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Potential Of Consumer Led Flexibility in Industry

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Executive Summary

Industrial Consumer-Led Flexibility (ICLF) represents a potentially significant but currently seldom-deployed means of supporting the UK's transition to a low-carbon electricity system. While many industrial processes are technically capable of providing flexibility, deployment remains limited due to a persistent gap between technical potential and commercial viability. Flexibility is rarely prioritised within industrial strategies, as uncertain revenues, operational risks and complex participation requirements outweigh perceived benefits.

The findings of this report highlight four core barriers:

- Industrial stakeholders perceive flexibility as a risk to operational stability, product quality and competitiveness, particularly in energy-intensive sectors optimised for continuous production.
- Flexibility potential varies significantly across sectors depending on process design and the availability of thermal or material buffers, which limits the effectiveness of one-size-fits-all policy approaches.
- Knowledge gaps persist around sector-specific flexibility potential, economic feasibility and viable business models, compounded by limited availability of high-resolution operational data.
- Current market structures fail to provide stable and sufficient incentives, with administrative complexity and weak price signals discouraging participation.

Addressing these challenges requires coordinated action across policy, technology and industry including,

- Policy reforms should prioritise sector and product-specific market mechanisms, stable pricing frameworks like a two-way Contracts for Difference (CfD), simplified participation rules, and improved data infrastructure through sub-metering and digitalisation.
- Technical interventions, including process optimisation, storage integration, and advanced energy management systems, could help convert theoretical flexibility into dispatchable capacity.
- Industry must be incentivised to build internal capability for site-level assessments and automation, as well as encouraged and empowered to adopt collaborative approaches to market participation.
- Aligning flexibility with broader industrial decarbonisation pathways, including electrification, hydrogen, and carbon capture, will be critical as electricity demand grows and system variability increases. A stable and coherent framework that reflects industrial realities is essential to unlock this potential.

Without such interventions, industrial flexibility will remain largely theoretical; with them, it could become a practical and valuable component of the UK's clean power system and achieve the goals of Clean Power 2030.

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While this report has been informed by extensive stakeholder feedback, the content does not necessarily represent the views of all individual members and partner organisations of IDRIC. The responsibility for the content of this report, including for any errors, lies with the editorial team. Whilst every effort has been made to ensure the accuracy of the information within this report at time of publication, IDRIC does not warrant its accuracy or will assume liability for any foreseeable or unforeseeable use made of this report which liability is hereby excluded.

Note from IDRIC Director

This report comes at a pivotal moment for UK energy and industrial policy. Delivering the UK Government's Clean Power 2030 ambition requires a substantial increase in system flexibility to manage higher levels of variable renewable generation. At the same time, industrial decarbonisation and electrification are set to increase both the scale and strategic importance of industrial electricity demand. The decisions being taken now on market design, infrastructure and industrial policy will therefore play a critical role in determining whether industry becomes an active contributor to system flexibility or remains a largely untapped resource.

Our research shows that Industrial Consumer-Led Flexibility has genuine potential to support system balancing, improve network efficiency and facilitate the integration of low-carbon generation. However, this should not be confused with what can realistically be delivered. Industrial processes are designed first and foremost for safe, efficient and competitive production, meaning that flexibility participation will only occur where policy and market frameworks adequately recognise operational constraints, manage commercial risks and provide a credible value proposition.

Unlocking this potential therefore requires flexibility to be designed around industrial realities. Sector-appropriate market mechanisms, clearer and more stable incentives, better data and digitalisation, and closer alignment with wider decarbonisation pathways will all be important. The central policy message of this report is that industrial flexibility should be viewed not as a standalone energy market intervention, but as a strategic component of the UK's industrial decarbonisation and energy security agenda.

We hope this timely report helps move the conversation from theoretical potential to practical delivery. By creating the right policy, regulatory and market conditions, industrial flexibility can genuinely contribute to a more resilient, affordable and low-carbon electricity system while supporting a competitive, resilient and decarbonised UK industrial base.

Prof Mercedes Maroto-Valer OBE
IDRIC Champion and Director

1. Introduction

1.1 Industry developments

According to DESNZ's *Energy Consumption in the UK 2025*, industrial energy consumption and energy intensity have declined markedly over the long term, reflecting improvements in energy efficiency and structural shifts towards higher-value production. Energy-intensive sectors, including iron and steel, mineral products and chemicals, nevertheless remain central to industrial decarbonisation. The Climate Change Committee's Seventh Carbon Budget identifies electrification of industrial heat as the largest source of emissions reduction in industry; electricity accounted for 28% of industrial energy use at the time of its assessment and is projected to reach 36% by 2030 in the CCC's Balanced Pathway Industry has traditionally used a variety of energy supplies and stores, including coal, oil and gas alongside electricity. Going forward, it will be important to adopt a broader, whole energy system approach. This will allow organisations to select and integrate the best combination of energy components to support the needs of the various sectors and organisations to invest in and operate their manufacturing plant.

Whilst this report primarily addresses electricity-focused flexibility, due to its growing system importance and potential UK market, flexibility across all energy vectors (e.g. gas, hydrogen, heat) remains essential for viable and comprehensive industrial decarbonisation.

1.2 Electricity system developments

The transition to a low-carbon electricity generation system in the UK has accelerated rapidly over the past decade, driven by the phase-out of coal-fired generation and the large-scale deployment of renewables, particularly offshore wind.

As the sector moves toward the government's target of Clean Power 2030, the system-balancing challenges will grow significantly, as increasing reliance on variable renewable energy adds intermittency and forecast uncertainty on to the existing variability of demand.

At the same time the usage patterns in the electricity system will change as much more demand from the heat, transport and industry sectors is electrified.

1.3 Balancing, stability and flexibility

Traditionally, electricity system balancing and stability were provided by dispatchable fossil generators with their associated large-scale and long-duration fuel stores. However, as these assets decline, other sources of balancing services are being sought from the supply ***and*** the demand side, including from industrial users.

This report focuses on this latter group of electricity consumers and tries to identify if, where, and how they can adapt to provide balancing services, or 'flexibility'.

Representatives from government, academia and some elements of the electricity system suggest that flexibility services from industry could represent a large, untapped opportunity[1] to help manage and balance the electricity system.

[1] Energy Consumption in the UK (ECUK) 2025. Department for Energy Security and Net Zero, 24 September 2025. Available at: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2025/energy-consumption-in-the-uk-ecuk-2025

In this vision of Industrial Consumer-Led Flexibility (ICLF), users would actively adjust their electricity demand through load shifting, load shedding and on-site optimisation in response to system needs and/or price signals.[2] In theory, such flexibility could provide significant value to the electricity system by reducing peak demand, integrating higher shares of renewable generation, and lowering overall system costs. However, despite this strong technical potential, the deployment of industrial flexibility in the UK remains limited.

Based on extensive engagement with industry, we have built an evidence base which helps to differentiate critically between the theories and aspirations of those outside of industry and the realities faced by those who invest in, build and operate such manufacturing plants in the UK.

This report evaluates the realisable potential of demand-side flexibility in UK industry, assessing stakeholder understanding of the scale of technical flexibility, its value, and the key barriers to its realisation. Drawing also on international comparisons (Annex B), it identifies potential policy and market reforms which could help to unlock industrial flexibility as a component of a net-zero electricity system.

[2] International Energy Agency (n.d.) *Demand response*. Available at: https://www.iea.org/energy-system/energy-efficiency-and-demand/demand-response

2. Defining Industrial Consumer-Led Flexibility

2.1 Definition and Scope

Industrial Consumer-Led Flexibility (ICLF) refers to the voluntary adjustment of electricity demand by industrial consumers in response to price, market, network or system signals. It can involve changing the timing, level or source of electricity consumption in ways that reduce costs for participating businesses and support the efficient operation of the electricity system. [3] [4]

In this report, ICLF is understood as a strategic capability rather than a single technical measure. The flexibility available at any site will be shaped by its production processes, operational schedule, tolerance for changes in output, and access to enabling assets and technologies. Depending on these conditions, industrial sites may be able to shift electricity-intensive activities between periods, adjust consumption over shorter timeframes, use thermal or electrical storage, or vary the operation of on-site generation and demand-side equipment. In particular, flexibility viability is shaped by whether production processes are continuous or batch-based, the availability of material, thermal or product storage, the scale and timing of electricity demand and the operational consequences of changing consumption.

