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Exploring Flexibility Potential of Energy-Intensive Industries in Energy Markets

Laureana Luciani *, Juliana Cruz, Victor Ballestin and Boniface Dominick Mselle

CIRCE–Technology Center, Avenida Ranillas 3D 1ºA, 50018 Zaragoza, Spain; jmcruz@fcirce.es (J.C.); vballestin@fcirce.es (V.B.); bdmselle@fcirce.es (B.D.M.)
* Correspondence: lluciani@fcirce.es

Abstract: The European Union, in pursuit of the goal of reducing emissions by at least 55% by 2030 and achieving climate neutrality by 2050, is deploying different actions, with industry decarbonization as a key strategy. However, increasing electricity demand requires an intensification of energy generation from clean technologies, and the energy system's expansion is hindered by renewable generation's climatic dependencies and the imperative for substantial electrical infrastructure investments. Although the transmission grid is expected to grow, flexibility mechanisms and innovative technologies need to be applied to avoid an overwhelming growth. In this context, this paper presents a thorough assessment, conducted within the FLEXINDUSTRIES project, of the flexibility potential across seven energy-intensive industries (automotive industry, biofuel production, polymer manufacturing, steel manufacturing, paper mills, pharmaceutical industry, and cement production). The methodology followed during the analysis entails reviewing the state-of-the-art existing flexibility mechanisms, industries' energy markets engagement, and technical/operational readiness. The results highlight the feasibility of the proposed actions for enabling energy market flexibility through demand-response programs, quantifying energy opportunities, and pinpointing regulatory and technical barriers.

Keywords: flexibility; renewable energy sources; energy consumption; electricity market; decarbonization; smart technological solutions

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1. Introduction

1.1. General Overview; Trends, Literature Mapping, and State-of-the-Art

The increasing complexity of modern energy systems, driven by the integration of renewable energy sources and evolving consumer demands, requires enhanced flexibility in energy management [1]. The use of multi-energy sources and the techno-economic analysis of hybrid energy systems are widely explored, and studies of optimal sizing and operation have been conducted [2]. Moreover, optimized multi-energy sharing models depict the potential for significant economic and environmental benefits [3]. However, the decarbonization of processes through electrification or the use of multi-energy sources allows for the modification of process operations, making them more flexible to generate the necessary remuneration to make this transition sustainable for industrial users. Flexibility in energy systems is defined as the ability to adjust and respond to fluctuations in energy supply and demand in real time, ensuring stability and efficiency [4]. This adaptability is becoming increasingly critical, as energy grids incorporate higher proportions of variable renewable energy sources, such as wind and solar power, which are inherently intermittent and unpredictable [5].

To explore the literature on flexibility and energy, we searched the Scopus database using the query (TITLE-ABS-KEY ("Energy* and flexibility*") and retrieved all documents up to 28 May 2024 (Figure 1). A total of 124 documents were retrieved, with most (61.3%)

being article papers and 29.8% being conference papers. From the figure, it is evident that there is increased interest in implementing flexibility mechanisms in the energy sector. This trend has strongly grown especially in the last four years, peaking in 2023.

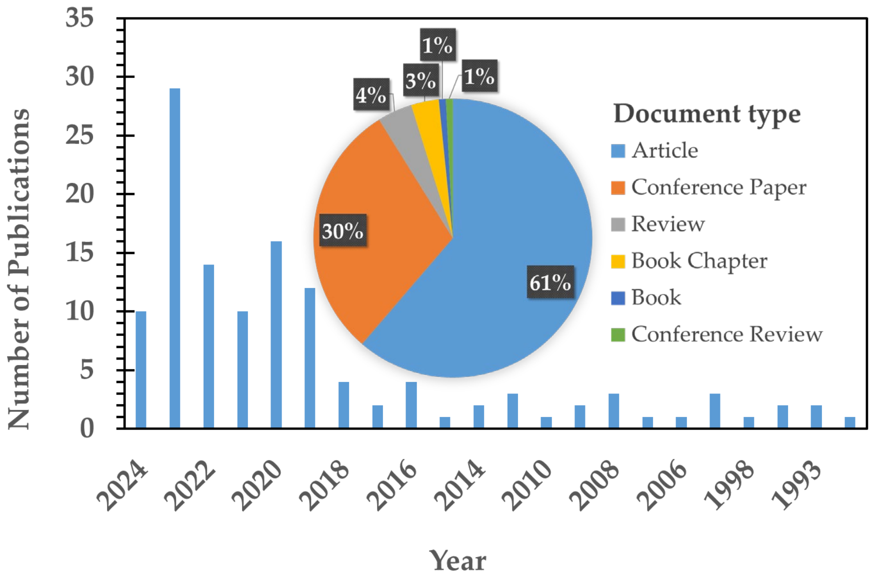

Figure 1. Evolution of the available literature on energy flexibility.

To further interpret the literature landscape on the implementation of flexibility mechanisms in the energy sector, a keywords analysis of the retrieved documents was carried out following the methodology exemplified by Mselle et al. [6]. From the documents, a total of 1452 keywords were identified; then, they were grouped and presented (minimum threshold of seven occurrences) in Figure 2. This literature-mapping analysis was carried out using Vos Viewer version 1.6.20 software. From the figure, the implementation of flexibility in the energy sector can be classified into three main clusters, i.e., market, infrastructure, and performance indicators.

