLAB | Integration of smart variable speed milling to power system. |
| [18] | 2020 | Peak shaving of power system | Day-ahead Bilateral | Electricity price | Robust Optimization | GAMS MATLAB | Optimization of operation of responsive industry in worst-case realization of electricity price. |

**Table 7**
The quantification of energy management plans in cement industries worldwide.

| Reference | Country/ Region | Cost Reduction (%) | Electricity Consumption reduction (%) | Peak Reduction (%) |
|---|---|---|---|---|
| [109] | Portugal | 6 | × | × |
| [110] | Global | × | 15 | × |
| [54] | The UK | 4.2 | × | × |
| [105] | China | × | 16 | × |
| [111] | Ethiopia | × | 16 | × |
| [112] | Turkey | × | 6.7 | × |
| [18] | Iran | 10 | × | 37.5 |
| [113] | Taiwan | × | 25 | × |
| [114] | Thailand | × | 16.9 | × |
| [89] | Bangladesh | × | 4–5 | × |

consumption are changed. In smelting pots, the volume of aluminum oxide has a strong correlation with power consumption. Therefore, the Factory Energy Management System (FEMS) controls the feedstock of aluminum oxide to manage the power consumption of the potlines. To unlock the demand flexibility of the potlines, the smelting pots are subject to the following measures:

(1) Turning the whole pots (potline) on/off
(2) Turning the pots (potline) up/down

The former refers to load shifting/interruption. In this case, the whole pot is turned off/on in response to power shortage/excess in the power system. The off/on states are normally rotated among different pots not only to satisfy the daily production level but also to maintain the pots in service. The main advantage is that the DR scheme integrates high values of demand flexibility into the power systems. The negative point is that the DR requests should be sent to the FEMS hours before loading the pots. Therefore, it can participate in DR programs on long and mid advance notices, e.g. the day-ahead [118] and intraday markets [119].

The latter shows the partial power control (increase/decrease) without smelting interruption. In this case, the input voltage and/or the feedstock aluminum oxide are controlled [120]. The value of demand flexibility is lower than the first DR program. However, the main advantage is that the power consumption can be changed in real-time in response to the availability of intermittent renewable energies [121]. When a power deficit/excess occurs in the electricity market, the smart pots decrease/increase the input voltage to provide up-/down-regulation for the supply side. Consequently, this type of DR program is appropriate for flexibility requests on short advance notice, e.g. regulation [122] and balancing markets [123].

In both cases, the thermal balance of the smelting pots is a key limiting factor. The pots envelope is made of carbon. The electrolysis takes place in a cryolite bath which contains aluminum oxide and some mineral combinations. When normal electrolysis is processed, the cryolite is frozen near the envelope and molten near the anode. In order to maintain this feature, thermal balance is required to prevent melting cryolite near the envelopes and solidating near the anode. Therefore, the time and duration of pot interruption must meet the thermal balance. It means that the interruption requests have to be sent to the FEMS hours ahead. Moreover, the duration of the interruption is limited. In smelting plants, the smelting processes are normally uninterrupted with discrete loading-unloading cycles. It means that once the smelting started, the process continues without interruption. After finishing the smelting cycle, the next smelting cycle can be interrupted in response to flexibility requirements. Note that short interruption may be allowed by the FEMS during the smelting process. The interruption may happen from a few minutes to hours depending on the characteristics of the pots, the volume of aluminum oxide, and ambient temperature. In this way, power loss and lost aluminum production are the first repercussions. Fig. 5 depicts the schematic diagram of an aluminum smelting plant. Based on the figure, the FEMS receives the flexibility requirements from the power system operator. Then, the FEMS uses three leverages, including feedstock control, switch control, and voltage control, to unlock the flexibility potentials of the potlines in response to the power system requirements.

In the literature on the aluminum industries, some research studies have been conducted to unlock the flexibility potentials of the plants. Among them, minimizing the energy consumption cost [124],

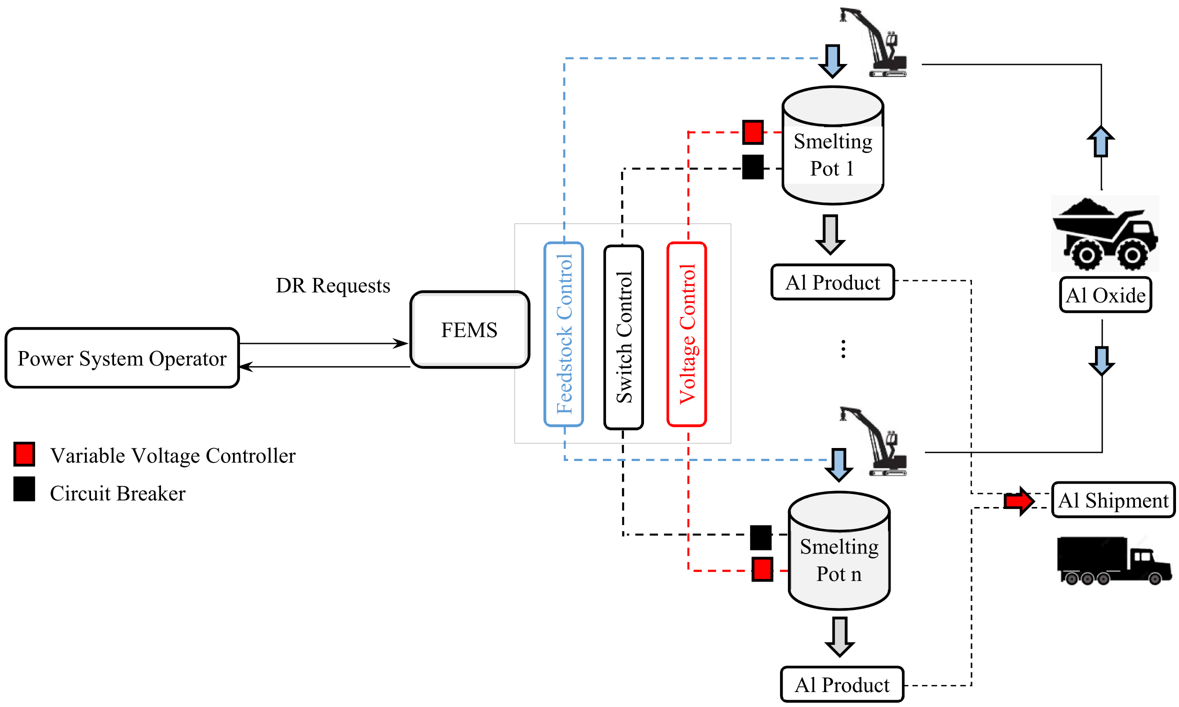


**Fig. 5.** Implementation of DR programs in an aluminum smelting plant with n pots.

**Table 8**
A survey of DR studies on aluminum/metal/steel plants with distinctive characteristics.

| Ref. | Year | Principal Aim | Electricity Market | Uncertainty(s) | Mathematical Structure | Software | Main Contribution(s) |
|---|---|---|---|---|---|---|---|
| [136] | 1994 | Minimizing energy consumption cost | NA | Deterministic | Experimental | SPMS | Cost savings and improved plant reliability with no production downtime. |
| [137] | 1999 | Minimizing Energy Consumption | NA | Deterministic | NA | NA | Cascade use of waste heat in industries to save energy |
| [138] | 2009 | DR opportunities of aluminum plants | (1) Ancillary (2) Regulation | Deterministic | NA | NA | Comprehensive flexibility potentials of aluminum smelters in the US. |
| [139] | 2011 | Price-based flexibility of aluminum industries | European markets | Electricity price | NA | TSP | Flexibility potentials of aluminum smelters in response to variable electricity price |
| [129] | 2012 | Energy management in smart grid | (1) Retail market (2) Ancillary service | Deterministic | NA | NA | Potentials of energy management and demand flexibility in smart grids |
| [140] | 2013 | Minimizing energy consumption cost | (1) Day-ahead (2) Intraday (3) Real-time | Deterministic | MILP problems | GAMS CPLEX | Providing flexibility to energy system considering energy constraints of the industrial processes |
| [141] | 2014 | Increasing energy efficiency and decreasing the energy cost | NA | Deterministic | Linear Optimization | GAMS | Provide strategies to manage production structures, production costs, energy use, and emission reduction in steel making. |
| [142] | 2015 | Maximizing profit | Wholesale market | Deterministic | MILP | CPLEX | Energy flexibility, co-optimizing energy usage, and material flow |
| [143] | 2016 | Energy/exergy analysis of aluminum smelters | NA | Deterministic | LP | NA | Waste heat recovery/thermal integration of aluminum smelters |
| [144] | 2017 | Minimizing energy consumption cost | Wholesale market | Deterministic | MIP | Matlab TOMLABCPLEX | Using smart melting to provide demand flexibility |
| [145] | 2018 | Cost minimization Providing near-real-time flexibility to power system | (1) Day-ahead (2) Ancillary | Deterministic | MILP | Gurobi | Provide ancillary and real-time flexibility to power system |
| [19] | 2019 | Using demand response to facilitate the integration of renewable energies | (1) Day-ahead (2) Adjustment (3) Balancing | Non-deterministic Electricity price Wind power | Three-stage stochastic programming | GAMS MATLAB | Integration of smart variable voltage smelting pots to power system |
| [146] | 2020 | Theoretical DR potential for Brazilian industries | Brazilian market | Deterministic | LP/NLP | NA | Industrial DR potentials to overcome RES intermittency |
| [127] | 2021 | DR and flexibility potentials of industries | NA | Deterministic | LP | NA | Electrolyzers show great potential in transition to 100% renewable energy supply |