ICLF can be delivered through two broad routes[5]:

- Implicit flexibility occurs when a site responds autonomously to price signals, for example by moving suitable processes to lower-price periods.
- Explicit flexibility occurs when a site provides an agreed response to a third party, such as an electricity-system operator, network operator, supplier or aggregator. Explicit arrangements may enable participation in balancing, capacity or ancillary-service markets.

The ability to provide flexibility, and the value that can be realised from doing so, will vary considerably across industrial sites. Relevant factors include the duration and frequency of a possible response, process ramp rates, required notice periods, available storage, automation and controls, site-space constraints, workforce requirements, and any effects on product quality, production volumes or commercial revenues. These factors determine whether flexibility can be delivered without unacceptable operational disruption and which market or contractual route is most appropriate.

Where technically and economically viable, ICLF can help balance electricity supply and demand, reduce system peaks, absorb periods of abundant low-carbon generation and alleviate network constraints. It can therefore complement investment in generation and network infrastructure, while creating potential commercial opportunities for industrial consumers. [6]

[3] Energy UK (2026) *How consumer-led flexibility works in power markets*. Available at: https://www.energy-uk.org.uk/publications/energy-uk-explains-how-consumer-led-flexibility-works-in-power-markets/
[4] Department for Energy Security and Net Zero (DESNZ) (2026) *Clean Flexibility Roadmap: 2026 Update*. Available at: https://assets.publishing.service.gov.uk/media/6a50fce4a4890e65cce64d07/clean-flexibility-roadmap-2026-update.pdf
[5] Department for Energy Security and Net Zero (DESNZ) (2026) *Clean Flexibility Roadmap: 2026 Update*. Available at: https://assets.publishing.service.gov.uk/media/6a50fce4a4890e65cce64d07/clean-flexibility-roadmap-2026-update.pdf
[6] Department for Energy Security and Net Zero (DESNZ) (2026) *Clean Flexibility Roadmap: 2026 Update*. Available at: https://assets.publishing.service.gov.uk/media/6a50fce4a4890e65cce64d07/clean-flexibility-roadmap-2026-update.pdf

Some industrial sites may have the scale, capability and market knowledge to participate directly in flexibility arrangements. Others may engage through an aggregator, which can combine capacity across multiple consumers and provide support with technical integration, market access and contract management.

This report uses Industrial Consumer-Led Flexibility (ICLF) to refer specifically to voluntary electricity-demand flexibility provided by industrial consumers. Demand-Side Flexibility (DSF) is used as a broader energy-system term that includes ICLF alongside other forms of flexible demand. Related terms include demand-side response, demand response and demand flexibility.

2.2 Flexibility Market and Incentive Landscape

Industrial consumers in Great Britain can access flexibility revenues through a range of mechanisms, each with different technical requirements, risk profiles and revenue structures. The main categories are:

- System-operator balancing and frequency-response services: These include automatic and manual frequency-response products and other balancing services procured by NESO. They typically require fast, automated response and are suited to assets that can change demand or generation within seconds to minutes.[7]
- The Capacity Market: This provides payments in return for a commitment to be available to reduce demand or increase generation during system-stress events. Participation involves prequalification, testing and delivery obligations, with penalties for non-performance.[8]
- Demand Flexibility Service (DFS): This pays for voluntary reductions in electricity demand during specified dispatch periods. It is open to industrial and commercial consumers, often via aggregators and uses a defined baseline methodology to measure performance.[9]
- Network and local flexibility services: Distribution network operators and, in some cases, transmission-level actors procure local flexibility to manage constraints. These are often accessed through tenders or frameworks and may be less transparent than national schemes.[10]
- Wholesale and retail price responses: Some industrial consumers respond autonomously to wholesale price signals or retail tariff structures, for example by shifting load to lower-price periods. The strength of these incentives has changed over time, including with the removal of the Triad peak-charging arrangement.[11]

The suitability of each route depends on site-specific factors, including response speed, duration, notice periods, metering and control capability and the operational consequences of changing demand.

[7] National Energy System Operator (NESO) (2026) *Frequency response services*. Available at: https://www.neso.energy/industry-information/balancing-services/frequency-response-services

[8] Department for Energy Security and Net Zero (DESNZ) (2026) *Capacity Market: proposed changes for Prequalification 2026 - Government response.* Available at: https://assets.publishing.service.gov.uk/media/6a0449b6e71c4cdf4026bae7/capacity-market-proposed-changes-for-prequalification-2026-gov-response.pdf

[9] National Energy System Operator (NESO) (2026) *Demand Flexibility Service*. Available at: https://www.neso.energy/document/376621/download

[10] Energy Networks Association (ENA) (2025) *Flexibility services: Distribution network operators*. Available at: https://www.energynetworks.org/

[11] Ofgem (2019) *Targeted Charging Review: Decision and Impact Assessment*. Available at: https://www.ofgem.gov.uk/decision/targeted-charging-review-decision-and-impact-assessment

3. Stakeholder Insights and Workshop Synthesis

The evidence base for this report builds on an initial literature review (Annex B) and is significantly informed by direct engagement with industry actors, through a structured stakeholder workshop followed by one-to-one interviews. This two-stage engagement process was designed to first capture high-level thematic consensus and then delve into the granular, sector-specific practicalities of flexibility deployment (see also Annex A).

3.1 Workshop Findings: Identifying Thematic Consensus

3.1.1 The Potential for Industrial Consumer-Led Flexibility

Industrial Consumer-Led Flexibility (ICLF) could provide a valuable source of flexibility to a future low-carbon electricity system. In this report, a low-carbon electricity system is understood as one in which electricity is generated predominantly from low-carbon sources and in which demand can respond to changing system conditions without increasing overall emissions or undermining security of supply.

Many industrial processes have some inherent scope to vary electricity demand. Depending on the process and operating conditions, this may involve temporarily reducing or interrupting non-critical electricity use, rescheduling energy-intensive activities to periods of lower electricity-system demand or lower carbon intensity or increasing consumption when there is abundant low-carbon generation. Such actions can help balance supply and demand, reduce network constraints and support the integration of variable renewable generation.

The potential system value of industrial flexibility could be significant. The Clean Flexibility Roadmap identifies substantial theoretical flexibility potential across the non-domestic sector, although this category extends beyond energy-intensive manufacturing and includes commercial and other non-domestic consumers.[12] The proportion of this potential that is practically available from individual industrial subsectors will depend on process characteristics, production schedules, electricity demand profiles, site infrastructure and the risks associated with disrupting production.

Industrial and commercial consumers already participate in several forms of demand-side flexibility, including capacity, balancing and ancillary-service markets, distribution-network flexibility services, and price-responsive load shifting. However, workshop participants considered that participation remains materially below the technical potential identified in high-level assessments. They attributed this gap primarily to a perceived mismatch between the risks, costs and rewards of participation.

Accordingly, the challenge is not simply to demonstrate that industrial load can be adjusted. It is to establish when flexibility can be delivered without unacceptable effects on output, quality, safety, equipment condition or commercial performance, and to ensure that market arrangements provide a sufficiently clear and reliable return. Effective interventions will need to address the technical, economic and regulatory conditions that shape industrial participation.

[12] Department for Energy Security and Net Zero, Ofgem and National Energy System Operator (2025) *Clean flexibility roadmap*. Available at: https://www.gov.uk/government/publications/clean-flexibility-roadmap/clean-flexibility-roadmap

3.1.2 Workshop Summary (More detailed discussion of the workshop evidence is provided in the previously published report.[13])

The Industrial Consumer-Led Flexibility workshop brought together representatives from energy-intensive industries, technology providers and regulatory bodies to explore perceived and actual barriers to ICLF. A clear theme emerging from the discussion was the distinction between technical capability and commercial viability. Participants agreed that many industrial processes can physically modulate load, but that the current market and regulatory frameworks do not provide the stable and attractive value proposition needed to incentivise meaningful levels of participation.