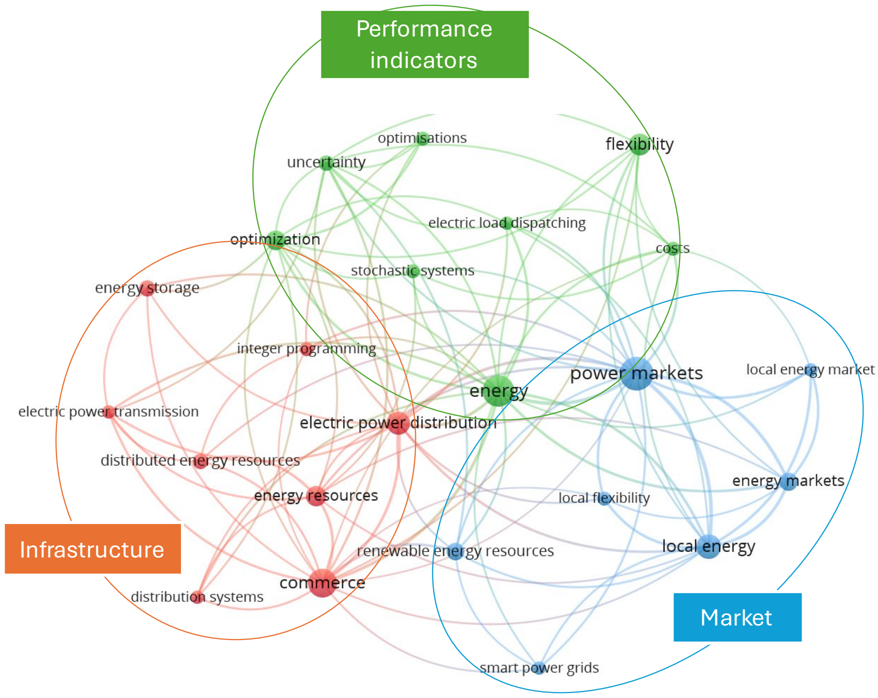

Figure 2. Literature map of the most occurring keywords.

For the performance indicators, the existence of terms such as "optimization", "uncertainty", "electric load dispatching", "costs", etc., are predominant. All these keywords show a great connection. In particular, the existence of "stochastic systems" showcases the potential need to address the variability and uncertainty in energy supply and demand [7]. For instance, effective "electric load dispatching" optimizes generation and minimizes costs while maintaining reliability [8], while advanced optimization techniques, such as stochastic programming, enhance decision-making [9]. Recent studies emphasize the importance of incorporating flexibility to improve system performance and reduce operational costs [10].

In the context of infrastructure, flexibility in energy systems hinges on advancements in technology and system integration, focusing on "energy storage", "distributed systems", "electric power transmission", "distribution", etc. Energy storage solutions, like batteries, enhance grid stability and reliability [11]. "Distributed systems", including microgrids, support local energy resilience and adaptability [12]. Efficient electric "power transmission" is essential for balancing supply and demand across regions [13]. The commercialization of these technologies drives innovation and reduces costs.

In the context of the market cluster, keywords such as "energy markets", "local energy", "local energy market", "power markets", etc., are evident. Renewable energy resources also take part in this cluster, showing a close connection between the evolving energy landscape's necessity for flexibility to manage the variability of renewable energy sources and ensuring grid stability. In context, there are also efforts to adapt energy markets and policies to support flexible technologies, such as energy storage and smart grids [14]. Local energy systems, including microgrids, enhance resilience and adaptability [15]. As renewable energy integration increases, mechanisms like demand response and time-of-use pricing become vital [16].

1.2. Market Overview and Characterization

One of the key elements for the implementation of flexibility is the market both in terms of price variability and demand-side mechanisms to provide balancing services. Here, the state of the art of the market is assessed, characterizing the three categories, i.e., electricity, gas, and district heating are summarized.

1.2.1. Electricity-Market Characterization

The wholesale market model serves as the foundation for the current electricity market where EIIs interact. There are variations in electricity prices where industrial facilities' case studies are located. In a previous study, electricity price dynamics for the case-scenario countries were reported. It was noted that electricity prices remained stable from 2012 to 2020 while registering a drastic rise from 2021 to date [17]. This unexpected skyrocketing effect is explained mainly by external factors, e.g., the impact of the increase in electricity demand, the economic crisis due to COVID-19, and the Russian natural gas cut-off that caused an increase in gas and CO_2 prices. In the study, Greece has the highest price increase rate over the last decade (141%), due to its dependence on natural gas (40.6% of it is electricity-generation mix). Countries such as Poland are slightly affected because of their dependence on coal [18]. Moreover, it was found that, during the day, the highest electricity prices are reported during peak hours, and furthermore, a high dispersion in prices is observed.

Beyond the expectation that electricity prices will stabilize by 2030 due to the increase in renewable energies and their integration into the electric system, there is the phenomenon known as the "duck curve" [19]. This term describes the variability of electricity prices throughout the day caused by the timing imbalance between peak demand and renewable energy generation, particularly from solar power. The "duck curve" results in significant price fluctuations, with lower prices during periods of high solar generation and higher prices during peak demand times when solar generation drops. Companies and industries alike can play a critical role by providing a demand response to the market enhancing the flexibility of the system. By decreasing or increasing energy consumption in a specific period, firms are not only taking advantage of the specific energy prices of the market but also providing an adequate response to the grid's needs.

