



Article 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

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%)

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Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/license s/by/4.0/). 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 cutoff that caused an increase in gas and CO₂ 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-fordifference (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 CO₂ 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 FLEXIN-DUSTRIES 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 incentivedriven 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:

Energy Generation Storage		Load Manageability		
		Specific characteristics of pro-		
Installed Canadity [kW]	Storage Technology	cesses and loads to be consid-		
Instaned Capacity [KW]	Storage Technology	ered for participation in de-		
		mand-side management.		
Associated Energy Flow	Energy Storage Capacity	Working Cycle		
Associated Energy Flow	[kWh]	Working Cycle		
Annual Energy	Power Transfer	Decision Intervals		
Generation [MWh]	Capacity [kW]	Decision intervais		
Enorm Calf Consumption	Operating condition: Charg-			
	ing/Discharging	Consumption Patterns		
[70]	Process			
Sold to the grid.		Idle Energy		
[%]		Idle Energy		

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

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.

Country	Capacity Mech	anism	Interruptible I	Loads
Country	Characteristics	Retribution	Characteristics	Retribution
Bulgaria	DSR is remunerated through the w MW to participate in programs su (FCR), and Frequency Restoration 1 of capacity and interruptibility sche	holesale market. There ach as Replacement R Reserves (FRR). There eme [33].	e are programs for prosumers eserve (RR), Frequency Conta are no specific retribution med	that can supply 5 ainment Reserves chanisms in terms
Germany	Procurement methods vary re- garding technology. Capacity re- serve is procured in periods of 24 months. Industries interested in partici- pating in this mechanism may not have participated in balancing market for the last three years.	vailability payments UR 68,000/MW per y 4].	Required time response is a min for quickly interruptib loads and 350 Ms for imm diately interruptible loads. rear Industries interested in pa ticipating may have avail bility of 120 quarter-hou blocks in one week.	¹⁵ EUR 500/MW e per week ca- pacity price and EUR r-400/MWh in a- case of activa- tion.
Greece	Transitory Remuneration Flexi-A bility Mechanism (TRFM) was used until 2021 [35].	ay-as-bid auctions. verage remuneration)20 was E 3,818.41/MW [35].	Frequency of procurement was every three months ar pay-as-cleared auctions. In UR terruptible contracts impose a minimum bid size of	nt Average// nd Type 1: EUR n- 63,775/MW se 2 ^{year.}

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

	Permanent Capacity Remunera	1-	MW. Two types of interrup	oti-Type 2: EUR	
	tion Mechanism is being evalu	1-	ble loads:	44,912.5/MW	
	ated.		Type 1. Reaction time:	5year.	
	Capacity minimum required is	1	min/Maximum duration	on:	
	MW. It requires a ramp of at least	st	48h and 288 h per year.		
	8 MW/min and for response to b	e	Type 2. Reaction time:	1	
	maintained for at least thre	e	min/Maximum duration: 1	l h	
	hours [36].		and 36 h per year.		
Italy	DSR is remunerated through the wholesale market. Industries do not receive direct capacity payments; the participat tion is rewarded in partial exemptions from the adequacy fees that customers should otherwise parties to the TSO.	e Existing and new produ tion units receive a pr mium equal to the low value between the declared ma ginal price and their r	re-Procurement through pa eras-cleared auctions. Loa above 1 MW can participa nr-[34]. Ability to be interrupt re-by TSO within 200 ms.	Average. EUR 80,000/MW- ay- ids Interruptible ate contracts pay per disconnec- tion based on the spot price.	
Poland	Minimum capacity is 2 MW bu no more than 50 MW [37].	The main auction for deli ery year 2021 cleared atPLN 240.32/kW-year, whi the additional auction f the same year cleared PLN 286.01/kW-year	v-Minimum bid size to parti atpate is 1 MW (can ileachieved by aggregation). orAvailability for time atsponse could vary betwe 30 min to 4 h.	Max prices of- ici-fered by the contractors var- ied from PLN 12,900/MWh to PLN 13,121/MWh	
	Demand Side Reserve. Retribu	1-			
	tion is procured through bids b	у			
	TSO.		Minimum bid size to parti	ci-	
	Industries interested in partic	i-	pate is 1 MW (cannot	be	
Türkiye	pating in this DSF mechanism i Türkiye must have an annua electricity consumption of at least	nPrices are established l alTSO. at	by achieved by aggregation). Consumers must be able	Pay-as-bid auc- totions.	
	10 GWb and be connected d	i_	be interrupted in relays of 15		
	rectly to the transmission ne	۰ ۲_			
	work.	•			