The workshop also revealed a broader disconnect between the "top-down" policy and system/network-operator view of flexibility as an asset which can bring value to them, and the "bottom-up" industrial view of flexibility as a potential risk to their core production activities.

There was broad agreement that short-term and volatile price signals are poorly aligned with the multi-year investment cycles typical of energy-intensive sectors. In this respect, the workshop highlighted again that technical feasibility alone is not enough to drive adoption.

Participants highlighted several knowledge gaps that continue to hinder deployment. These included limited understanding of sector-specific flexibility potential, weak evidence on the economic viability of participation, a lack of high-resolution operational data to quantify and verify flexibility performance and insufficient clarity around effective business models and incentive structures.

Future research that would be needed to support industry includes:

- better quantification of technical flexibility potential at site and sector level
- standardised methods for evaluating economic feasibility
- improved data collection on electricity demand, process constraints and flexibility performance
- digitalisation of monitoring, control and market-participation systems
- further work on market design and participation mechanisms.

Overall, the workshop concluded that ICLF has potential to support a low-carbon electricity system, understood in this report as an electricity system in which the majority of generation is from low-carbon sources and system operation relies increasingly on flexible demand and storage to balance variable renewable output, but that any significant level of adoption will require coordinated action across research, technology, policy and market reform.

3.2 One-to-One Interviews: Practical and Sector-Specific Realities

Building upon the themes identified in the workshop, one-to-one interviews provided deeper insights into the cross-cutting and sector-specific challenges of flexibility.

A key flexibility enabler discussed was buffering, which can act as a practical bridge in batch industries. Buffering involves creating a temporary stock of an intermediate material between production stages. This allows an electricity-intensive stage to be paused or delayed during periods of grid stress, while downstream

[13] Gupta, D. and MacLean, K. (2026) *Industrial Consumer-Led Flexibility: Workshop Summary Report*. IDRIC. Available at: Industrial Consumer-Led Flexibility Workshop: Summary Report | IDRIC

operations continue using material that has already been produced and stored. The paused production stage can then resume later, when system conditions are more favourable.

- Interview evidence also highlighted several sector-specific issues: The steel sector emphasised the failure of current 'baseline' methodologies to accommodate the sharp fluctuations inherent in batch processes which do not operate with a constant baseline, like Electric Arc Furnaces.
- Cement sector representatives noted that clinker storage enables some flexibility, but duration is strictly limited by physical silo capacity and logistical costs of excess inventory.

The interviews indicated that, for many firms, electricity costs are a dominant concern and flexibility revenues remain too small and uncertain to influence strategic investment decisions positively. This is compounded by the administrative burden of participating in fragmented markets and regulatory schemes, with many stakeholders calling for more transparent communication and simplified participation mechanisms.

Details of two case studies follow in the next chapter and further cross-sector and international evidence is included in the annexes A and B respectively.

4. Sector Case Studies

This section presents two sectoral case studies to illustrate how ICLF considerations manifest themselves in practice across energy-intensive industries. The steel and cement sectors were selected to reflect a range of operational characteristics, particularly in terms of process continuity, storage capacity, and exposure to electricity costs, which are key determinants of flexibility viability as outlined in Section 2. The analysis draws on a combination of stakeholder interviews, industry reports and publicly available data.

4.1 Cement Sector (Including Lime and Asphalt): A Study in Limited Buffers

4.1.1 Background

For sectors such as cement, lime and asphalt, electricity use is high and represents a significant input cost. Although electricity represents only part of total process energy use in cement and lime, it remains an important operating cost and a potential source of flexibility. Production processes are often continuous and closely tied to material flows and customer demand. This creates a tension between the theoretical technical potential for flexibility arising from substantial electricity consumption and the operational realities of their production processes. This case study explores that tension by examining the scale of flexible demand, current participation in flexibility mechanisms and the wider context of energy costs and decarbonisation.

The UK cement industry produces approximately 7 million tonnes of cement annually.[14] Electricity consumption across the sector is around 900 GWh per year, equivalent to an average electricity demand of approximately 100 MW across the year, making electricity costs an important factor in operational competitiveness.[15] At the same time, the industry remains a significant source of industrial greenhouse gas emissions. Direct emissions covered by the UK Emissions Trading Scheme (ETS) are just under 5 million tonnes of CO_2 per year, while total emissions associated with cement and concrete production are estimated at around 6 million tonnes annually.[16] These emissions reduction challenges are driving increased interest in both energy efficiency and low-carbon production pathways, which may influence future flexibility opportunities.

4.1.2 Load Profile and Flexibility

An illustrative large integrated cement site, based on stakeholder evidence, has electricity demand of around 25 MW during normal operation. [17] Roughly half of this is base load, linked to continuous processes such as rotary kilns and associated systems. Although kilns are primarily fuelled by coal and waste-derived fuels, they still require electricity for supporting equipment and control systems. The remaining half of the load is more flexible and is mainly associated with the grinding of clinker into cement. This stage involves milling clinker, blending it with gypsum and storing the finished product in silos before dispatch.

[14] Mineral Products Association (MPA), 2026. *Annual cementitious materials statistics (UK) – 2026*. [online] Available at: https://cement.mineralproducts.org/MPACement/media/Cement/Industry-Statistics/2026/2026-04-01_Annual_cementitious.pdf

[15] MPA data

[16] Mineral Products Association (MPA), 2025. UK Concrete and Cement Industry: Roadmap to Beyond Net Zero – Progress Report 2025. [online] Available at: https://cement.mineralproducts.org/MPACement/media/Cement/Publications/2025/CC_Roadmap_to_Beyond_Net_Zero_Progress_Report_2025.pdf

[17] Anonymised cement-site load profile.

One of the main potential sources of flexibility in cement production is the ability to pause clinker grinding without immediately affecting supply. While the electricity share of clinker grinding varies between plants, it is widely recognised as one of the largest individual electrical loads in cement manufacture. In addition, cement can be stored in silos allowing operators to build up inventory and temporarily interrupt grinding activity. This creates a useful buffer between production and dispatch to customers.

However, in practice the flexibility is limited by finite storage capacity and by the working capital tied up in inventory. As a result, when operators use flexibility, this tends to be within narrow operational boundaries, usually over a short response window of some minutes to a few hours.

Taken together, the non-baseload element of the representative site demand described above may provide an illustrative upper-bound flexibility potential of around 12.5 MW for approximately one hour. If this full load reduction were available, it would equate to approximately 12.5 MWh of potential demand reduction or load shifting. This could make cement suitable for some short-duration balancing services. Frequency-response services use automated changes in electricity demand or generation to help maintain system frequency close to 50 Hz, and participation would require site-specific assessment of response speed, control capability, availability and production impacts. Achieving this potential would require flexibility arrangements that do not hinder production rates or create unacceptable operational risks.

In all events, flexibility remains secondary to the core objective of maintaining consistent output and meeting customer needs.

4.1.3 Operational Constraints

The ability to provide flexibility is shaped by the distinction between “just in case” and “just in time” production. In cement manufacture, “just in case” production refers to activities where intermediate or finished product can be manufactured in advance and held in inventory, such as clinker grinding and finished cement storage in silos. “Just in time” production refers to activities that must be closely aligned with immediate customer orders or delivery schedules, such as certain ready-mix concrete operations or time-sensitive dispatch requirements.

Cement grinding can operate partly on a “just in case” basis because finished cement can be stored in silos and dispatched later, creating room to adjust production timing. By contrast, processes that are tightly linked to immediate delivery requirements are far less adaptable. This distinction helps explain why some cement-related electricity loads are more flexible than others.

A further limitation is the asymmetry between reducing and increasing demand. While it is feasible to reduce electricity consumption by pausing grinding processes, there is much less scope to increase demand above normal operating levels. Cement plants usually operate close to capacity, which leaves limited room to absorb extra electricity during periods of surplus supply. This means that the sector’s contribution to upward flexibility is constrained, even though such flexibility is becoming more important in a power system with high levels of intermittent/variable renewable generation and inflexible nuclear.