Resources of Flexibility in Electricity Markets

Providing flexibility in electricity markets necessitates operational adjustments, technical components, and effective control systems. It is crucial to assess fluctuations in mass and energy balances and ensure existing systems can accommodate flexibility events. Three key technical parameters are vital for evaluating industrial technologies' flexibility [20]: start-up time (the duration needed to reach full load), ramp rate (the speed at which output can be adjusted), and power output (nominal generation capacity, emphasizing maximum output). Various technologies, especially those within case-study industries, have been assessed for their flexibility potential and constraints. Their technical response capabilities critically determine their suitability and performance across different market segments. These technologies support services such as frequency and voltage regulation, black start capability, reserves, peak shaving, load leveling, and self-consumption, collectively reducing distributed generation impacts and grid costs. Energy storage plays a crucial role by providing ancillary functions like frequency and voltage regulation and reserves, enhancing distribution-network adaptability. In energy management, storage supports demand management strategies, including peak shaving, load leveling, self-production, and self-consumption.

Flexibility Potential of Commonly Used Technologies in Industries

The flexibility potential and limitations of various industrial technologies are critical for providing flexibility in electricity markets. Key technical parameters, such as ramp rate and demand flexibility potential, are crucial for assessing each technology's capabilities. A common trend among these technologies is their ability to offer either capacity or manageable load flexibility, which is essential for maintaining grid stability and optimizing energy usage. For instance, steam turbines and gas engines provide substantial capacity flexibility, with ramp rates of 10% within 10–60 s for steam turbines and a rapid 50–100% within 60 s for gas engines. However, these technologies face limitations, such as thermal and pressure stress for steam turbines and the risk of transformer overheating for gas engines during cold start-up [20].

Additionally, Organic Rankine Cycles (ORC) systems, although capable of capacity flexibility with a ramp rate of 2–5% per 60 s, are designed for optimal performance at a single operating point, making part-load conditions less efficient [20].

In contrast, technologies like electric boilers, heat pumps, and charging EVs primarily offer manageable load flexibility. Electric boilers and charging EVs have no specified ramp rates, indicating a more stable but less dynamic adjustment capability [21]. Heat pumps, while providing manageable load flexibility, suffer from increased abrasion and reduced component lifetimes due to frequent on–off cycles, and their dependence on synthetic refrigerants poses a deployment barrier [22].

Storage systems stand out by offering both capacity and manageable load flexibility without specified ramp rates, indicating their versatile role in energy management, including peak shaving and load leveling [23]. Overall, while each technology has unique strengths and constraints, the common objective remains to enhance the flexibility and stability of the electricity grid through the careful management of demand and capacity.

1.2.2. Natural Gas Market Characterization

Natural gas prices in the EU are influenced by supply and demand, resulting in significant cost variations for consumers despite efforts to unify the European energy market. A single market could address supply challenges and climate change, and encourage investment. Central to the gas infrastructure, natural gas hubs serve as primary pricing locations, with gas exchanges facilitating anonymous trading to manage short-term demand and supply fluctuations. Each European market area has a virtual trading point (VTP), acting as a non-physical center for gas trading.

Gas prices are defined by various market types: spot markets (ranging from hourly to multi-day items), forward markets (covering half a year to one calendar year), and prompt and forward markets (for near-curve products from one month to one quarter). The Dutch TTF Gas hub is the main benchmark for European gas prices, with contracts for physical delivery made at the Title Transfer Facility (TTF) Virtual Trade Point, managed by Gasunie Transport Services (GTS) in the Netherlands. Trading, facilitated by Intercontinental Exchange Inc. (ICE), is based on over-the-counter (OTC) and contract-for-difference (CFD) financial instruments.

In this complex market environment, gas-fired power plants must adopt optimal bidding strategies to remain competitive and comply with low-carbon policies. A study on the optimal bidding strategy of a gas-fired power plant in interdependent low-carbon electricity and natural gas markets provides crucial insights into how these plants can navigate market dynamics effectively [24]. This research underscores the importance of aligning operational strategies with market conditions and regulatory frameworks to optimize economic outcomes while meeting emissions-reduction targets. By leveraging strategic bidding approaches, gas-fired power plants can enhance their operational efficiency and market responsiveness. This not only supports their economic viability but also contributes to the overall stability and sustainability of the energy market.

1.2.3. District Heating Market Overview

The EU’s heating market is primarily driven by direct heating from fossil fuels and natural gas, with district heating covering over 12% of the current heat demand through 17,000 heat networks. This is above the global average of 8.5%, as reported by the IEA in 2021 [25]. District heating is most prevalent in the colder regions of North and Eastern Europe, including Poland and the Nordic and Baltic countries, but is less common in Southern and some Western European countries like the Netherlands and the United Kingdom. Germany has the largest district heating market in Europe, followed by Poland and Sweden [26]

Collecting data on district heating is challenging due to its localized nature and the varying reporting standards across different countries. For example, in Italy, the National Authority (ARERA) sets connection tariffs for district heating, while supply costs depend on market conditions, as outlined in Legislative Decree 102/2014. Specific agreements are required between district heating network operators and companies generating waste heat to determine the feasibility of selling excess heat. As a result, comprehensive and comparable data on district heating are scarce at both the European and global levels. High-quality, accurate statistics are essential for informed policy and investment decisions, particularly as efforts intensify to achieve climate neutrality by the end of the century.

1.3. Objectives and Scope

While the residential and transport sectors have been extensively analyzed due to their predictable growth, the benefits obtained from HVAC and lighting appliance management [27], the development of forecasting models for the optimal operation of hybrid energy systems in residential environments [28], and the benefit estimations for following demand-side programs have been assessed [29]. The demand-response potential of energy-intensive industries (EII) is more complex due to their ability to schedule processes or incorporate process electrification. To achieve the EU’s 2030 goals and the Net Zero Emissions target by 2050, transitioning to a clean energy system is crucial, with EIIs needing to take proactive steps. This includes developing sustainable technologies, creating innovative policy frameworks, and strengthening flexibility markets [30]. Despite the importance, there is a literature gap in detecting and understanding the flexibility potential of EIIs, which this paper aims to address.