**Table 9**
The quantification of energy management plans in metal/steel/aluminum smelting industries.

| Reference | Energy Consumption Cost Reduction (%) | Demand Flexibility and/ or Efficiency Improvement (%) | $CO_2$/Emission Reduction (%) |
|---|---|---|---|
| [147] | × | 5.69% | × |
| [148] | 7.5% | × | × |
| [149] | × | 14.07% | 6.65% |
| [150] | 29.7% | × | × |
| [151] | × | (2.95–6.99) % | × |
| [152] | × | 2.66% | × |
| [153] | × | 2% | × |
| [154] | 34.2% | 16.5% | 16.5% |
| [155] | × | (11.98–20.70) % | × |
| [156] | × | 4.92% | 6.85% |

increasing energy efficiency [125], minimizing the carbon footprint [126], facilitating the integration of RES into power systems [127], and providing peak-shaving and valley-filling for the power systems [128] are the main objectives. Considering the most important research studies in the last decade, first of all, in 2011, the economic and technical potentials of aluminum industries were investigated to provide demand-side flexibility for balancing markets [56]. This study made projections on the extent to which flexibility potentials and/or DR programs from aluminum plants can provide economic benefits in electricity markets with high RES penetration. In 2012, the aluminum industries are investigated to determine flexibility potentials as well as automated DR programs in the smart grid [129]. In 2013, the energy strategies of aluminum industries were surveyed to increase the energy efficiency of the industrial processes [130]. Moreover, the economic and technical evaluations were conducted for energy self-generation in aluminum plants. In 2014, a research study addressed the voltage control of aluminum smelters as a workable solution to overcome frequency stability issues in power systems [121]. In 2015, aluminum electrolysis was suggested as a practical solution to provide frequency balance in isolated power systems with high wind power penetration [131]. Besides, a model predictive control was designed in aluminum industries to provide frequency regulation for the power system during wind power fluctuation [132]. In 2016, an energy audit was carried out in China to determine the role of aluminum industries on overall greenhouse gas emissions [133]. The study concluded that further energy efficiency improvement reduces the carbon footprint in aluminum industries.

In 2018, a comprehensive scoping study was conducted to propose energy efficiency measures in aluminum industries [125]. Based on this study, the aluminum plants are subject to halved greenhouse gas emissions by 2050, while the demand for aluminum will increase up to three times in the same duration. Therefore, energy efficiency measures not only meet the carbon footprint goals but also reduce pressure on power systems. In 2019, three-stage stochastic programming was suggested to integrate the flexibility potential of aluminum smelting plants into the Danish Electricity Market [19]. In this study, three market floors, including day-ahead, intraday, and balancing markets were addressed. The on/off states of the smelting pots were scheduled in the day-ahead market. The input voltage of the smart pots was controlled in the balancing market to provide up-/down-regulation in the opposite direction of the power system imbalance. In 2020, a dynamic model for aluminum smelter loads was derived to provide a hierarchical frequency control [55]. This study designed a model predictive control for the smelters current with lower control cost. In Ref. [134], the research study extracted an electrothermal characteristic model of aluminum smelter load to investigate the interaction between input power and electrolyte temperature. This model helps FEMS to employ the direct load control on the smelters satisfying the thermal balance constraints. The review study [135] surveyed different energy conservation technologies and heat recovery technologies for iron and steel industries. Case studies and practical projects are addressed all over the world and a general guideline is provided for energy optimization in the iron and steel industries.

Finally, Table 8 summarizes the key characteristics of some research studies in the last decade about energy management in aluminum industries. In this table, the main aims, uncertain variables, and target electricity markets are also surveyed.

Table 9 quantifies the demand side management in the metal, steel, and aluminum industries. The data are stated in terms of energy cost reduction, amount of demand flexibility, and contribution to emission reduction. As the table reveals, the energy cost reduction varies from 7.5% up to 34.2%. For the energy consumption, the industries have experienced between 2% and 20.70% demand flexibility or energy efficiency improvement. Regarding the emission reduction, the energy management plans cause a 6.65%–16.5% reduction in emission production. Note that the values of demand flexibility, energy efficiency, and emission reduction are strongly dependent on the case studies, energy management plans, and the strength of demand side management.

## 4. Oil refinery plants

The Oil Refinery Industries (ORI) are energy-intensive plants that refine the crude oil into petro production like petroleum naphtha, gasoline, diesel fuel, asphalt base, heating oil, kerosene, liquefied petroleum gas, jet fuel, and fuel oils [157]. The refinery processes consume a large amount of energy in terms of power, heat, and steam. Due to the importance and criticality of the ORI, the industrial processes are normally supplied by self-generation facilities, e.g. gas turbines and CHP [158]. In this way, the waste heat of the generation units mainly supplies the heat/steam demand of the refinery processes. Besides, industrial boilers are operated to compensate for the lack of heat/steam generation by the CHP units [159]. Considering the strong correlation between heat and power generation (consumption) in CHP units (refinery processes), the energy management of the ORI is a complex problem.

The ORI is also connected to the power grid to exchange power. Therefore, from the viewpoint of energy management, the ORI is an industrial microgrid that can be exploited in both grid-connected and stand-alone. The microgrid structure makes it possible to inject the overgeneration of self-generation units into the main grid when a power shortage occurs on the supply side or draw power from the upstream network when an unscheduled failure causes a power deficit in the ORI. In addition, the ORI is connected to the gas network to supply the fossil fuel generation units. As a result, the ORI is considered a multi-carrier microgrid with power and gas flexibility potentials.

Without loss of generality, the whole refinery processes of a typical ORI can be split into three main sub-sections as follows [160,163]:

(1) Refinery Process 1: Primary Refining Processes (PRP). This process is comprised of the Crude Distillation Unit (CDU). In the CDU, the crude oil is fractionated into wet gas, kerosene, naphtha, diesel, gas oil, and residual fractions. The output of this unit provides the feedstock to the next refinery process.
(2) Refinery Process 2: Secondary Refining Processes (SRP). This process is comprised of four main sub-processes. In the Gas Recovery Unit (GRU), the wet gas is refined into Liquefied Petroleum Gas (LPG), naphtha, and fuel gas. In the Hydrogen Treatment Unit (HTU), the kerosene and naphtha are hydrotreated to meet clean fuel requirements. In Fluid Catalytic Cracking (FCC), the heavy oil gas is converted into gasoline and some byproducts. Finally, the Vacuum Distillation Unit (VDU) produces three or four waxy distillate side cuts.
(3) Refinery Process 3: Final Refining Process (FRP) is comprised of six further refinery sub-processes. Firstly, in the Catalytic Reforming Unit (CRU), the naphtha is transformed into gasoline through isomerization and alkylation. In the Distillate