4.1.4 Participation in Flexibility

Although participation varies by company, cement producers are already active in a range of flexibility mechanisms. These include demand flexibility services, frequency response and, in some cases, the

capacity market. Demand flexibility services pay for voluntary reductions in electricity demand during periods of high system stress; frequency-response services use automated changes in demand or generation to help maintain system frequency close to 50 Hz; and the Capacity Market provides payments in return for a commitment to be available to reduce demand or increase generation during system-stress events. Some operators also reduce load voluntarily in response to electricity price signals, although stakeholder evidence indicates that this is now much less common than historically under the now abolished Triad scheme.

The extent of participation can also depend on electricity purchasing arrangements. Firms that hedge their electricity costs through forward contracts are less able to benefit from short-term price movements, while others may engage more readily in opportunistic load shifting when market conditions are favourable.

The choice of scheme reflects a balance between risk and reward. The capacity market may offer higher returns, but it also exposes participants to penalties for non-performance. By contrast, lower-risk options tend to offer smaller financial returns, but they are often preferred because they are easier to align with normal production priorities and the risks are manageable.

Participants stressed that even the more attractive schemes still only represent secondary or tertiary incentives and feature well behind the primary business drivers in corporate decision making.

4.1.5 Storage and Inventory in Cement Production

Storage is central to flexibility in cement production, but it is not without cost. The principal flexibility option is to interrupt or reschedule clinker grinding and silo storage is what makes this possible without immediately disrupting dispatch. Other potential sources of flexibility, such as adjusting auxiliary loads or optimising the timing of raw-material preparation, are more constrained by process interdependencies and customer requirements. The ability to accumulate and draw down inventory allows operators to shift electricity use without immediately affecting output or ability to meet customer needs. However, maintaining large inventories ties up capital and can create logistical difficulties. For this reason, storage is used strategically rather than maximised for flexibility purposes. This reinforces the short-duration nature of most demand response activity in the sector.

This feature also helps explain why flexibility in cement is real but limited. The sector can adjust load within defined windows, but it cannot offer open-ended response without affecting production efficiency or logistics. In that sense, storage is an enabler of flexibility, but also a constraint on how far it can be pushed.

4.1.6 Sector Comparison

Flexibility potential varies across the cement, lime and asphalt sectors, reflecting differences in process continuity, storage capacity and delivery requirements.

Table 1: Flexibility characteristics across cement, lime and asphalt

Sector	Process Type	Storage/Buffering	Typical Flexibility Potential (Load Shifting)
Cement	Continuous kiln; separable grinding and finishing	Clinker and cement silos allow multi-hour to multi-day buffering	Moderate, mainly short-duration load shifting
Lime	Largely continuous kiln and processing	Limited, shorter-duration intermediate and product storage	Low to moderate, constrained by continuity
Asphalt	Batch production, hot-mix	Very limited; hot material must be dispatched quickly	Low, primarily through aggregation of small sites

This comparison focuses primarily on the potential to shift or interrupt electricity demand associated with production processes. Other forms of flexibility, such as behind-the-meter storage, onsite generation or fuel switching, are not considered here.

This comparison matters because it shows that flexibility is not an industry-wide characteristic, but something that depends on process design and operational structure. Cement sits in the middle of the spectrum, with some meaningful but bounded flexibility. Lime and asphalt are progressively more constrained.

4.1.7 Decarbonisation Implications

Future flexibility will also be shaped by the chosen decarbonisation pathways:

- In cement and lime, carbon capture is expected to play a major role, alongside greater use of alternative fuels including hydrogen, biomethane and waste (biomass) derived fuels. There is limited opportunity for electrification. CCUS will, and fuel changes may, increase electricity consumption, but are unlikely to offer significant additional flexibility potential beyond existing process constraints.
- In asphalt, hydrogen is among the options under consideration for replacing natural gas in heating and drying,[18] while electrification is likely to play a supporting role rather than dominate. Electrification of drying processes could create additional flexibility potential, although drying currently accounts for a relatively small share of total energy use.

Some emerging technologies may create new flexibility opportunities. Electrified quarry vehicles, for example, could provide flexible charging demand where site geography allows recovery of energy during

[18] Drying processes account for up to 15% of energy consumption in the process industry, once electrified there could be potential for more flexibility.

operation. However, these possibilities remain at an early stage and are not yet central to the sector's flexibility potential.

4.1.8 Economic and Market Context

Energy costs remain a dominant factor in production economics. Electricity, fuel and carbon costs together represent a substantial share of total costs. Efficiency gains can be economically attractive, but flexibility revenues remain relatively small in comparison. Their variability also makes them difficult to incorporate into investment decisions. Even where firms may be able to estimate possible opportunities, these are not guaranteed and depend on market conditions and scheme design. Flexibility is therefore treated as an additional fringe benefit rather than a core revenue stream.

International competitiveness pressures further limit flexibility as an investment driver in the UK. Many cement and lime producers operate globally and compare sites across jurisdictions when allocating capital. High energy costs in the UK place domestic plants at a disadvantage relative to facilities in other countries. In this context, flexibility revenues do not outweigh wider concerns about operating costs and policy stability.

4.1.9 Practical Barriers

There are also practical barriers to participation in flexibility markets and incentive schemes. These include limited visibility of system needs, unclear communication of flexibility-service events and administrative complexity. Even in relatively well-established mechanisms, such as the Demand Flexibility Service (DFS) and the Capacity Market's Demand Side Response (DSR), participants report challenges in interpreting dispatch signals, understanding baseline and settlement rules and managing performance risk.

Others are harder to engage with because they are less transparent, such as certain distribution-network flexibility services and tenders or fragmented aggregator platforms. There is also a perceived imbalance between risk and reward, with the possibility of penalties usually outweighing the uncertain returns. Improving participation would therefore require simpler processes, clearer signals and a better fit with operational realities.

4.1.10 Conclusion

Overall, the cement sector offers a modest but potentially meaningful source of demand-side flexibility, mainly through clinker grinding. Some of this flexibility is already being used, but it remains constrained by operational, financial and logistical factors.

Lime and asphalt offer more limited opportunities because of their process characteristics. For these reasons, flexibility remains a secondary consideration compared with energy costs and decarbonisation, and while it can deliver incremental value, it is unlikely to be a decisive factor in shaping investment or operational strategy.

4.2 Flexibility and Competitiveness in the UK Steel Industry

4.2.1 Background

The steel industry is especially instructive in the context of this report, as it is highly energy intensive, has already been subject to extensive offshoring and is undergoing significant structural changes through electrification and decarbonisation in what remains of the sector in the UK. Crude steel production in the UK was around 5.6 million tonnes in 2023, concentrated in a small number of large sites, including Port Talbot and Scunthorpe.[19] In 2019, the UK steel industry emitted about 12 million tonnes of CO2 equivalent (CO2e), underlining the scale of the decarbonisation challenge facing the sector.[20] Prior to the closure of Tata Steel's blast furnace at Port Talbot in September 2024, the industry used approximately 2.25 TWh of electricity and 4.36 TWh of natural gas, as detailed in the *UK Steel Net Zero* report, which also provides the underlying emissions data.[21]

Steel production is inherently carbon intensive, with conventional blast furnace to basic oxygen furnace (BF-BOF) routes emitting close to 2 tonnes of CO_2 per tonne of steel. Around 60% of these emissions arise from process emissions, primarily the use of coke to chemically reduce iron ore, with a further approximately 30% from the high temperature energy required and approximately10% from downstream refining.[22][23] Transitioning to electric arc furnaces (EAFs), which primarily use scrap steel, can significantly reduce emissions by avoiding the need for iron ore reduction. However, while EAF production has much lower direct emissions, the availability and quality of scrap constrain its role, and primary steel production remains necessary to meet demand and maintain material performance. [24][25][26]

In the UK, the transition towards electric arc furnace (EAF) production is expected to increase electricity demand while potentially creating new opportunities for flexibility service provision to the electricity system. However, the extent to which this potential can be realised depends not only on technical capability, but also on market design, regulatory frameworks and broader economic conditions. This case study explores these issues through insights drawn from industry interviews, with particular attention paid to operational characteristics, policy mechanisms and investment decisions.