This study, aligned with the FLEXINDUSTRIES project's objectives, assesses seven energy-intensive industries across different sectors to understand their potential participation in the current energy flexibility mechanisms. These industries, including pulp and paper, iron and steel, cement and lime, chemicals, polymers, fertilizers, and refining, were selected for their high CO_2 emissions in the EU. The analysis begins with a review of the regulatory frameworks and existing flexibility mechanisms in the electricity market. It characterizes the energy purchasing practices and baseline consumption volumes of these industries in various countries. By establishing a common baseline, the study identifies context-specific opportunities and challenges related to demand-side response. Additionally, the study evaluates the contribution of flexible, manageable loads and conducts a technical analysis of energy processes, identifying relevant constraints. The potential for participating in energy flexibility mechanisms, including renewable energy generation technologies, energy storage systems, and process load management, is then estimated based on the available data and theoretical baselines. Moreover, it supports the FLEXINDUSTRIES project's goal by summarizing the current energy-market characteristics and identifying the flexibility potential of pilot actions, ultimately designing and testing sustainable business models for an inclusive energy transition. This novel approach highlights the flexibility potential within each industry, paving the way for enhanced connectivity, secure energy management, and support for local renewable energy sources and flexibility growth in real-life industrial settings.

2. Methodology

In this section, the methodology adopted for conducting the work and an analysis of the flexibility potential of the proposed actions within the defined project scope are presented.

The methodology encompasses the identification of explicit demand-side flexibility available by country, followed by the characterization of baseline conditions, the interaction with the energy market, and the assessment of existing and recent technologies in each one of the EIIs.

The data collection was conducted from reiterative interactions and interactive exchanges of information with seven EIIs. The process was initiated by sending a general questionnaire to each of the companies, requesting them to fill it in with the relevant information. After the initial iteration, the questionnaire was modified, tailoring the questions to the special situations reported by each company. For example, if, in the initial questionnaire, they stated that the purchase of energy was made based on bilateral agreements, they were asked about the specific characteristics of this PPA. This adjustment aimed to gain a deeper understanding of each case and its specific characteristics.

This process played a pivotal role in gathering comprehensive insights and perspectives from each one of the sectors studied. In general terms, the methodology followed corresponds to an approach like that proposed by other authors in articles related to the technical–economic evaluation of the assessment of technological alternatives in decarbonization processes [31].

2.1. Analysis of Explicit Demand Flexibility Remuneration Mechanisms by Country

Demand-side flexibility can be provided by different resources, including RES integration, energy storage, and demand manageability. Participation in flexibility events contributes to reducing energy costs for consumers/prosumers and assists energy-system operators (TSO, DSO, and electric system agents) in planning and ensuring the quality and stability of the power supply.

There are two primary avenues for participation in these events, known as implicit DSR and explicit DSR. The former pertains to optimizing networks, energy costs, or imbalance charges through price-based signals. Instead, the latter involves offering a product (volume) in the market, encompassing wholesale, balancing, system support, and reserve markets, or providing grid-related services to system operators through specific incentive-driven mechanisms [32]. Thus, mechanisms to participate in the explicit DSR could be classified according to the support it provides.

Resource-adequacy mechanisms that support mainly the DSO include load interruptibility and capacity mechanisms (renewable generation and power-to-X technologies) and participation in balancing markets that provide capacity to the TSO to manage the grid and are characterized by country, considering their main characteristics and retribution schemes.

2.2. Baseline Characterization: Consumption and Interaction with Energy Market

The project objectives and demonstration actions are grounded in an initial state, referred to as the baseline. It serves as the starting point for assessing flexibility potential within EII scenarios. The scope of the project is defined, encompassing the specific processes, production lines, or equipment to be considered for analysis. Key parameters defining the baselines include:

- electricity consumption [MWh];
- fuel consumption [MWh]: natural gas, gasoil, fuel oil, RDF, biodiesel;
- electric power generation [MWh];
- thermal energy generation [MWh].

Regarding interaction with the energy market, the objective is to delineate the energy procurement framework typically adopted by these EII sectors. Furthermore, the intention is to examine whether EIIs employ bilateral contracts, participate in day-ahead or intraday market mechanisms, ascertain the involvement of intermediaries like market operators, or maintain a direct line of communication with the distributor. Additionally, it aims to understand their motivations for participating in implicit demand-response programs. Moreover, the study seeks to identify whether each of the analyzed EIIs engages in explicit demand-response initiatives or possesses prior experience with such undertakings and if there is a regulatory framework of flexibility where they are participating.

2.3. Technological Resources for Implementing Flexibility Measures: Existing and New Technologies

At this point, the already existing and new technologies developed with the financing of the flexindustries in each EII are defined and quantified. These technologies are referred to as energy generation, storage, and load manageability. Each one of the parameters considered to characterize the technologies are summarized in Table 1:

Table 1. Technical parameters analyzed by technology types commonly used in EII.

Energy Generation	Storage	Load Manageability
Installed Capacity [kW]	Storage Technology	Specific characteristics of processes and loads to be considered for participation in demand-side management.
Associated Energy Flow	Energy Storage Capacity [kWh]	Working Cycle
Annual Energy Generation [MWh]	Power Transfer Capacity [kW]	Decision Intervals
Energy Self-Consumption [%]	Operating condition: Charging/Discharging Process	Consumption Patterns
Sold to the grid. [%]		Idle Energy

At this point, the flexibility provided by different technologies is studied and considered as either internal or external. When flexibility is internal, it signifies that it is inherent to the industry and influences operational decisions tied to the process. For example, the ability to address an energy demand using one resource (as an energy generation facility) or another during peak consumption periods, for which no contractual coverage exists. On the other hand, external flexibility is that which is enacted to alter interactions with energy providers, such as the readiness to provide ancillary services to the grid.