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	-
many	Electricity consumption paper mil	346,341	[MWh/year]	Electricity is purchased at a fixed price. In case
ll/Ger	Electricity consumption power plant	44,935	[MWh/year]	ing market (BM) through a balancing service
per mi	Fuel-oil consumption (during 2021)	1144	[m³/year]	establishes a tolerance of variation of electric-
Pa	RDF consumption	385,200	[Tn/year]	ity generation in terms of 10% per day.
	Total electricity	184,000	[MWh/year]	Electricity is purchased in day-ahead and in-
aiye	Total natural gas	220,000	[MWh/year]	traday markets. Electricity has fixed price in
Automotive/Türk	Paint-shop electricity Paint-shop natural gas	90,000 191,520	[MWh/year] [MWh/year]	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. Tü- rkiye System Operator is the main owner of the ancillary services provision. Particular agreement for charging station EVs
	Total electricity	900	[MWh/vear]	agreement for charging station EVS.
D)	Biogas production electricity consumption	410	[MWh/year]	Electricity has fixed tariff established through a bilateral contract. As generators, they re-
/Greeo	Biodiesel production electricity Consumption	85	[MWh/year]	ceive a benefit of EUR 225/MWh. The current production capacity is 2.1 MW, but only 2.0
iofuel/	CHP1 auxiliaries electricity consumption	203	[MWh/year]	MW are offered to the grid, the monthly energy injected into the grid is about 1440 MWh,
щ	CHP2 auxiliaries electricity consumption	203	[MWh/year]	obtaining an average of benefits of EUR 3.8 M per year.
	Diesel	120	[MWh/year]	
Ce- ent/Gi eece	Total electricity consumption Kiln section electricity con-	100.6 27.8	[GWh/year]	Electricity is purchased by a bilateral contract. It is a monthly based purchase directly from
me	sumption	27.0	[Gwii/year]	grid operators.
/Bul- ria	Total electricity consumption Average total deviation be-	479,200	[MWh/year]	Part of electricity has fixed tariff. Another part is acquired in day-ahead and intraday market.
Steel ga	tween real and forecasting con- sumption	20.4	[MWh/year]	The interaction is directly through a DSO in high voltage.
Pharmaceutical/Italy	Electricity consumption	77,700 262,000	[MWh/year] [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 pur- chased 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
	Electricity consumption	39 400	[MM/b/woor]	month. Bilateral contracts with a fixed tariff that can
Poly- mers/P ₋ land	Natural gas consumption	5700	[MWh/year]	suffer some changes during the year. The in- teraction is directly through DSO.

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.

EII/Country	Technology Action	Installed Power [kWp]	l Energy Gen- erated [MWh/year]	Self-Con- sumption [%]	Sold to the Grid [%]	Constraints to Implement Flexibility
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.
per mill/C	Shell boilers	28,000	700	100	0	NG prices, % PCM load. Shell boilers cover steam peak demand from paper- mill plant.
Pa	PV system	500	500	100	0	N/A
uto- lo- kiy	Solar wall		5640	100	0	Outside solar radiation and temperature.
Au m tiv ür	PV plant	3680	3000	100	0	N/A
reece	CHP	3696	29,568	2	98	The priority is biodiesel generation; pro- duction of biodiesel depends on the pro- duction demand from customers. Lim- ited maximum capacity to interact with the network by regulation.
Biofuel/G	ORC	150	600	It will be decid ering the mar tions at the mor ORC operation	led consid ket condi ment of the	load of ORC which depends on heat gen- erated from CHPs. Limited maximum -capacity to interact with the network by eregulation. The ORC turbine may react to upward and downward regulation signals from the power grid with ramp rates up to 15–30%/min.
Ce- ment/ Greec e	TEG	250	1860	100	0	Process continued production. Low con- version efficiency.
Pharmaceu- tical/Italy	Biogas CHP	576	2400	0	100	Energy generated is derived from biogas production with process waste, so en- ergy generated depends on schedule and production optimization.