4.2.2 Sector Engagement with Flexibility

[19] Jozepa, I. (2025) *UK steel industry: Statistics and policy*. House of Commons Library Research Briefing, CBP 7317. London: House of Commons Library. Available at:https://researchbriefings.files.parliament.uk/documents/CBP-7317/CBP-7317.pdf
[20] Future carbon pricing: Briefing for BEIS Select Committee (2020). Written evidence submitted to the Business, Energy and Industrial Strategy Committee, UK Parliament. Available at: https://committees.parliament.uk/writtenevidence/14920/html/
[21] UK Steel (2022). Net Zero Steel: A Vision for the Future of UK Steel Production. Available at: https://www.uksteel.org/steel-news-2022/net-zero-steel
[22] Environmental Defense Fund. *Steel industry decarbonization*. Available at: q5e7524w5qe53l5y0mx243h7yv8gu4i8.pdf
[23] Sustainable Ships (2022) *What is the carbon footprint of steel?* Available at: https://www.sustainable-ships.org/stories/2022/carbon-footprint-steel
[24] Columbia Business School (2023) *Steel sector overview*. Available at: https://business.columbia.edu/insights/climate/cki/steel/overview
[25] Carmona, L.G., Whiting, K. and Sousa, T. (2019) *The evolution of resource efficiency in the United Kingdom's steel sector: An exergy approach. Ecological Economics.* Available at: https://www.sciencedirect.com/science/article/abs/pii/S0196890419307319
[26] European Parliament (2021) *Carbon-free steel production: Cost reduction options and usage of existing gas infrastructure*. Brussels: European Parliamentary Research Service. Available at: https://www.europarl.europa.eu/RegData/etudes/STUD/2021/690008/EPRS_STU(2021)690008_EN.pdf

The UK steel industry currently engages with demand side flexibility in a limited and largely opportune way. Although some firms participate in the Capacity Market, either directly or through aggregators, this is generally seen as a supplementary source of revenue rather than a strategic business activity. Participation in other flexibility mechanisms, such as balancing services or the Demand Flexibility Service, remains limited and highly site-specific (see Section 2.2). For most steel producers, flexibility does not feature significantly in core decision making, where steel production remains the primary focus.

This limited engagement reflects the fact that flexibility must fit around production, not the other way around. It must certainly not interrupt it. Where participation does occur, it usually aligns with existing operational patterns rather than requiring major changes to plant behaviour. As a result, flexibility is understandably treated as an occasional commercial opportunity rather than a central operational strategy.

4.2.3 Production Processes and Technical Constraints

- Electric arc furnaces melt scrap steel in discrete cycles, which means operators can alter the start time of batches without interrupting an active process. This also makes the route materially more electricity-intensive than blast furnace/basic oxygen furnace production: one estimate suggests BF-BOF uses around 0.05 MWh per tonne of steel, while EAF uses around 0.45 MWh per tonne.[27] Alongside the option to delay operations to reduce system deficits, this is one of the few examples where production may also be rescheduled to consume electricity at times of system surplus.

- By contrast, blast furnaces operate continuously and are highly sensitive to interruption. Halting production can damage equipment and create substantial costs. This all but completely discourages participation in flexibility services. Some limited opportunities may exist in auxiliary or downstream processes, but these are relatively small-scale compared with the main production activities. UK steel strategy expects the sector to move further toward EAF production in the future, so the flexibility opportunity is likely to grow as the sector electrifies.

4.2.4 Energy Efficiency and Investment

High electricity prices do not appear to incentivise significant energy-efficiency investment within the UK steel sector. Although economic theory suggests that higher energy costs should encourage firms to improve efficiency, this may not apply in industries facing intensive international competition, where companies may instead prioritise investment in plants located in jurisdictions with more competitive electricity prices and wider operating conditions. This again underlines the importance of cost competitiveness in shaping investment choices.

As a result of international competition, UK steel sites face underinvestment, which limits progress on both efficiency and decarbonisation. The issue is not simply the level of electricity prices, but the position of the UK relative to competitor countries.

That makes competitiveness a central concern in any discussion of industrial flexibility. If relatively high-value efficiency-savings are insufficient to drive investment in UK plants, there is little chance for lower-value and potentially higher risk flexibility services.

[27] Fastmarkets (2025) EAF steel: Addressing decarbonization in the sector. Fastmarkets Insights. Available at:https://www.fastmarkets.com/insights/eaf-steel-addressing-decarbonization-in-the-sector/

4.2.5 Limitations of Existing Mechanisms

Existing demand response schemes are often poorly aligned with industrial operating characteristics. This is particularly relevant for baseline-based demand-turn-down services such as NESO's Demand Flexibility Service, where delivery is assessed against a consumption baseline. Many schemes rely on 'baseline' methodologies that establish normal consumption from historical data and are unsuitable for EAF operations where demand naturally fluctuates between high consumption and idle periods.

Establishing a meaningful baseline is therefore difficult, and plants are unable to respond to demand reduction signals if they are already idle (although there may be the potential for turn-up). As a result, facilities may be excluded from compensation mechanisms despite having genuine flexibility potential. Current market arrangements weaken the incentive to participate for batch-based industrial processes which otherwise might be potential candidates to provide flexibility services.

4.2.6 Conclusion

This case study highlights the gap between the technical capability of the UK steel industry to provide flexibility and the current design of market and policy frameworks. While many steel plants, particularly those using electric arc furnaces, possess inherent flexibility, existing mechanisms do not capture this potential effectively.

The findings suggest that relatively modest interventions could unlock some flexibility, particularly if policy and market design were better aligned with batch production processes. Clearer price signals, simpler participation arrangements and more suitable baseline or reward structures would improve the business case for participation without requiring major additional capital investment.

5. Technical and Operational Barriers

Further evidence from other sectors was collected (see Annex A) and combined with that from the two detailed case studies above to produce the insights in this section. The barriers described here are interrelated, with technical, economic and regulatory constraints often reinforcing one another.

5.1 Process Constraints

Continuous high-intensity processes are particularly difficult to interrupt. In sectors such as aluminium, load modulation may be possible but is constrained by process stability requirements, since repeated curtailments can reduce efficiency and disrupt production, leading to product quality issues and/or production loss These consequences may impose substantial costs that outweigh the potential benefits of participating in flexibility markets. Similar issues arise in other continuous processes, where stopping or shifting load can affect product quality, equipment integrity and delivery schedules.

Restart effects can also reduce the value of flexibility. Bringing a process back online may require additional fuel, longer ramp-up periods and extra operational input, which can increase emissions and partly offset the environmental gains of reducing demand at times of high electricity emissions intensity. As a result, the true economic and environmental cost of flexibility must include both the reduction period and the restart period.

5.2 Equipment and Infrastructure Limitations

Many industrial sites still rely on legacy equipment that lacks modern control systems, automated load management, or detailed sub-metering. This makes it difficult for operators to identify where flexibility exists, how much can realistically be offered, and what effect it will have on production.

However, not all flexibility requires large-scale interruption of production. In many cases, “small flex” opportunities exist through better control of auxiliary equipment such as pumps, fans and compressors. Although these loads may be technically controllable, some are essential to safe and stable operation and may therefore have limited availability, response duration or scope for adjustment. Variable speed drives and digital controls can allow these loads to be turned down, paused, or in some cases turned up, in response to system needs without stopping the core production process.

Physical infrastructure can create further limits. Older sites may not have the space or layout required for behind-the-meter battery storage, local generation, thermal storage, or additional digital equipment. These technologies can either enable more responsive control or help decouple electricity consumption from immediate production requirements.

This means that even where flexibility would be useful, site conditions may prevent the installation of the assets needed to support it. More broadly, the evidence suggests that flexibility should be understood as a spectrum: from low-disruption operational adjustments on auxiliary loads, through process-level load shifting to deeper capability investments such as onsite generation, dual-fuel operation and thermal or electrical storage.

5.3 Operational Risk and Production Priority

A consistent theme is that production continuity takes priority over flexibility provision. Industrial managers are often reluctant to expose core operations to any risk that could affect safety, quality, output or customer service commitments. This creates a strong disincentive to participate in schemes that require rapid response or repeated changes in operating pattern.

For many sites, flexibility is therefore confined to non-critical, buffered or auxiliary processes. However, where processes are tightly linked to safety, temperature control or continuous material flow, the tolerance for disruption is very low. In practice, this means that flexibility may have technical potential but is commercially or operationally unacceptable.