2.4. Determination of Flexibility Potential

The determination of the flexibility potential within the EII is summarized from a comprehensive examination of its interaction with the energy market, existing technologies, and novel technological implementation undertaken throughout the project's development. Moreover, this assessment delves into the intricate realm of technical and operational constraints, which often wield decisive influence over the feasibility of integrating flexibility measures. Through this multifaceted analysis, the evaluation process encapsulates the interplay between industry dynamics, energy-market demands, and technological advancements, ultimately shaping the pathway for informed decisions concerning the incorporation of flexibility measures.

3. Results

This section shows the data-collection results of the different scenarios proposed by each EII, as well as a brief analysis from the point of view of the flexibility potential detected.

3.1. Analysis of Explicit Demand Flexibility Remuneration Mechanisms by Country

Table 2 presents a comprehensive analysis of explicit demand-side response (DSR) mechanisms in various countries, detailing the capacity mechanisms and interruptible load characteristics within energy-intensive industries. This investigation highlights the heterogeneity and commonalities in DSR approaches across nations like Bulgaria, Germany, Greece, Italy, Poland, and Türkiye, which are essential for advancing toward net-zero emissions by 2050.

Table 2. Explicit demand-side flexibility mechanisms by country.

Country	Capacity Mechanism		Interruptible Loads	
	Characteristics	Retribution	Characteristics	Retribution
Bulgaria	DSR is remunerated through the wholesale market. There are programs for prosumers that can supply 5 MW to participate in programs such as Replacement Reserve (RR), Frequency Containment Reserves (FCR), and Frequency Restoration Reserves (FRR). There are no specific retribution mechanisms in terms of capacity and interruptibility scheme [33].			
Germany	Procurement methods vary regarding technology. Capacity reserve is procured in periods of 24 months. Industries interested in participating in this mechanism may not have participated in balancing market for the last three years.	Availability payments of EUR 68,000/MW per year [34].	Required time response is 15 min for quickly interruptible loads and 350 Ms for immediately interruptible loads. Industries interested in participating may have availability of 120 quarter-hour blocks in one week.	EUR 500/MW per week capacity price and EUR 400/MWh in case of activation.
Greece	Transitory Remuneration Flexibility Mechanism (TRFM) was used until 2021 [35].	Pay-as-bid auctions. Average remuneration in 2020 was EUR 33,818.41/MW [35].	Frequency of procurement was every three months and pay-as-cleared auctions. Interruptible contracts impose a minimum bid size of 2	Average// Type 1: EUR 63,775/MW year.

	Permanent Capacity Remuneration Mechanism is being evaluated. Capacity minimum required is 1 MW. It requires a ramp of at least 8 MW/min and for response to be maintained for at least three hours [36].		MW. Two types of interruptible loads: Type 1. Reaction time: 5 min/Maximum duration: 48h and 288 h per year. Type 2. Reaction time: 1 min/Maximum duration: 1 h and 36 h per year.	Type 2: EUR 44,912.5/MW year.
Italy	DSR is remunerated through the wholesale market. Industries do not receive direct capacity payments; the participation is rewarded in partial exemptions from the adequacy fees that customers should otherwise pay to the TSO.	Existing and new production units receive a premium equal to the lower value between the declared marginal price and their respective cap price.	Procurement through pay-as-cleared auctions. Loads above 1 MW can participate [34]. Ability to be interrupted by TSO within 200 ms.	Average. EUR 80,000/MW-year. Interruptible contracts pay per disconnection based on the spot price.
Poland	Minimum capacity is 2 MW but no more than 50 MW [37].	The main auction for delivery year 2021 cleared at PLN 240.32/kW-year, while the additional auction for the same year cleared at PLN 286.01/kW-year	Minimum bid size to participate is 1 MW (can be achieved by aggregation). Availability for time response could vary between 30 min to 4 h.	Max prices offered by the contractors varied from PLN 12,900/MWh to PLN 13,121/MWh
Türkiye	Demand Side Reserve. Retribution is procured through bids by TSO. Industries interested in participating in this DSF mechanism in Türkiye must have an annual electricity consumption of at least 10 GWh and be connected directly to the transmission network.	Prices are established by TSO.	Minimum bid size to participate is 1 MW (cannot be achieved by aggregation). Consumers must be able to be interrupted in relays of 15 min.	Pay-as-bid auctions.

The table demonstrates that capacity mechanisms generally involve a structured approach, with competitive auctions and minimum participation requirements, while interruptible load schemes are noted for their quick response times and dual remuneration for availability and activation. These mechanisms reflect each country's regulatory frameworks, technological capabilities, and strategic priorities in energy-market flexibility, emphasizing the diverse and auction-based compensation strategies adopted. This understanding is crucial for policymakers and industry stakeholders aiming to optimize energy management and contribute to a sustainable energy transition.

3.2. Baseline Characterization: Consumption and Interaction with Energy Market

As a result of interviews and data acquisition from the seven EIIs mentioned above, Table 3 contains the energy consumption by source and their current interactions with energy markets until 2022. The main points detected are that EIIs have a high reliance on electricity for industrial operations, with consumption varying widely among each.

Table 3. Energy baselines and interaction with energy market.