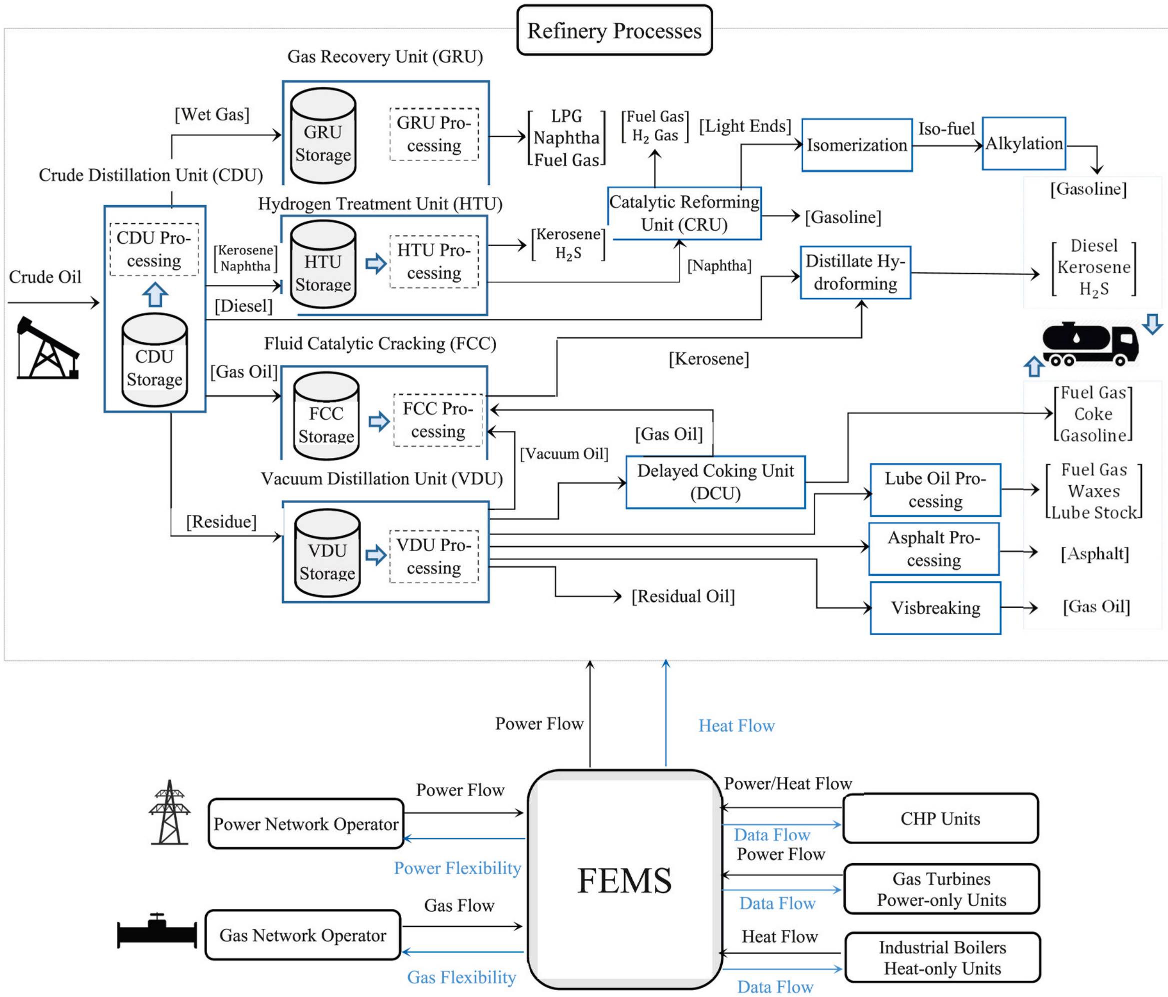


**Fig. 6.** Interaction of ORI units with multi-carrier girds to provide demand-side flexibility [163].

Hydroforming Unit (DHU), the diesel and kerosene are refined to reduce the Sulphur content. In the Delayed Coking Unit (DCU), fuel gas, coke, and gasoline are produced from the residual oil. In the Lube Oil Processing Unit (LPU), the physicochemical properties of the petrochemical products are improved to produce fuel gas, waxes, and lube oil. The Asphalt Processing Unit (APU) produces asphalt for road coating objectives. Finally, Visbreaking improves the quality of the residual oil by fractioning the large hydrocarbon molecules.

The three main refinery processes show that the ORI is comprised of various refinery sub-processes with different energy intensities. Besides, the products and byproducts of the processes are stockpiled in the downstream storages to provide the feedstock of the further processes. In this way, two flexibility potentials can be unlocked. First of all, the energy consumption, i.e. power and heat, of the refinery processes are dependent on the feedstock flow. Therefore, the variable mass flow model makes it possible to unlock the flexibility potentials of the processes in response to DR requests [59]. The flexibility opportunities are integrated into the power and gas networks through power and heat demand flexibilities, respectively. Besides, the feedstock storages play a key role in providing flexibility for the energy networks. The storage makes it possible to supply the downstream refinery processes without interruption in the daily production. Therefore, an energy-intensive process may be turned down in response to flexibility requirements while the downstream processes are supplied by the storage uninterruptedly. All in all, the flexibility opportunities of the ORI can be classified as follows:

1. Turn up/down the power and heat consumption of the refinery processes through the variable mass model.
2. Supply the downstream refinery processes by the upstream storage.
3. Generation scheduling of self-generation facilities, including CHP and industrial boilers.

In the literature on the ORI, to the best of authors' knowledge, there are a few studies focused on flexibility potential. The main reason is the complexity of energy management in refinery processes. Firstly, in 2003, a research study proposed a general framework to determine the optimal operational strategies of industrial cogeneration including both electrical and thermal systems [161]. The study showed that how self-generation facilities, including steam turbines, gas turbines, diesel generators, steam boilers, waste heat recovery boilers, and steam header configuration with grid connection, can be exploited in the petrochemical industry to provide peak-shaving for the power system. In 2013, a decision-making procedure was proposed to optimize load control in the ORI [162]. The study developed mathematical models to unlock demand flexibility in operational sequences of refinery processes in a smart grid. In 2019, an energy management system was suggested for ORI to unlock the flexibility potentials of refinery industries in response to dynamic energy prices [59]. The study addressed the variable mass flow model to integrate the demand flexibility of the ORI into power grids. Besides, it optimized the operating strategies of the self-generation facilities including CHP, industrial boilers, and on-site

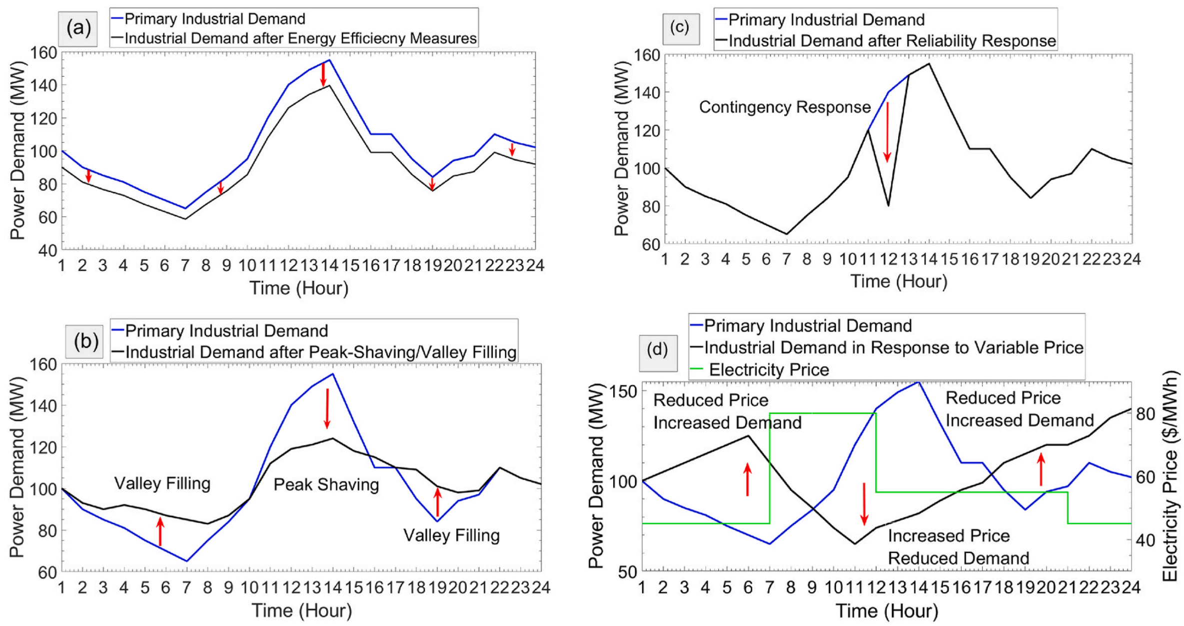


**Fig. 7.** Impact of energy management in load profile of an industrial plant (a) Energy efficiency measures (b) Peak-shaving and valley-filling (c) Reliability enhancement (d) Price responsive.

solar power generation units. In 2020, the energy consumption of the ORI is modeled mathematically to unlock the flexibility of the ORI when a power shortage occurs in the power grid [163]. The study modeled the industrial boiler and CHP to supply the power and heat demand of the refinery processes. A robust optimization approach was addressed to integrate the joint heat-power flexibility into the power system under electricity price uncertainty. The study concluded that the ORI can provide peak-shaving for power systems when a power shortage occurs.