A further constraint, which is often overlooked, is process safety. Most equipment used to provide demand response, including pumps, fans and other auxiliary systems, will already have been assessed through hazard identification (HAZID), hazard and operability (HAZOP), or safety integrity level (SIL) studies as part of the wider industrial process safety framework. These assessments usually assume that equipment or processes may shut down only a limited number of times per year. By contrast, demand response applications could involve switching events several times per week, or even within the same day. This materially changes the underlying assumptions in the safety case and may trigger a formal Management of Change process. In some cases, operators may need to revisit existing studies or undertake new ones entirely, creating significant cost, time and specialist resource requirements before flexibility can be deployed at scale. This may also affect start-up and shut-down procedures that were originally defined and risk-assessed as part of the HAZOP and wider process safety framework.

5.4 Data and Digitalisation Gaps

There is a lack of granular, near-real-time data on industrial electricity use, as well as high-accuracy short-term forecasts for demand day ahead and within the final hours before operation. Stakeholders highlighted that many companies do not have sufficiently detailed monitoring systems to understand consumption patterns across different processes, nor the integration between these monitoring systems and production scheduling needed to produce reliable near-term forecasts. This matters because such forecasts are needed to determine whether a demand response event would make a meaningful difference to the distribution network operator (DNO) and to assess its value to the wider network. Better post-event data would also help establish the actual impact of flexibility interventions on network conditions.

DNOs may also fail to provide real-time network capacity and price signals, leaving scheme participants without the full operational picture. Without reliable data, firms cannot accurately quantify flexibility potential, assess whether participation is operationally worthwhile, or manage it in practice.

There is also a wider digitalisation issue. Industrial control systems are often not interoperable with grid operator platforms, which raises transaction costs and complicates participation in flexibility markets. Digital infrastructure is therefore essential not only for monitoring, but also for low-latency dispatch, automated response and settlement in modern ancillary service arrangements.

5.5 Energy System Interface Issues

Grid connection processes and network charging arrangements also reduce participation. Administrative complexity can make it time-consuming and costly to join flexibility schemes, while high network charges further weaken the business case. The impact of Ofgem's Targeted Charging Review[28] has been especially significant, since it increased cost exposure for many industrial users and reduced the incentive to shift load in response to system needs.

In addition, physical network constraints can limit flexibility. Sites in constrained areas may face long lead times for connection upgrades or reinforcement, restricted export or import capacity, and uncertainty over who bears the cost of enabling works. These factors can delay or prevent investment in flexibility-enabling assets, even where the technical potential exists.

5.6 Commercial Uncertainty

Flexibility revenues are often too small, too volatile or too uncertain to shape strategic investment decisions. For many firms, flexibility is treated as a potential, occasional bonus rather than a reliable revenue stream. This is especially true in energy-intensive sectors where electricity, fuel and carbon costs dominate financial planning.

Because payments are uncertain, businesses struggle to justify investment in new controls, automation or storage assets. Even where flexibility is technically possible, the commercial case may be too weak to support internal approval.

5.7 Market Design Mismatch

Many flexibility mechanisms are designed around stable, predictable demand reductions, rather than batch processes or highly cyclical industrial loads. This creates a mismatch between market rules and industrial operating realities.

Some industrial users may have flexibility but still fail to qualify for payment because the market framework is not designed to recognise their pattern of demand. This limits participation and reduces the effectiveness of current schemes. More suitable designs would need to account for batch production, delayed restart and industrial-specific response profiles.

5.8 Administrative Complexity

Stakeholders also identified fragmented participation rules, communication processes and settlement arrangements as major barriers. Many schemes are administratively burdensome, especially for firms without dedicated energy teams or advanced market expertise. The effort required to understand multiple services, manage compliance and respond to system events can outweigh the expected benefit.

[28] Ofgem (2019) *Targeted Charging Review: Decision and Impact Assessment*. Available at: https://www.ofgem.gov.uk/decision/targeted-charging-review-decision-and-impact-assessment

This burden is particularly challenging for smaller sites and firms with limited digital maturity. Even where technical flexibility exists, complexity can deter participation. Simplifying access rules and improving transparency would therefore be an important step towards wider uptake.

5.9 Limited Visibility of System Needs

Industrial users are not always given clear or timely information about when flexibility is actually needed. If signals are inconsistent, delayed or difficult to interpret, firms cannot plan production changes with confidence. This weakens trust in the system and reduces willingness to commit operational capacity.

Clearer communication would help businesses understand what is being asked of them and when. Without that visibility, flexibility remains too uncertain to embed in routine operations. This is particularly important where production decisions must be made well in advance. This challenge is closely interrelated with other barriers: without timely, high-quality data and usable system interfaces, even well-designed flexibility signals cannot be translated into actionable operational decisions.

5.10 Sectoral Heterogeneity

The evidence shows that flexibility potential varies sharply across sectors and process types. Batch processes can offer meaningful flexibility, while continuous high-temperature systems such as glass or certain chemical processes are much more rigid. Cement sits somewhere between these extremes, with some limited flexibility in grinding but far less in kiln operations.

This variation means that no single policy or market mechanism will work equally well across all industries. A one-size-fits-all approach risks overstating the flexibility potential of some sectors while missing realistic opportunities in others. Flexibility policy therefore needs to be sector-specific and grounded in actual operational conditions.

5.11 Conclusions

Taken together, these barriers show that industrial flexibility is constrained not just by technology, but by the interaction of process design, data availability, market rules, infrastructure limits and commercial incentives. Unlocking industrial flexibility will require more than encouragement alone, since many of the barriers are structural and, for good reason, embedded in the way industrial sites and electricity markets currently operate.

6. Lessons Learnt and Further Insights from the Sector Case Studies

Evidence from detailed case studies and wider sector understanding (Annex A) reveals that while technical potential for ICLF exists, its realisation is constrained by a combination of operational, economic and regulatory factors. These constraints are consistent across sectors, but manifest differently depending on process characteristics, market exposure and policy context.

6.1 Alignment between System Needs and Industrial Realities

A central finding is the misalignment between electricity system requirements and industrial operating conditions. Policymakers and system operators tend to frame flexibility as a dispatchable and reliable system resource, whereas industry views it as a source of operational risk.

Industrial processes are typically optimised for efficiency, throughput, and product quality rather than load balancing. Deviations from steady-state operation can introduce risks to equipment integrity, safety, and output consistency. As a result, flexibility carries an implicit risk premium, which discourages participation, particularly in globally competitive sectors where even minor disruptions have financial consequences. Therefore, although flexibility may be technically feasible, it is rarely prioritised within plant-level or corporate strategies.

6.2 Technical Potential and Process Dependency

Flexibility potential varies significantly across and within sectors, reflecting differences in process design:

- Batch processes, such as electric arc furnace (EAF) steelmaking, can offer flexibility by shifting or delaying production cycles (for example, postponing the start of the next batch).
- Processes with intermediate storage, such as cement grinding, allow short-term load shifting without affecting upstream production.
- Continuous, high-temperature processes (for example, glass and lime production) are inherently inflexible due to thermal and operational constraints.

The presence of thermal or material buffers is a key determinant of flexibility. This heterogeneity demonstrates that flexibility is a sector-specific characteristic rather than a uniform industrial attribute, limiting the effectiveness of generic policy mechanisms.

6.3 Alternative Models for Flexibility Provision

Evidence from countries such as France, particularly through mechanisms like Dispositif d'interruptibilité, highlights the value of designing flexibility mechanisms around industrial processes. [29] Rather than relying on reductions relative to a predefined baseline, some schemes incentivise the delay of load resumption following production cycles.

[29] République française (2015) *Arrêté du 22 décembre 2015 pris en application de l'article L. 321-19 du code de l'énergie*. Available at: Decree of 22 December 2015 issued pursuant to Article L. 321-19 of the Energy Code - Légifrance

For example, an EAF operator may delay initiating the next melt during periods of system stress, rather than interrupting an active process. This approach aligns with batch production realities, avoids challenges associated with baseline calculation, and reduces operational disruption and participation barriers.

Such models demonstrate how process-aware design can make flexibility more accessible and practical for industrial users.