EII/Country	Baseline	Interaction with Energy Market

	Parameter	Quantity	Unit	
Paper mill/Germany	Electricity consumption paper mil	346,341	[MWh/year]	Electricity is purchased at a fixed price. In case of energy injection, they participate in balancing market (BM) through a balancing service provider (BSP). Current agreement with BSP establishes a tolerance of variation of electricity generation in terms of 10% per day.
	Electricity consumption power plant	44,935	[MWh/year]	
	Fuel-oil consumption (during 2021)	1144	[m^3/year]	
	RDF consumption	385,200	[Tn/year]	
Automotive/Türkiye	Total electricity	184,000	[MWh/year]	Electricity is purchased in day-ahead and intraday markets. Electricity has fixed price in paint shop, TL 3.57/kWh. It is bought from company in a standard purchasing process. Natural gas price considered is TL 1.879/kWh. Aggregator manages demand strategy. Türkiye System Operator is the main owner of the ancillary services provision. Particular agreement for charging station EVs.
	Total natural gas	220,000	[MWh/year]	
	Paint-shop electricity	90,000	[MWh/year]	
	Paint-shop natural gas	191,520	[MWh/year]	
Biofuel/Greece	Total electricity	900	[MWh/year]	Electricity has fixed tariff established through a bilateral contract. As generators, they receive a benefit of EUR 225/MWh. The current production capacity is 2.1 MW, but only 2.0 MW are offered to the grid, the monthly energy injected into the grid is about 1440 MWh, obtaining an average of benefits of EUR 3.8 M per year.
	Biogas production electricity consumption	410	[MWh/year]	
	Biodiesel production electricity Consumption	85	[MWh/year]	
	CHP1 auxiliaries electricity consumption	203	[MWh/year]	
	CHP2 auxiliaries electricity consumption	203	[MWh/year]	
	Diesel	120	[MWh/year]	
Cement/Greece	Total electricity consumption	100.6	[GWh/year]	Electricity is purchased by a bilateral contract. It is a monthly based purchase directly from grid operators.
	Kiln section electricity consumption	27.8	[GWh/year]	
Steel/Bulgaria	Total electricity consumption	479,200	[MWh/year]	Part of electricity has fixed tariff. Another part is acquired in day-ahead and intraday market. The interaction is directly through a DSO in high voltage.
	Average total deviation between real and forecasting consumption	20.4	[MWh/year]	
Pharmaceutical/Italy	Electricity consumption	77,700	[MWh/year]	50% of electricity is purchased in day-ahead market, so tariffs are fully variable (hourly spot price). The rest of the volume is purchased by a bilateral contract (PPA). Fixed price is different between peak hours and off-peak hours. There is the possibility of fixing slot of energy (at least 1 MW and 1 month). The supplier in this case is chosen by purchase tender. Participation in UVAM project offers power to provide ancillary services, receiving an average benefit of EUR 1456/MW per month.
	Natural gas consumption	262,000	[MWh/year]	
Polymers/Poland	Electricity consumption	39,400	[MWh/year]	Bilateral contracts with a fixed tariff that can suffer some changes during the year. The interaction is directly through DSO.
	Natural gas consumption	5700	[MWh/year]	

The various approaches to engaging with the energy markets, such as bilateral contracts, market auction participation, and the provision of ancillary services, show a dedicated strategy catered to the requirements of each industry. Furthermore, the EIIs' involvement in the provision of ancillary services underscores their growing significance in guaranteeing the stability and flexibility of the grid. EIIs using a variety of fuels, including diesel, biodiesel, and natural gas, demonstrate the diversity of fuels available to cover their energy needs. This is probably due to factors like availability, affordability, and environmental impact. Lastly, the impact of regulatory frameworks on energy management practices is emphasized, as contractual agreements shape strategies for market engagement and operational flexibility. Overall, Table 3 emphasizes how difficult it is to manage energy across industries and how crucial it is to use customized strategies that take into account market conditions, legal requirements, and consumption patterns.

3.3. Technological Resources for Implementing Flexibility Measures: Existing and New Technologies

Table 4 shows the main technical specifications for generation technologies in industrial facilities by case study and constraints to implement flexibility measures.

Table 4. Energy generation technologies by case study.

EII/Country	Technology Action	Installed Power [kWp]	Energy Generated [MWh/year]	Self-Consumption [%]	Sold to the Grid [%]	Constraints to Implement Flexibility
Paper mill/Germany	Steam turbine	300,000	175,500	26	74	The minimum load should not affect production; the priority is to ensure the steam supply for the paper mill.
	Shell boilers	28,000	700	100	0	NG prices, % PCM load. Shell boilers cover steam peak demand from paper-mill plant.
	PV system	500	500	100	0	N/A
Automotive/Türkiye	Solar wall		5640	100	0	Outside solar radiation and temperature.
	PV plant	3680	3000	100	0	N/A
Biofuel/Greece	CHP	3696	29,568	2	98	The priority is biodiesel generation; production of biodiesel depends on the production demand from customers. Limited maximum capacity to interact with the network by regulation.
	ORC	150	600	It will be decided considering the market conditions at the moment of the ORC operation.		Electricity generated depends on % of load of ORC which depends on heat generated from CHPs. Limited maximum capacity to interact with the network by regulation. The ORC turbine may react to upward and downward regulation signals from the power grid with ramp rates up to 15–30%/min.
Cement/Greece	TEG	250	1860	100	0	Process continued production. Low conversion efficiency.
Pharmaceutical/Italy	Biogas CHP	576	2400	0	100	Energy generated is derived from biogas production with process waste, so energy generated depends on schedule and production optimization.