Although there are few studies in the case of flexibility management in the ORI, the energy efficiency measures are heeded in many studies. Most of these studies focused on increasing the energy efficiency of refinery equipment and restoring the waste heat of refinery processes. In 2013, a research study was conducted to evaluate the impacts of four heat supply alternatives, including natural gas combined cycle, natural gas boiler, biomass boiler, and excess heat, on the carbon footprint of the ORI [164]. In 2016, an eco-technical study was done to investigate the role of the heat recovery systems of refinery processes on the cash flow and greenhouse gas emissions [165]. In 2017, a research study showed that waste gases from oil refinery plants can be retrieved for electric power generation [166]. In 2019, a practical study analyzed energy recovery solutions based on the pump-as-turbine technology in the ORI [167]. Moreover, a research study proposed energy efficiency measures as a pathway for greenhouse gas emissions reductions in the ORI [168]. In 2020, a practical study was conducted to show the impacts of solar-based systems in increasing the energy and cost efficiencies of refinery processes [169]. In 2021, a comprehensive study was carried out to investigate the interaction of water-energy-environment nexus in a hybrid system including an ORI, a thermal power plant, and a heat recovery steam generator. The hybrid system aimed to meet the electrical and gas demand of the residential and industrial sectors [170].

To sum up the demand-side management in the ORI, Fig. 6 depicts the general structure of energy management in a modern ORI. Based on the figure, the FEMS optimizes the energy generation of the self-generation facilities, i.e. CHP units, steam boilers, and power-only units, as well as the power/heat consumption of the refinery processes to provide demand flexibility for the upstream power and gas networks.

## 5. Main objectives and market floors

In power system studies, demand side management is implemented in the industrial sector to fulfill the key following aims:

1. Increasing energy efficiency of industrial processes
2. Providing peak-shaving and/or valley-filing for power system
3. Enhancing power system reliability
4. Providing up-/down-regulation for intermittent power systems
5. Provoking price responses

First of all, many technical measures have been introduced to improve energy efficiency in industrial processes. Besides, due to increased environmental concerns and global warming, the energy efficiency measures are more heeded to reduce greenhouse gas emissions. In Ref. [171], an extensive survey is conducted to introduce energy efficiency approaches and technologies in different industrial processes of cement manufacturing plants, from crushing to cement mills. The study concluded that the largest recorded values of energy savings are 3.4 GJ/t and 35 kW h/t for thermal and electrical energies, respectively. Moreover, the highest emission reduction in this industry is 212.54 kgCO2/t to date. In the aluminum industry, a research study proposed 52 energy efficiency measures [125]. Based on the study, the energy consumption of electrolysis and recycling processes are highly affected by the measures. In the US, a comprehensive study suggested a framework to improve energy efficiency in the pulp and paper industries [172]. In this study, the energy efficiency measures are evaluated quantitatively in key processes including raw material preparation, chemical pulping, mechanical pulping, and papermaking. In Ref. [173], the energy-saving opportunities of oil refinery plants are presented. In this way, practical solutions are offered for industrial motors, pumps, compressors, and fans in different refinery processes. Meanwhile, the energy management of self-generation facilities, including CHP, gas turbines, and industrial boilers, are investigated. Regarding peak-shaving and valley-filling, the industrial sector shifts the power consumption of energy-intensive processes from peak hours to off-peak hours. In Ref. [14], an incentive-based DR program is suggested to encourage the heavy industries, including 8 cement plants, 9 metal industries, and 1 automaking factory, to reduce the power consumption during peak hours of

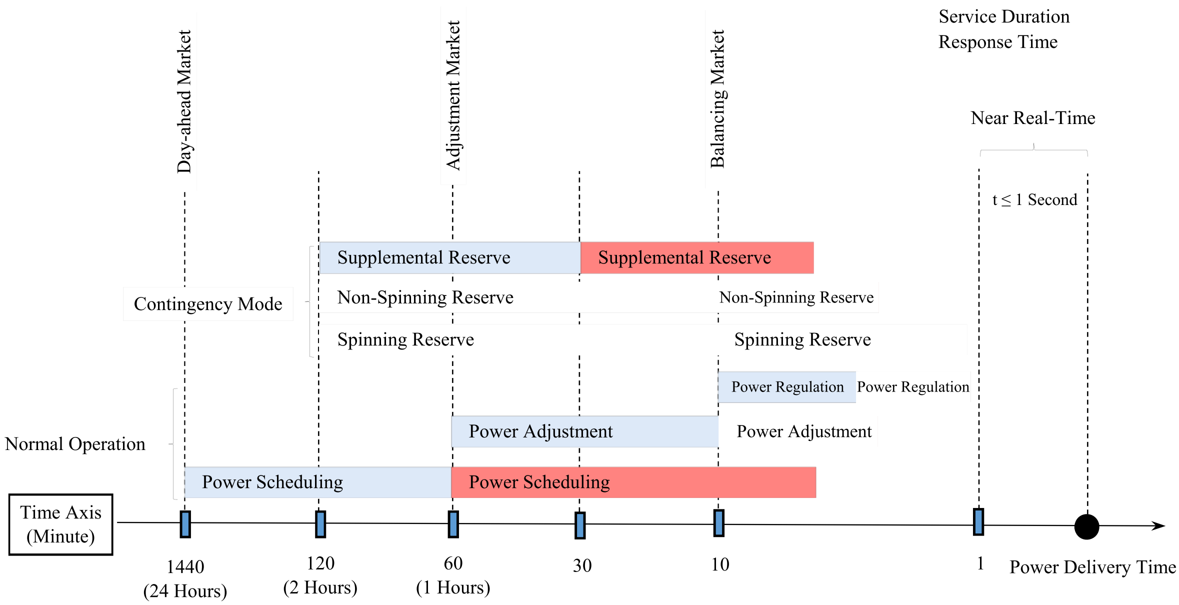


**Fig. 8.** Time response and duration of short-term market floors and ancillary services in a graphical presentation.

summer days when Iran Power Grid faces a surge in power consumption of residential and commercial cooling systems. With the development of the smart grid, research study [98] proposed flexible industrial processes of cement and metal smelting plants to maintain power system reliability and to provide power regulation in ancillary service markets. The research study [174] provides a theoretic framework and practice-oriented survey of industrial demand flexibility in response to different pricing schemes. To give a general overview, Fig. 7 describes how the key objectives affect the load profile of an industrial plant.

To fulfill the abovementioned aims, the flexibility potentials of the industrial plants are integrated into the trading floors of electricity markets. The market floors are so designed to meet the flexibility requirements of the supply-side from hours before energy delivery time until near real-time. In power systems with high RES penetration, the daily electricity markets are normally comprised of three market floors, including the day-ahead, adjustment, and balancing markets. In the normal operation, the main energy consumption of heavy industries is scheduled in the day-ahead market 24 h before power delivery time [175]. For example, a cement plant can make a decision about the main power consumption of energy-intensive processes, e.g. crushers and mills, in the day-ahead market [176]. Approaching the power delivery time, the adjustment market is performed 60 to 10 min before power delivery time. In the case of flexibility requests by the power system operator, the cement plant can turn off/on the interruptible processes, e.g. crushers, and supply the feedstock from the silos [19]. Finally, the balancing market is cleared a few seconds before power delivery time. Consequently, the factory may turn up/down the power consumption of the VSD mills in response to power system imbalance to provide down-/up-regulation at the opposite side of power system imbalances [177]. Therefore, the flexibility potentials of the factories are integrated into the three successive market floors hierarchically on long, mid, and short advance notices.