6.4 Market Interaction and Participation Constraints

The Capacity Market provides stable and predictable revenues in exchange for availability during stress events, which can make it appealing to some industrial operators, but participation also carries delivery obligations and potential penalties for underperformance.[30] Participation may restrict involvement in other flexibility markets where service rules, availability obligations, exclusivity provisions or delivery requirements are incompatible. While revenue stacking is possible in some circumstances, firms may need to choose between revenue certainty (Capacity Market) and more dynamic but uncertain flexibility opportunities where commitments overlap. This trade-off reduces engagement in flexibility as a broader strategic activity.

6.5 Economic and Regulatory Barriers

UK industrial electricity prices remain consistently higher than in competitor countries such as France and Germany, influencing multinational investment decisions. Although higher and more variable electricity prices can strengthen incentives to shift demand, flexibility revenues may still be too small or uncertain to outweigh the operational risks, opportunity costs and investment required for participation.

Regulatory changes have further eroded the business case: the Triad system removal weakened peak avoidance incentives, while the Targeted Charging Review increased network charges for industrial users (despite partial compensation).[31] The steel industry has proposed a two-way price stabilisation mechanism benchmarking UK price against competitors, excluding peak periods to maintain flexibility incentives.[32] Any wider application of this mechanism would require assessment of fiscal exposure, consumer-bill impacts and subsidy-control implications.

6.6 Digitalisation and Data Visibility

A key lesson from the case studies is that digital infrastructure should be treated as an enabling condition for ICLF. Sub-metering, near-real-time data, forecasting capability and interoperable control systems are needed to identify flexibility, assess its operational value, verify delivery and manage performance risk.

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[30] Capacity Market: The Capacity Market (CM) is part of the Electricity Market Reform programme. It ensures the UK has enough electricity to meet future demand. The CM aims to keep electricity costs low for consumers by allowing energy providers to earn payments for being available when needed.
National Energy System Operator (NESO) *Capacity Market*.Available at: https://www.neso.energy/what-we-do/energy-markets/electricity-market-reform-emr-delivery-body/capacity-market

[31] British Gas Business (n.d.) *Ofgem's Targeted Charging Review explained*. Available at: https://www.britishgas.co.uk/business/blog/ofgems-targeted-charging-review-explained
The Targeted Charging Review was introduced by Ofgem to make network charging fairer, as rising grid costs were being recovered from a shrinking group of users. It aims to ensure all consumers contribute fairly while allowing network operators to recover the revenue needed to maintain the electricity system.

[32] UK Steel (2025) *New report: UK industrial electricity still uncompetitive – steel industry sets out plan to fix it*. Available at: https://www.uksteel.org/steel-news-2025/new-report-uk-industrial-electricity-still-uncompetitive-steel-industry-sets-out-plan-to-fix-it

Investment in monitoring, automation and low-latency dispatch interfaces would improve the accuracy of flexibility measurement and support aggregation models capable of pooling distributed industrial loads. Without these capabilities, sites may be unable to quantify or offer flexibility reliably, even where technical potential exists.

6.7 Solvable and Structural Barriers

Barriers to industrial flexibility can be divided into two categories:

- Solvable barriers include complex participation rules, unsuitable baseline methodologies, and data limitations. These can be addressed through regulatory reform, market redesign and targeted investment.
- Structural barriers are inherent to process design, particularly in continuous or safety-critical operations. Addressing these requires technological innovation, such as process electrification, hybrid energy systems or advanced materials enabling temporal decoupling.

Recognising this distinction is critical. If barriers are treated as uniform, this risks both overstating achievable flexibility in some sectors and underutilising it in others. Policies may focus on removing regulatory and market obstacles in sectors where the primary constraints are in fact structural and technology-driven and vice-versa. They may underestimate readily accessible flexibility in sectors where barriers are largely administrative or market based.

6.8 Policy, Governance and Strategic Integration

Policy clarity, stability, and coherence are key enablers of participation. Effective frameworks should include simplified and transparent market mechanisms with predictable revenues, sector-specific participation models that reflect operational realities, and integration of flexibility into broader industrial decarbonisation strategies, including electrification, carbon capture and storage (CCS) and hydrogen.

Emerging reforms proposed by the National Energy System Operator (NESO), such as shorter settlement periods, unit-level bidding, and improved dispatch transparency, could strengthen price signals and reduce system inefficiencies. [33]

Collaborative governance models, including aggregation and public-private partnerships, can further reduce risk and build trust.

The need for better demand visibility and stronger process-safety governance points to a broader policy conclusion: flexibility should be integrated into industrial electrification strategy from the outset rather than treated as an optional extra. Where government support is offered for electrification, project developers should be encouraged to consider the potential to provide flexibility alongside emissions reduction and cost effectiveness at relevant gate reviews. This would help ensure that supported projects are designed not only to consume electricity, but also, where practicable, to interact with the power system in ways that support reliability and balancing.

[33] National Energy System Operator (2026) *Reformed National Pricing: Call for Input*. Available at: https://www.neso.energy/industry-information/reformed-national-pricing/reformed-national-pricing-call-input-cfi

6.9 Reframing Flexibility as Industrial Value

A recurring theme is the need to reposition flexibility from an operational burden to a source of strategic value. For flexibility to be embedded in standard industrial practice, it must deliver clear and reliable financial benefits, present manageable and well-understood risks, and offer co-benefits such as resilience and exposure to appropriately designed incentives.

In practice, this means distinguishing between “big flex” and “small flex”. Big flex includes load shifting, batch rescheduling or triad-style peak avoidance associated with larger demand response events. “Small flex” includes continuous operational optimisation, such as modulating pumps, fans, and other auxiliary systems, which can provide useful grid value without disrupting production.

There is also a third category: capability flex. This refers to investment in assets and systems that create future flexibility options, including onsite generation, thermal storage, electric boilers, dual-fuel systems, hydrogen readiness, automation, and advanced energy management systems. This form of flexibility is especially important as industrial sites electrify and become much larger electricity users than they are today.

For these reasons, flexibility should not be treated only as a response mechanism for exceptional events. It should increasingly be designed into industrial electrification and decarbonisation decisions from the outset, including any government support offered for electrification. Where financial support is provided from taxpayers or consumers, flexibility could usefully be included as a decision gate or design criterion, so that, where viable, supported projects contribute not only to emissions reduction but also to system balancing and future operational adaptability.

Without a more systematic integration of flexibility into both industrial decision-making and policy support frameworks, flexibility will remain a marginal activity rather than become a core component of industrial energy management.

Reframing flexibility in this way also requires recognising that industrial sites are not simply large electricity consumers; they are operational systems with safety constraints, planning cycles, and management processes that must be respected. The value of flexibility therefore lies not only in the ability to shift demand, but in the ability to do so safely, predictably, and with sufficient visibility for both operators and network stakeholders.

6.10 Towards "Flexibility in Flexibility"

The combined evidence highlights the need to move beyond one-size-fits-all approaches. Effective flexibility frameworks must accommodate the diversity of industrial processes, operational constraints, and market conditions.

This implies designing adaptive, sector-sensitive mechanisms that align electricity system needs with industrial realities, enabling flexibility where it is feasible while recognising its limits where it is not. As industrial sites electrify, many currently medium-sized consumers will become much larger electricity users, making the incorporation of flexibility into site design, support schemes, and investment decisions increasingly important.

In that context, future policy should distinguish between immediate operational flexibility and longer-term capability-building. The first supports day-to-day grid balancing; the second ensures that industrial decarbonisation does not simply create larger passive demand, but instead builds a more resilient, responsive, and system-aligned industrial energy base.

In practice, this means that industrial flexibility should be developed with “flexibility in flexibility”: flexibility in how demand is measured, flexibility in how operating constraints are assessed, and flexibility in how safety, production, and system needs are balanced. As industrial demand grows through electrification, this will become increasingly important for ensuring that flexible demand is technically credible, operationally safe, and commercially viable.

7. Summary of Findings

Any approach must address the technical, economic and regulatory drivers and barriers simultaneously.

7.1 Technical Capability and Commercial Viability

A clear theme emerging from the stakeholder engagement was the distinction between technical capability and commercial viability. While flexibility is technically possible in many cases, it is rarely prioritised within plant-level or corporate strategies. Flexibility is therefore treated as an additional fringe benefit rather than a core revenue stream.