Trigeneration system	12,300	91,898	97	3	Loads changes must not affect production, it depends on scheduling and production optimization.
PV plant	500	600	100	0	Maximum capacity due to surface availability. No storage system associated with this technology.
Heat Pump-Heating	869.7	7018	0	100	Availability to inject heating to DH grid. It depends on agreements.
Heat Pump-Cooling	1486	11,986	100	0	N/A

It is appreciated that technology actions related to energy generation with higher installed capacity, such as steam turbines and trigeneration systems, tend to have a higher proportion of energy sold to the grid, indicating excess capacity that can be leveraged to provide external flexibility services. Conversely, technologies with a lower installed capacity, such as PV plants and solar walls, exhibit a high percentage of self-consumption, positioning them better for internal flexibility measures and adapting quickly to internal demand fluctuations. The operational limitations identified, such as the need to maintain continuous production and regulatory restrictions, must be considered in the design of these measures. Nonetheless, the rapid-response capability of some technologies, such as the organic Rankine cycle (ORC) in biofuels, which can react to regulation signals with significant ramp rates, demonstrate a substantial potential to contribute to grid stability.

Two key types of storage are distinguished and described in Table 5: thermal and electrical energy storage.

Table 5. Storage technology characterization by case study.

EII/Country	Storage Technology	Energy Carrier Used	Energy Storage Capacity [MWh]	Power Transfer Capacity [MW]	Operating Conditions	Constraints
Paper mill/Germany	PCM	Molten salt	2.23	13	Charging: during time of the paper plant's normal operation or paper tear-offs. Discharging: thermal energy is used during peak load which occurs after production stops when the paper mill is restarted.	The destination of the thermal energy is defined for internal use in the plant.
Automotive/Türkiye	BESS system	Electricity	0.10	0.05	Charging process: from PV plant production or when prices are low. Discharging process: to charging EVs.	Charging process depends on PV Plant production.
Pharmaceutical/Italy	BESS system	Electricity	0.49	0.40	Charging: when grid prices are low or by CCHP already existing in the plant. Both possible. Discharging: when prices are high or when HP requires.	Charging process depends on CCHP electricity production.

These systems offer valuable mechanisms for postponing capacity upgrades, enhancing equipment utilization, and cost savings. Thermal storage (PCM) captures and stores heat from industrial processes, enabling internal flexibility and optimized processes. On the other side, electrical storage demonstrates responsiveness to market price signals and internal demand fluctuations, so it can be suitable for supporting flexibility across day-ahead, intraday, and ancillary services markets.

Regarding manageable loads, three cases have been analyzed as follows:

Case 1: EII/Country—Paper Mill/Germany

Process/Load—Paper Mill starts/Steam demand.

Beyond the identification of this manageable load (See Table 6), such as the demand for thermal steam energy, which benefits from an associated PCM storage technology, the feasibility of utilizing this load for demand-response initiatives is constrained. This limitation arises from the necessity of addressing peak steam demand in the paper mill, a requirement that ensures the uninterrupted progress of the production process. In this case, the flexibility identified is internal because it is possible to cover this peak demand using energy stored by PCM or to use already existing technologies, such as shell boilers, which already exist and have been detailed previously.

Table 6. Manageable load: steam demand.

Energy Consumption [MWh/year]	Peak Demand [MW]	Time Duration [min]	Operating Conditions	Constraints
700	20	20	Possibilities of previous irritations in the paper production	The storage capacity of PCM. Peak demand coverage is the priority.

Case 2: EII/Country—Automotive/Türkiye

Process/Load—Charging station of EVs/electricity demand.

The loads identified in Table 7 present a potential for manageable consumption, making them suitable candidates for participation in DR programs if implemented. This opens opportunities to optimize the utilization of renewable energy sources (RES) for charging stations (PV system detailed in Table 4), as well as to implement implicit demand-response strategies based on hourly electricity pricing. Additionally, there is the potential for flexibility through participation in explicit mechanisms, such as providing ancillary services in the balancing market, facilitated by the rapid charging capabilities of the station.

Table 7. Manageable load: charging station EVs.

Working Cycle [min]	Nº of Vehicles	Power Required of Charging Station [MW]	Peak Simultaneous Power Demand in 4 Charging Stations [MW]	Simultaneous Demand in 4 Charging Stations [MWh]	Operating Conditions	Constraints to Implement Flexibility
10 min/vehicle	5 vehicles per hour	0.3	1.2	In one hour: 1	Vehicles consume 25 kWh during 10 min of charging.	It is not possible to interrupt the loading of vehicles once this action starts. There are 4 charging stations, each one capable of charging two vehicles at the same time.
2 min other operations	320 vehicles per day			In one day: 8	Vehicles are delivered with 45% of battery according to shipment regulation	

Case 3: EII/Country—Steel/Bulgaria

Process/Load—several manageable loads have been identified and are detailed in Table 8.

Table 8. Manageable loads from steel industry.

Process/Load	Working Cycle	Immediate Decision [min]	During Day [min]	Decision for Next Day [h]	Idle [kWh]	Consumption in 15 min Intervals [kWh] during Peak Production	Consumption Hourly [kWh]

Electric arc furnace 1-Melting shop	1 h	10	10	1	0	17,743	70,972
Electric arc furnace 3-Melting shop	1 h	10	10	1	0	12,859	51,436
LF1-Melting shop	1 h	10	10	1	0	16,333	65,332
LF2-Melting shop	1 h	10	10	1	0	9558	38,232
VD-Melting shop	1 h	0	0	1	0	4	16
Plate Mill	Continuous	15	60	4	250	580	2320
Long Rolling Mill	Continuous	15	60	4	6	32	128

It is significant to emphasize that this EII has the goal of minimizing the repercussions linked to procuring energy within the intraday energy market. Considering this objective, it becomes crucial to distinguish between decision categories for the upcoming day (day ahead) and decisions made during the day (intraday). The former pertains to making choices regarding loads to partake in the day-ahead market, whereas decisions made during the day are focused on determining the optimal time frame within which decisions can be formulated concerning load interruption within the same day.