In addition to the normal operation, ancillary service markets provide required flexibility in a contingency operation. In this way, generally, three types of reserve services are considered, including spinning reserve, non-spinning reserve, and supplemental (replacement) reserve [46]. The spinning reserve is an online power generation capacity that is extracted from the running generators connected to the power system. The spinning reserve is normally provided within a few seconds up to 10 min. In the industrial sector, some industrial processes can turn down the energy consumption in few minutes in response to

**Table 10**
Quantitative characteristics of time response and time duration for short term market floors and ancillary services.

| Power System State | Service Type | Response Speed | Duration | Cycle Time |
|---|---|---|---|---|
| Normal Operation | Long Notice Power Scheduling | ≈1 Hour | Hours | Hours |
| | Mid Notice Power Adjustment | 10 Minutes ≤ t ≤ 60 Minutes | 10 Minutes to Hours | 10 Minutes to Hours |
| | Short Notice Power Regulation | ≈1 Minute | Minutes | Minutes |
| Contingency State | Spinning Reserve | Seconds ≤ t ≤ 10 Minutes | 10 Minutes ≤ t ≤ 120 Minutes | Hours to Days |
| | Non-spinning Reserve | t ≤ 10 Minutes | 10 Minutes ≤ t ≤ 120 Minutes | Hours to Days |
| | Supplemental Reserve | t ≤ 30 Minutes | ≈120 Minutes | Hours to Days |

flexibility requirements. The contingency state may be due to a renewable power shortage or a failure in power system facilities. For example, in aluminum smelting plants, the variable voltage controller of the pots can provide power flexibility within a few minutes without imposing interruption to the whole pot [117]. The non-spinning reserve is the generation capacity of offline generators that can be connected to the power system on short notice, i.e. fast-run generators. In industrial plants, the power consumption of some processes, e.g. crushers and cement mills, can be turned off within a few minutes. Meanwhile, the self-power generation facilities of industries, e.g. gas turbines and diesel generators, can be synchronized with the power system to support the non-spinning reserve market [178]. The supplemental reserve is normally used to restore the spinning and non-spinning reserve to a pre-contingency operational state. In contrast to the spinning and non-spinning reserves, the time response of the supplemental reserve is more than half an hour and may take up to 2 h. Some industrial loads with 0.5–2 h time response can integrate power flexibility to this market service. As an example, the operation time of a running smelting pot takes around 45–60 min. Therefore, the running pots can respond to flexibility requirements as the supplemental reserve without interruption. Completing the operation of the running pot, the next operation cycle of the pot is postponed to provide power flexibility for the supplemental reserve market. Fig. 8 and Table 10 explain the characteristics of the market floors and ancillary services in the normal operation and contingency mode. The data are extracted from Refs. [138,179].

## 6. Challenges and opportunities

Industrial demand flexibility is a necessity, especially for future power systems with high intermittent power penetration. Although both the power system and industry owners take advantage of the Demand Side Management (DSM), some challenges may discourage the industries to participate in DR programs.

In the energy markets, data availability, including energy price and demand level, is a challenging issue. In power systems with high RES penetration, there is a strong correlation between electricity price and renewable power availability [180]. The intermittency of the RES, as well as the uncertain nature of demand level, impose a great deal of uncertainty on the industrial DR programs [181].

Market power and economic withholding is a critical issue that is performed by heavy industries, especially large-scale ones. In metal smelting plants, the nominal power consumption of a smelting pot is up to 100 MW. Therefore, such heavy industries may bid high prices (or request high financial incentives) surpassing the conventional incentive for small- and mid-scale industries. In this way, economic withholding [182] emerges, especially when the power system balance depends heavily on the operation of heavy industries.

To encourage the industries to participate in DR programs, the industries are normally offered price-based [58] or incentive-based programs [183]. The uniform incentive or price schemes are not satisfactory for different industries. The reason is that the revenue of shifting/curtailing energy consumption is not the same for various industries. Therefore, to compensate for the lack of financial losses, the DR incentives should be offered based on the financial characteristics of the target industries individually. As an example, the incentive for textile industries should be different from the metal smelting plants.

The responsive plants are not allowed to participate directly in the electricity market. As a result, an intermediary agent is required between the power system and industrial plants. The third party is called the industrial demand response aggregator and industrial demand response provider in the literature [184]. The basic structure and protocols of such agents are still under investigation in many studies [185]. The intermediary agent is responsible for informing the contracted industries of the DR programs and provide them with compelling incentives to encourage them. Widespread adoption is a challenge for the third parties to raise consciousness in the industrial sector and attract more industrial plants to join the DR programs.

Shifting the operational strategies of industries to off-peak hours, the working hours of the industries' crew need to be extended. Besides, the working load of the crew in the production line increases/decreases in off-peak/peak hours of the power system [186]. It may impose a challenge to the industries and affects crew availability. The crew availability and the associated cost should be taken into account before deciding on participation in DR programs.

The key feature of the smart grid is the two-way communication between supply and demand sectors which makes it possible to unlock power flexibility [187]. In the industrial sector, technical data play a key role in operational scheduling and flexibility management. The data includes the supply side, e.g. electricity price, incentive plans, flexibility requirements, and the demand side, e.g. production line limitations and operational strategies. A data lake is required to store, manage and preprocess the raw data to be tailored for industrial demand flexibility [188]. In this way, data collecting, communicating, storing, and processing are still controversial issues.

Implementation of DR programs in industries needs technical skills

**Table 11**
Classification of main challenges and opportunities of industrial demand side management.

| Challenge/ Opportunity | Type | Description | | Discussed References |
|---|---|---|---|---|
| **Challenges** | Energy Markets | Data Availability, e.g. energy price, demand level. | | [51,200,201] |
| | | Market Power by Large-scale Industries | | [51] |
| | | Pricing mechanisms and optimal scheduling | | [73,85] |
| | Behavioral Interaction | Lack of trustworthy parties | | [51] |
| | | Widespread adoption of DR programs | | [50,51,202] |
| | | Customer understanding and participation | | [85,203] |
| | Technological | Data and IoT | Data Collection<br>Data Process<br>Data Communication | [204,205] |
| | | Technical Skills | | [206,207] |
| | | Non-interruptible industrial processes | | [73] |
| | | Big data analytics-based decision support. | | [85] |
| | | The emergence of RES and storage devices | | [79] |
| | | Implementation issues: implementation of flexibility management is a complex action in industries practically | | [79] |
| | Regulatory | Lack of regulation for flexible industries | Tax | [208–210] |
| | | | GHG Emission | [211–213] |
| | | Utility reconstruction issues | | [46,214] |
| | | Program requirements and aggregation | | |
| | | Measurement and verification variety | | |
| | | Limitations on market regulations. | | |
| | | Inclusion in energy efficiency programs. | | [46,215] |
| | | Various regulations in different countries | | [51,184,216] |
| | | The market mechanism is not perfect | | [50] |
| | Financial | Lack of persuasive incentives | | [46] |
| | | Lack of exact evaluations for DR benefits | | [46] |
| | | Capital accessibility and preconditions of third parties | | [87] |
| **Opportunities** | Power System | Power frequency regulation | | [217–219] |
| | | RES facilitation | | [220–222] |
| | | Reduction in power system operation cost/emission production | | [223–225] |
| | | Flatten the load profile (Peak-shaving and/or Valley-filling) | | [226–228] |
| | | Improving power system reliability/security/resilience | | |
| | | Congestion mitigation and voltage improvement | | [196,229,230] |
| | | Unlocking DG/CHP capacity of industries | | [231–233] |
| | Industries | Incentive financial plans | | [234–236] |
| | | Reduction in electricity bills | | [237–239] |
| | | Effective maintenance scheduling | | [240–242] |
| | | Improved power quality and decelerate aging | | [243–245] |
| | | Prevent power interruption/ Sustainable power supply | | [246–248] |
| | | Decreasing in energy intensity | | [249–251] |

and expert knowledge. Otherwise, imposing interruption/curtailment on industrial processes may cause financial losses. Due to a lack of technical skills, many industries are reluctant to respond to DR programs and prefer to follow conventional operational strategies. Technical knowledge contributes to the acceptance of industrial DR [189]. Therefore, it is crucial to educate the industrial energy experts and production planning departments about DR skills.

The challenges are not limited to financial and technical issues. The regulatory problems are stated in many studies in recent years. Energy tax [190] and Greenhouse Gas Emissions (GHG), also known as the carbon tax [191], are two critical regulatory issues. Tax issues may be used as leverage to persuade the industries to participate in DR programs. The GHG emission is a barrier for some industries to shift the operational strategies, especially for industries close to urban areas. In this case, the industries are not allowed to produce GHG emissions in some seasons and even some hours a day depending on local emission constraints [192]. Such regulatory rules are quite localized in countries and do not follow the same pattern worldwide.

Despite the surveyed challenges, industrial demand flexibility provides perfect opportunities for both power systems and industries. Power frequency regulation [193] and facilitation of RES integration [194] are two key opportunities especially for power systems with high intermittent power penetration. For a power system with distinct peak demand, the industrial flexibility not only flattens the demand profile but also reduces the operational cost of the power system due to avoid investing in fast-run power plants [18]. In addition to the normal operation of the power system, the responsive plants can provide the required flexibility when an unforeseen failure affects power system reliability. The opportunities of responsive industries are not limited to the global power balance. Besides, the flexible industries contribute to the local congestion mitigation in weak power lines [195] and voltage regulation in connected buses and substations [196]. Meanwhile, there is a significant amount of unused thermal distributed generation capacity in industries that can be connected to the power system within a few minutes when a power shortage occurs. Most thermal Distributed Generations (DG) are normally used for emergency power system backup. The aggregated DG capacity offers a great flexibility potential for power systems during critical hours.