Table 4. Energy generation technologies by case study.

Trigeneration system	12,300	91,898	97	3	Loads changes must not affect produc- tion, it depends on scheduling and pro- duction optimization.
PV plant	500	600	100	0	Maximum capacity due to surface avail- ability. 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/Coun- try	Storage Technol- ogy	Energy Carrier Used	Energy Storage Ca- pacity [MWh]	Power Transfer Capacity [MW]	Operating Conditions Constraints
Paper mill/Germany	РСМ	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.
Automo- tive/Tü- rkiye	BESS sys- tem	Electricity	0.10	0.05	Charging process: from PV plant pro-Charging process duction or when prices are low. depends on PV Discharging process: to charging EVs. Plant production.
Pharmaceuti- cal/Italy	BESS sys- tem	Electricity	0.49	0.40	Charging: when grid prices are low or Charging process by CCHP already existing in the plant. depends on CCHP Both possible. Discharging: when prices are high or electricity produc- when HP requires.

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 dayahead, 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 irrita tions in the paper production	The storage capacity of PCM. Peak demand coverage is the priority.			
	Case 2: EII/	Country-Autor	notive/Türkiye				
Process/Load—Charging station of EVs/electricity demand. The loads identified in Table 7 present a potential for manageable consumption, mak-							

ing 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 Re- quired of Charging Sta- tion [MW]	Peak Simultane- ous Power De- mand in 4 Charg- ing Stations [MW]	Simultaneous Demand in 4 Charging Sta- tions [MWh]	Operating Condi- tions	Constraints to Imple- ment Flexibility
10 min/ve- hicle	5 vehi- cles per hour			In one hour: 1	Vehicles consume 25 kWh during 10 min of charging.	It is not possible to in- iterrupt the loading of vehicles once this action
2 min other operations	320 vehi- cles per day	0.3	1.2	In one day: 8	Vehicles are deliv- ered with 45% of bat- tery according to shipment regulation	starts. There are 4 charging stations, each one capa- ble of charging two ve- hicles at the same time.

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 Pro- duction	Consump- tion Hourly [kWh]
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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.

	Explic	cit Demand Side Flexibili	y Implicit Demand Side Flexibility	
EII/Coun try	- Distributed Genera- tion (Participation in Balancing Market)	Capacity and Power-to-X (Resource-Adequacy Mechanisms)	Load M (Based on RES Avai	lanagement lability or Price Signals)
Paper mill/ Ger-	Yes, in case of energy injection.	/N/A	Use of sensible heat stored fueled (price-signal based).	in the PCM or use shell boilers
Automo- tive/Tü- rkiye	° N/A	PV plant + BESS Systems	Charging station for EVs. Load shifting: 8 MWh-day Peak shaving: 1.2 MW.	Possibility to integrate BESS y;system and charging station for EVs.
Biofuel/Greece	Upward and down- ward aFRR/mFRR balancing energy.	Current capacity to offer: 2 MW. Integration of CHP system (3.5 MW) and ORC (0.1 MW). Total potential to of fer: 3.65 MW.	2 	
Ce- ment/Greec e	Upward and down- ward aFRR/mFRF balancing energy us- ing TEG system	N/A	N/A	
Steel/Bul- garia	N/A	N/A	Use Load Shifting 228.4avoi MWh kets high	of estimated 228.4 MWh to d participating in intraday mar- where energy prices may be er.

Pharmaceuti- cal/Italy	Upward and down ward aFRR/mFR balancing energy	Replicate previous n-pation (UVAM pr Rfering 10 MW 4h/day in a period (14:00–20:00 h).	s partici- oject) of- duringN/A l defined	Thermal energy generation (Heat pumps + CCHP) in DH market. BESS + heat pump charging sched- ules
Po ly m	ξN/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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