According to the data detailed in Table 8, the maximum load that can be programmed for the next day is identified. This information is what should be communicated to the electricity management company for reporting in the day-ahead market and to avoid electricity adjustments acquired in the intraday market.

3.4. Determination of Flexibility Potential

After analyzing the existing participation mechanisms by country and characterizing the baseline and expected actions per EII, Table 9 summarizes the highlighted and the main opportunities for each EII to implement flexibility measures.

Table 9. Determination of flexibility potential.

EII/Country	Explicit Demand Side Flexibility		Implicit Demand Side Flexibility	
	Distributed Generation (Participation in Balancing Market)	Capacity and Power-to-X (Resource-Adequacy Mechanisms)	Load Management (Based on RES Availability or Price Signals)	
Paper mill/Germany	Yes, in case of energy injection.	N/A	Use of sensible heat stored in the PCM or use shell boilers fueled (price-signal based).	
Automotive/Türkiye	N/A	PV plant + BESS Systems	Charging station for EVs. Load shifting: 8 MWh-day; Peak shaving: 1.2 MW.	Possibility to integrate BESS system and charging station for EVs.
Biofuel/Greece	Upward and downward aFRR/mFRR balancing energy.	Current capacity to offer: 2 MW. Integration of CHP system (3.5 MW) and ORC (0.15 MW). Total potential to offer: 3.65 MW.	N/A	
Cement/Greece	Upward and downward aFRR/mFRR balancing energy using TEG system	N/A	N/A	
Steel/Bulgaria	N/A	N/A	Load Shifting 228.4 MWh	Use of estimated 228.4 MWh to avoid participating in intraday markets where energy prices may be higher.

Pharmaceutical/Italy	Upward and downward aFRR/mFRR balancing energy	Replicate previous participation (UVAM project) offering 10 MW during 4h/day in a period defined (14:00–20:00 h).	N/A	Thermal energy generation (Heat pumps + CCHP) in DH market. BESS + heat pump charging schedules
Polym…	N/A	N/A	N/A	N/A

As can be seen, DR depends largely on the conditions of the production process. As an example, although all EIIs have generation technologies, in some cases, all energy production is used to supply the process and is still not totally covered. On the other hand, the process that involves biological factors makes it impossible to manage loads due to the specific conditions that need to be maintained during the operation.

4. Discussion

This study explores demand-response (DR) flexibility mechanisms across diverse energy-intensive industries (EIIs). In a case-study context, it focuses on various countries, including Bulgaria, Germany, Greece, Italy, Poland, and Türkiye, revealing the importance of strategies to optimize energy management for sustainable development. The main findings highlight the following.

The technical and regulatory challenges: are highlighted in the results by the significant impact of technical limitations, such as thermal process constraints, storage capacity, and load manageability, on the effectiveness of DR mechanisms. For instance, the strategic management of loads in the Bulgarian steel industry has demonstrated substantial operational savings and increased market participation. Additionally, Germany's rapid-response capabilities underscore the importance of advanced technologies in DR systems for immediate load demand responses. However, the lack of explicit flexibility mechanisms in several countries poses a challenge to broad EII participation, which is crucial for grid stability and energy efficiency.

For financial incentives and strategic planning, financial incentives within capacity mechanisms and interruptible loads are crucial for balancing market supply and demand, encouraging EII engagement in DR programs. The EIIs are recommended to align their strategies with the available explicit DR options, potentially involving technological upgrades or operational modifications to enhance cost efficiency and maintain production capabilities. Adapting policy frameworks to support emerging technologies and dynamic market conditions is vital as nations work towards the 2030 EU goals and the 2050 Net Zero Emissions target.

Collaborative efforts for market accessibility between EIIs and local authorities are critical to developing accessible flexibility markets, addressing technical, regulatory, and market challenges to ensure a cohesive approach to energy policy and industrial practices.

As to future research directions, this research sets the stage for further studies on DR mechanism efficiency and the integration of renewable energies. From the study, future studies are recommended to address comparative analyses across regulatory environments to discover best practices for global or local adaptation. Continued research into technological innovations, like advanced energy storage and control technologies, will further enhance the adaptability and efficiency of implicit and explicit DR strategies.

5. Conclusions

At the core of exploring demand-response flexibility mechanisms across diverse energy-intensive industries, this study reveals both technical and regulatory challenges. It identifies that industries limit their interaction with energy markets to purchasing energy according to their productive and operational needs.

In terms of explicit flexibility, it underscores available mechanisms in the electricity market and highlights a clear opportunity for participation by offering capacity and "power to x" in the automotive, biofuel, and pharmaceutical sectors. Moreover, it concludes that most industries can participate in providing balancing services by engaging in upward and downward aFRR/mFRR. In the case of natural gas and district heating markets, minimal flexibility retribution mechanisms are available.

In terms of implicit flexibility, the optimization of the use of manageable loads as a response to prices is not implemented by any of the studied EIIs. However, the potential is clearly identified in both Bulgaria and Türkiye. Conversely, if the use of manageable loads is studied based on the availability of RES or storage, a clear potential is observed for the automotive and pharmaceutical industries, as well as for paper mills.

A clear focus for future work is to study the different optimization strategies that industries could utilize to make informed decisions and maximize the benefits of available flexibility mechanisms and to consider the exploitation of implicit flexibility strategies.

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