On the other hand, the industries benefit from the DR programs. The industries are offered financial incentives in response to DR programs [197]. Moreover, they take advantage of reduced electricity bills by participating in price-based DR programs, e.g. Time-of-Use (TOU) and Critical Peak Pricing (CPP) [198]. Many industries schedule the minor maintenance and overhaul of the production lines in time durations when a considerable power reduction is required on the supply side [14]. In this way, the industries take advantage of financial incentives to reduce the annual maintenance cost. In some power grids with seasonal power shortages, if the industries do not participate in DR programs, the unscheduled power outage is possible. Therefore, the active flexible industries not only help power systems to provide a sustainable power supply but also improve the power quality in industrial zones. The low power quality and unscheduled power outage impose significant financial losses to the industries [199]. To sum it up, Table 11 classifies the key challenges and opportunities associated with industrial DSM.

## 7. Optimization algorithms and software

To model energy structures of industries, different technical models are suggested in the literature. In the model-based approaches, generally, two types of solution methodologies are used to optimize the energy consumption of the industries. The solution approaches include mathematical programming and nature-inspired (metaheuristic) algorithms. The mathematical programming uses mathematical approaches, e.g. Newton, quasi-Newton, steepest descent, and the Simplex methods to optimize the solution. These methods are capable to optimize simple mathematical energy models, normally in form of linear and convex, e.g. Linear Programming (LP). Increasing the dimension of the physical energy model, the computational burden of the optimization algorithms increases considerably. In the real world, the energy model of many industrial processes follows nonlinear and/or nonconvex structures. Although it is difficult to solve severe nonlinear models using mathematical approaches, some advanced methods, e.g. branch-and-bound [252] and benders decomposition [253], facilitate the optimization of nonlinear energy models. In the case of large-scale nonlinear models, heuristic and metaheuristic approaches are useful techniques to optimize the energy models. The main advantage of heuristic and metaheuristic approaches is that the optimized solution can be found easily with low time and computation burden. In contrast to the mathematical approaches, the optimized solution is an approximate answer instead of the exact solution found by mathematical approaches.

### 7.1. Linear programming

Linear programming shows a simple form of physical models with linear objective functions and constraints. The mathematical programming approaches can optimize the LP models easily in a low computational burden. In the industrial sector, some research studies have proposed LP models for the energy equations of the industrial processes. In Ref. [254], an LP is addressed to model the energy system of a textile industry while minimizing the annual operation cost of the plant. In aluminum smelting plants, the LP is used to maximize the integration of intermittent renewable energy into the industry [255]. This method is used in industrial microgrids to minimize the energy consumption cost of the industrial demands [256].

### 7.2. Mixed-integer linear programming

Mixed-integer linear programming (MILP) includes linear objective functions and constraints with at least one integer variable. In industrial demand management, the MILP is addressed to optimize the energy model of oil palm-based industrial parks [257]. The study aims to maximize the economic performance of the industrial units. A generic MILP model is suggested for industrial hubs to minimize energy and production costs, rewards, and penalties due to not meeting the production plan of industrial processes [258]. Regarding industrial microgrids, a MILP approach is presented to minimize the expected cost of industrial prosumers in battery manufacturing plants, including power procurement cost and operation cost of self-generation facilities [259]. In the steel milling industry, the MILP is adopted to optimize the operation of on-site power plants with the purpose of peak-shaving for the upstream network [260]. The research study [261] uses the MILP to determine the optimum operation of the refinery process in an ethanol biorefinery plant.

### 7.3. Mixed-integer non-linear programming

In Mixed-integer non-linear programming (MINLP), the objective function and/or constraints are nonlinear and at least one of the decision variables is an integer. In the research study [262], an MINLP is suggested to maximize the profit of smart power grids in presence of responsive industrial demands. In a large-scale ethylene plant, the MINLP is addressed to minimize the total energy consumption of the industrial processes [263]. This approach is addressed in Alberta's oil sands industry to facilitate the integration of renewables into the plant [264]. In Ref. [265], an MINLP model is proposed to maximize the profit of the industrial microgrid and minimize the industrial load shedding.

### 7.4. Metaheuristic approaches

In severe nonlinear models, the mathematical programming approaches may fail to find the optimum solution. In such a situation, the time and computational burden of the problem increase significantly

**Table 12**
Metaheuristic algorithms to optimize industrial energy models.

| No. | Reference | Algorithm | Target Industry |
|---|---|---|---|
| 1 | [266] | Non-dominated Sorting Genetic Algorithm (NSGA-III) | Iron And Steel Industry |
| 2 | [277] | Genetic Algorithm | Oil Industry |
| 3 | [267] | Particle Swarm Optimization (PSO) | Pulp And Paper Industry |
| 4 | [268] | Simulated Annealing (SA) | Smart Grid For Industry |
| 5 | [269] | Ant Colony Optimization (ACO) | Pulping Industry |
| 6 | [270] | Firefly Algorithm (FA) | Food Industry |
| 7 | [278] | Differential Evolution (DE) | Multi-Energy Industrial Network |
| 8 | [271] | Teaching Learning Based optimization (TLBO) | Foundry Industry |
| 9 | [272] | Gravitational Search Algorithm (GSA) | Chemical Industrial Processes |
| 10 | [273] | Cuckoo Search (CS) | Textile Industry |
| 11 | [274] | Grey Wolf Optimization (GWO) | Maritime Industry |
| 12 | [275] | Harmony Search Algorithm (HSA) | General Manufacturing Plants |
| 13 | [276] | Krill Herd (KH) | Liquefied Natural Gas Industry |

and make the problem intractable. Nature-inspire optimization approaches are practical solutions to find a fast optimum point. Although the optimum point may be approximate, the tractability and low computational burden may overweigh the mathematical methods. In the iron and steel industry, a Non-dominated Sorting Genetic Algorithm (NSGA) is addressed to optimize the objective function which is comprised of three terms including (1) minimization of energy consumption, (2) minimization of pollutant emission, and (3) minimization of total energy conservation and emission reduction cost [266]. In the paper milling industry, Particle Swarm Optimization (PSO) is suggested to minimize the energy consumption cost of the industrial processes [267]. In an industrial smart grid, the Simulated Annealing (SA) is proposed to minimize energy and production costs of industrial companies [268]. In the pulping industry, the Ant Colony Optimization (ACO), as well as the GA, PSO, Differential Evolution (DE), and Biogeography-based Optimization Algorithm (BBO), are addressed to increase the accuracy of energy management models [269]. Firefly Algorithm (FA) combined with PSO is addressed in the sugar industry to model industrial clarifying processes of the plant [270]. In the foundry industry, Teaching Learning Based Optimization (TLBO) is used to optimize the industrial operation of furnaces [271]. Gravitational Search Algorithm (GSA) is addressed in a research study [272] to minimize ignition energy of industrial processes of chemical industries. In a woolen mill plant, Cuckoo Search (CS) and Bio-Inspired Optimization Algorithms are suggested to optimize the objective function of the energy management system including minimization of the energy consumption cost, peak-to-average power ratio, and waiting time of customers due to production rescheduling [273]. In maritime industries, the Grey Wolf Optimization (GWO) is proposed to minimze the energy consumption of the self-generation facilities and electric ferries [274]. A holistic approach is presnted in study [275] to minimize the total energy consumption of production processes of industrial plants while fulfilling the customers' requirements by using Harmony Search Algorithm (HSA). In liquefied natural gas industries, Krill-Herd-Based investigation algorithm is addressed to minimize the required shaft work of industrial compressors [276].

Table 12 describes the metaheuristic approaches used in industrial energy management. In this table, 13 nature-inspired algorithms are stated. To the best of the authors' knowledge, some well-known algorithms, including Group Search Optimizer (GSO), Bee Colony, Invasive Weed Optimization (IWO), Artificial Immune System (AIS), Crisscross Optimization (CSO), Line-up competition algorithm (LCA), and Exchange Market Algorithm (EMA) are not examined in the industrial sector. It may provide an opportunity for energy researchers to investigate the functionality of the suggested algorithms in industrial energy management.

**Table 13**
Software tools addressed in industrial energy management studies.

| No. | Reference | Software | Target Industry | Homepage of Software Developer |
|---|---|---|---|---|
| 1 | [254] | AIMMs 4.32 | Textile | https://www.aimms.com/ |
| 2 | [279] | DIgSILENT | Industrial Energy Hubs | https://www.digsilent.de/ |
| | | GAMS | | https://www.gams.com/ |
| 3 | [299] | COMSOL Multiphysics 5.3 | Metal Hydride Hydrogen Compressors | https://www.comsol.dk/ |
| 4 | [300] | Aspen Plus | Cement | https://www.aspentech.com |
| 5 | [280] | Aspen Plus | Cement | https://www.aspentech.com |
| 6 | [281] | Fortran | Cement | https://fortran-lang.org/ |
| 7 | [286] | HOMER Pro-3.2 | Cement | https://www.homerenergy.com/ |
| 8 | [301] | GE Intelligent Platform | Paper Mill | https://www.ge.com/ |
| 9 | [287] | Simprosys 2.1 | Paper Industry | http://www.simprotek.com/ |
| 10 | [302] | reMIND | Pulp And Paper Industry | NA |
| 11 | [288] | SIMCA 14.1 | Pulp And Paper Industry | https://www.sartorius.com/ |
| 12 | [303] | Aspen Plus | Steel Industry | https://www.aspentech.com |
| 13 | [304] | Termolog EPIX 10 | Wine Industry | www.logical.it/software-per-la-termotecnica |
| 14 | [282] | MATLAB | Pulp And Paper Industry | https://www.mathworks.com |
| 15 | [283] | Python | Industrial Manufacturing Systems | https://www.python.org/ |
| 20 | [305] | OriginPro8.0 | Drilling Industries | https://www.originlab.com/ |
| 21 | [285] | SPSS | Cement, Steel, Pulp And Paper, Textile | https://www.ibm.com/products/spss-statistics/ |
| 22 | [284] | LEAP | Iron And Steel Industry | https://leap.sei.org/ |
| 23 | [306] | Computational Fluid Dynamics (CFD) | Ceramics Industry | https://www.simscale.com/ |
| 24 | [289] | Vensim | Textile Industry | https://vensim.com/ |
| 25 | [307] | DOE-2.2 | IT Industries | https://www.doe2.com/ |
| 26 | [308] | MATLAB | Agrifood Industries | https://www.mathworks.com |
| 27 | [309] | System Advisor Model (SAM) | Oil & Gas Industries | https://sam.nrel.gov/ |
| | | Aspen HYSYS | | https://www.aspentech.com/en/products/engineering/aspen-hysys |
| 28 | [310] | Superdecisions | Fuel-Oil, Coal, LPG, Natural Gas | http://www.superdecisions.com/ |
| 29 | [311] | REFPROP | Steel Industry | https://www.nist.gov/srd/refprop |
| 30 | [312] | GAMS | Chemical Industry | https://www.gams.com/ |

### 7.5. Software and solvers

In order to make a mathematical model for industrial processes,

**Table 14**
Software tools addressed in industrial energy management studies.

| Solver | LP | MILP | NLP | MINLP | Target Industry | Reference |
|---|---|---|---|---|---|---|
| ANTIGONE | | | ✔ | ✔ | Power Industry | [292] |
| BARON | ✔ | ✔ | ✔ | ✔ | Power Industry | [292] |
| CONOPT | ✔ | | ✔ | | Industrial furnace | [295] |
| CPLEX | ✔ | ✔ | | | Glass Container Industry | [290] |
| DICOPT | | | | ✔ | Process Industries | [293] |
| GUROBI | ✔ | ✔ | | | Refining furnaces | [291] |
| IPOPT | ✔ | | ✔ | | Process Industries | [296] |
| LINDO | ✔ | ✔ | ✔ | ✔ | Biodiesel industry | [297] |
| MOSEK | ✔ | ✔ | ✔ | ✔ | General Industries | [294] |
| XPRESS | ✔ | ✔ | ✔ | ✔ | Oil industry | [298] |

programming languages and simulation software are used. In simulation software, the mathematical model of energy systems, industrial processes, and objective functions with associated constraints are coded. In this way, the physical model is translated into machine language. The machine language makes it possible to optimize the target variables of the energy experts and production planners. In contrast to the simulation software, the solvers are optimization approaches to find the optimum point of the simulated problem. The type of solvers depends on the type of the objective functions and constraints in terms of linearity, nonlinearity, and problem dimensions.

Regarding the simulation software, AIMMs [254], GAMS [279], Aspen Plus [280], Fortran [281], MATLAB [282], Phyton [283], LEAP [284], SPSS [285], HOMER [286], Simprosys [287], SIMCA [288], Vensim [289] are used in cement manufacturing, metal and aluminum smelting, textile, wood and paper mills, and oil refinery industries.

For linear energy models, the LP and MILP are the most efficient solution methods offered by mathematical solvers, e.g. CPLEX [290], and GUROBI [291]. Regarding the non-linear energy models, the solution algorithm depends mainly on the non-linear strength of the problem. In this case, many mathematical solvers are addressed in industrial energy management including ANTIGONE [292], DICOPT [293], MOSEK [294], CONOPT [295], IPOPT [296], LINDO [297] BARON [292], and XPRESS [298]. To sum up, Table 13 illustrates some important software tools in industrial energy management. Besides, Table 14 describes some features of the used solvers in industrial energy management studies. Note that the table aims to show the software diversity instead of the software intensity. The official homepages of the software are also provided to help energy researchers accessing the software.

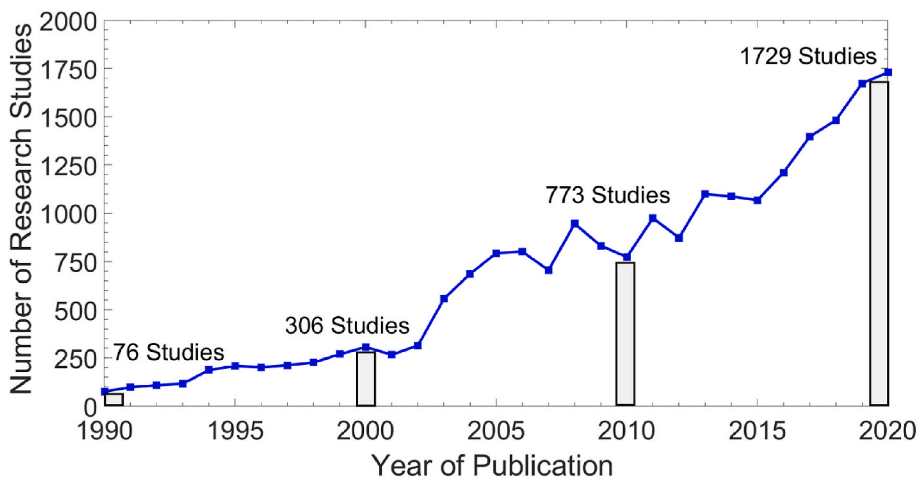


**Fig. 9.** The annual number of research studies from 1990 to 2020 in the field of industrial energy management.

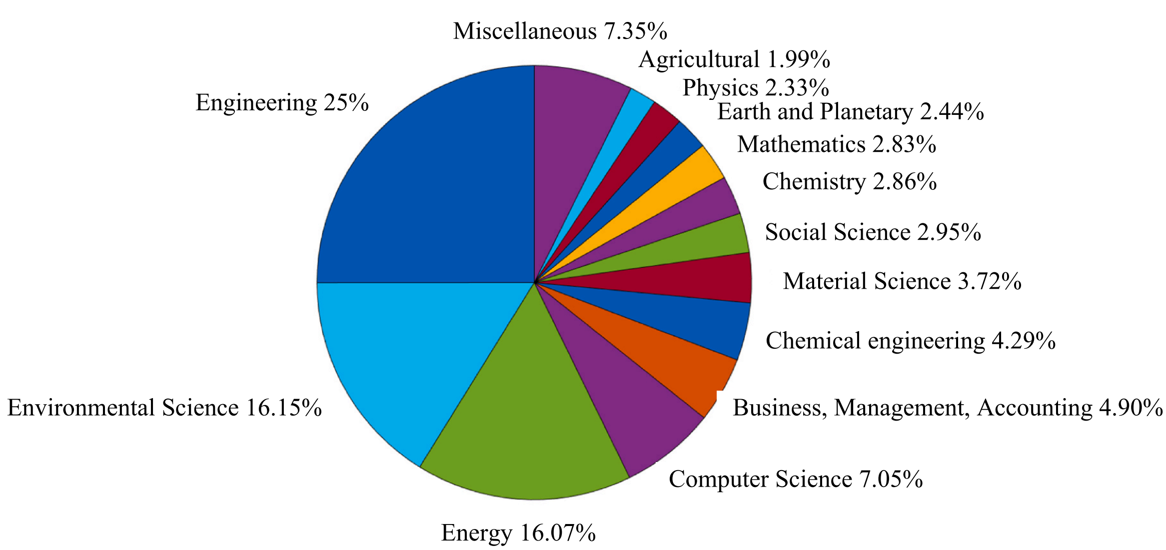


**Fig. 10.** Contribution of research studies to scientific disciplines in the field of industrial energy management.

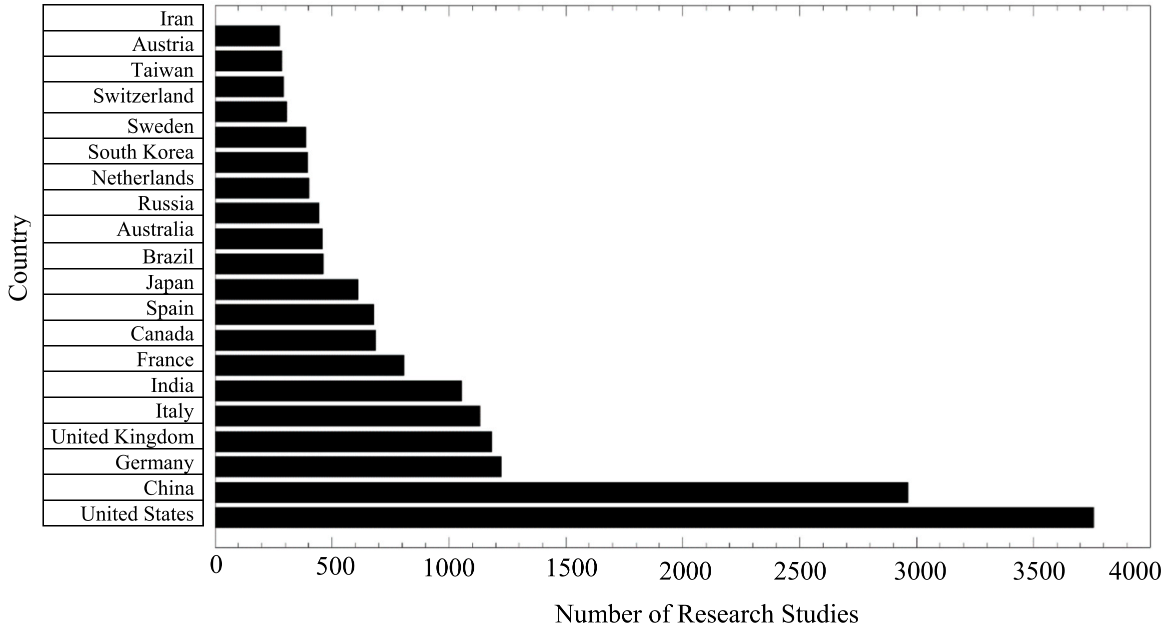


**Fig. 11.** Number of research studies in the field of industrial energy management in top 20 countries.

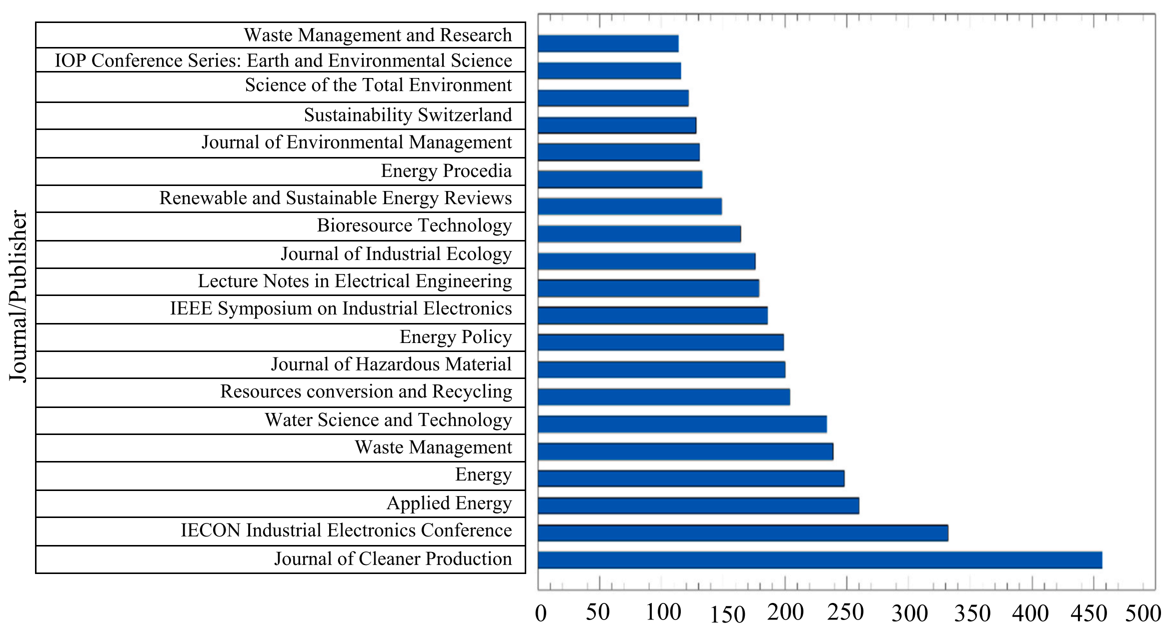


**Fig. 12.** Number of research studies in the field of industrial energy management in top 20 journal publishers.

## 8. Bibliographic and statistic survey

In this section, a bibliographic survey is presented to show the increasing importance of industrial energy management in the literature. The statistic data are extracted from Scopus [313] between 1990 and 2020. First of all, Fig. 9 describes the total number of research studies during the last three decades. As can be seen, the number of research studies in the field of industrial energy management increased from 76 in 1990 to 1729 in 2020. It shows that industrial energy management has attracted much attention in energy optimization, especially after 2000.

Fig. 10 illustrates the share of scientific disciplines in industrial energy management. Based on the pie chart, engineering, environmental science, and energy are the most top priorities for industrial energy management.

Fig. 11 explains the country-of-origin researches. As the bar graph reveals, the United States, China, and Germany published the most industrial research studies during the past thirty years.

Finally, Fig. 12 describes the distribution of the industrial publications in different journal publishers. As can be seen, the Journal of Cleaner Production, IECON Industrial Electronic Conference, and Applied Energy have published the most research studies in the last three decades.

## 9. Conclusion

Industrial demand management is a workable solution to meet the flexibility requirements of future power systems with high penetration of intermittent power. In the industrial sector, the heavy industries provide great flexibility potentials for power systems by scheduling/adjusting/regulating the energy consumption of energy-intensive processes. Cement manufacturing plants, aluminum smelting factories, and oil refinery industries show considerable potentials in providing power flexibility from 24 h prior to energy delivery time until real-time. In this way, the power consumption of industrial processes can be scheduled in the day-ahead market on long notice, then is adjusted in the intraday market on mid notice, and finally is regulated in the balancing market.

In heavy industries, some industrial processes are interruptible. Therefore, they can be turned on/off on short advance notice without imposing financial loss/damage to the factories. They can offer considerable flexibility values to the power systems in the day-ahead and intraday markets. In contrast, some industrial processes are uninterruptible; therefore, they can turn down/up the power consumption on short advance notice without causing interruption to the production line of the factory. Such processes are functional for real-time and ancillary service markets.

The simulation studies of industrial demand management show that cement manufacturing plants can provide up to 10% and 16.9% reduction in energy consumption cost and energy demand, respectively. The aluminum smelting factories can benefit from up to 34.2%, 20.70%, and 16.5% reduction in energy cost, energy demand, and emission production. The industrial processes of oil refinery industries exhibit great potentials for joint power and heat flexibility depending on the size of self-generation facilities, i.e. power generators and steam boilers.

The industrial demand response programs are beneficial for both the power system and industries. The power system mainly takes advantage of peak shaving and valley filling, frequency regulation, reduction in carbon footprint, and reduction in operational cost. In addition to the global support, the industries provide local power system support, e.g. congestion mitigation in power lines and voltage improvement in power substations. In response, the industries benefit from reduced energy consumption costs, financial incentives, improved power quality, and sustainable energy supply.

Although the supply and demand sides benefit from the DR programs, some challenges may discourage industries from participating in the DR programs. Regulatory barriers, data communication/storing/processing, and lack of financial incentives are the most important barriers reported in the studies. Moreover, the implementation of DR programs in heavy industries needs expert knowledge. As a result, education of technological skills raises consciousness and improves the acceptability of DR programs among industry owners. Finally, the regulation of the intermediary agent, i.e. the industrial demand response aggregators, is still a controversial issue that needs further investigation.

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## 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.

None.

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