7.2 Perceived Risk and Operational Constraints

Stakeholders consistently emphasised a fundamental misalignment between the perception of policymakers and system operators that flexibility is a manageable, dispatchable asset, and the industry view of flexibility as a potential risk to operational stability, safety, product quality, and economics.

Energy-intensive processes are optimised for output efficiency rather than load modulation, meaning that any deviation from standard operations introduces risks to product characteristics, equipment integrity, and delivery schedules. This perceived 'risk premium' acts as a powerful deterrent, particularly in globally competitive sectors where even minor disruptions have financial consequences.

7.3 Sectoral Variation in Flexibility

Flexibility is not an industry-wide characteristic, but something that depends on process design and operational structure. The presence of thermal or material buffers remains a critical determinant of technical flexibility potential. Process heterogeneity between and within sectors reinforces that no single market or policy mechanism can unlock flexibility uniformly, and that flexibility potential is best understood as a sector-specific characteristic rather than a generic industrial attribute.

7.4 Market and Economic Barriers

Despite evidence of technical flexibility potential, the current market architecture undermines its commercial viability. Stakeholders across all sectors cited insufficient or uncertain revenue streams from existing flexibility schemes. High levels of administrative complexity, combined with uncertain price signals, discourage participation, particularly for firms with limited internal energy management capacity.

Price volatility was identified as a potential but limited driver of flexibility. While time-shifting electricity demand to exploit periods of low prices and avoid peaks can create arbitrage value, this is typically a secondary or tertiary consideration for industrial users. In practice, high price volatility is often viewed as detrimental, introducing cost uncertainty that can negatively affect core operations rather than incentivising flexible behaviour.

Contract-based incentives were seen as more effective in enabling participation, particularly where they provide revenue certainty and reduce exposure to market risk. Arrangements with system operators, such as those historically used for fast frequency response services, offer clearer value propositions compared to reliance on wholesale price arbitrage.

The fundamental mismatch between risks and rewards effectively relegates flexibility to a peripheral activity for most industrial consumers. Flexibility revenues alone are very unlikely to influence major investment decisions, particularly in the context of wider concerns around energy costs and industrial competitiveness. The more the UK is seen as uncompetitive on energy costs, the less important flexibility becomes compared to overall cost exposure.

Current regulation tends to favour homogeneous, dispatchable assets rather than the heterogeneous, operationally constrained flexibility characteristic of industrial demand. Pursuing generic flexibility targets risks imposing unrealistic expectations on certain sectors while overlooking more achievable opportunities elsewhere.

7.5 Knowledge Gaps

Participants highlighted several knowledge gaps that continue to hinder deployment. These included limited understanding of sector-specific flexibility potential, weak evidence on the economic viability of participation, a lack of high-resolution operational data, and insufficient clarity around effective business models and incentive structures.

Future research needed to support industry includes better quantification of technical flexibility, standardised methods for evaluating economic feasibility, improved data collection and digitalisation, and further work on market design and participation mechanisms.

7.6 Alignment with Decarbonisation Pathways

The integration of industrial flexibility into broader decarbonisation policy and investment, including carbon capture, utilisation and storage (CCUS) and hydrogen fuel substitution strategies, can yield synergies. As electrification deepens through the 2030s, aligning flexibility policy with industrial energy transition pathways will become increasingly important to manage electricity system variability without compromising competitiveness.

8. Recommendations & Conclusions

Industrial consumer-led flexibility requires coordinated action across policy, technology, and industry practices to unlock its full potential. This consolidated section presents prioritised, actionable recommendations that address solvable barriers while respecting structural constraints.

8.1 Policy Recommendations

Create enabling frameworks that align system needs with industrial realities:

- Implement sector-tailored market mechanisms that accommodate batch processes (e.g., EAF steel) and storage-limited operations (e.g., cement grinding). Replace generic baselines with process-aware measurement methodologies.
- Assess a targeted two-way wholesale electricity-price CfD for eligible energy-intensive industries. Building on UK Steel's proposal, Government should examine whether benchmarking prices against relevant European markets could improve competitiveness beyond steel. Any scheme should use transparent eligibility criteria, complement existing support and preserve incentives for demand-side flexibility. Incentivise sub-metering for large industrial sites and offer grants for real-time energy management systems to enable accurate flexibility quantification.
- Reinstate Triad-like peak demand incentives with simplified participation rules to reduce administrative burdens.
- Integrate viable ICLF plans for all the necessary players within Clean Power 2030 and wider industrial decarbonisation strategies, including CCS and hydrogen.

8.2 Technical Recommendations

Incentivise cost-effective and otherwise viable upgrades which convert theoretical potential into dispatchable capacity, for example:

- Process Modifications: Optimise batch cycles in EAF steel production for programmable delays between tap-to-tap operations; enable interruptible milling in clinker grinding when silo storage allows; retrofit steam accumulators in pulp/paper mills for thermal buffering.
- Digital Systems: Install half-hourly sub-metering on major loads (>1 MW) and deploy AI-driven Energy Management Systems for automated curtailment based on price and system stress forecasts.
- Storage Solutions: Expand clinker silos in cement, pre-heat buffers for scrap in steel, and thermal tanks in chemicals for temporal decoupling.

8.3 Industry Recommendations

To capture the value of flexibility, industrial operators will need to develop internal capability for strategic participation, alongside the necessary technical and organisational readiness. This includes understanding site-level constraints, investing in enabling systems, and engaging collectively with markets and policymakers.

Conduct site-specific flexibility audits to map technical potential, buffer capacities and opportunity costs.

- Invest in automation and granular monitoring to enable real-time decisions between production and flexibility revenue.
- Form sector consortia for joint market bidding, starting with high-potential sectors like pulp/paper and steel.
- Advocate through trade associations for stable incentives that justify capex in flexibility-enabling technologies.

Annex A - Technical Potential Across Industrial Sectors

This annex focuses on the technical potential for demand-side flexibility (DSF) across industrial sectors. While technical feasibility provides an upper bound, the realisable potential in practice will also depend on economic viability, operational risks, and market conditions, which are often more restrictive than technical constraints.

A.1 Cement

As noted in the earlier case study, cement manufacturing combines a largely inflexible high-temperature kiln process with more adaptable grinding and finishing operations. Evidence indicates that cement mills, raw mills, crushers, and packaging systems can be paused or rescheduled, allowing a portion of electricity demand to be shifted to different times of day without disrupting overall production. In some documented cases, approximately one-quarter of daily electricity demand can be shifted within a 24-hour period under controlled operational conditions.[34]

However, the kiln, which is central to clinker production, requires stable thermal conditions and continuous operation. Ramp rates are limited, and shutdowns risk significant efficiency losses as well as emission spikes during restart. As a result, cement sector flexibility is typically moderate in scale and limited to short-duration adjustments.

Emissions impacts are relatively constrained because the majority of emissions arise from the calcination process. Calcination refers to the chemical decomposition of limestone (calcium carbonate) into lime (calcium oxide) and carbon dioxide when heated at high temperatures in the kiln. [35] This process inherently releases CO_2 and accounts for a large share of total sector emissions, independent of fuel or electricity use.[36] Nevertheless, shifting electricity demand to periods of lower grid carbon intensity can deliver modest reductions in Scope 2 emissions. Operational trade-offs, including potential increases in NOx emissions under altered combustion conditions, require careful management.

A.2 Chemicals

The chemical sector's flexibility potential varies enormously between sub-sectors and companies. Batch production facilities offer scheduling flexibility, while continuous petrochemical plants are more constrained. Many chemical sites operate large, combined heat and power (CHP) systems, creating opportunities for internal dispatch optimisation between heat and electricity generation.[37]

[34] Mossie, A.T., Khatiwada, D., Palm, B. and Bekele, G. (2025) *Energy demand flexibility potential in cement industries: How does it contribute to energy supply security and environmental sustainability?* Applied Energy, 354, 124143. Available at:https://www.sciencedirect.com/science/article/pii/S0306261924019913

[35] World Resources Institute (2024) *Laying the foundation for cement and concrete decarbonization*. Available at: https://www.wri.org/update/laying-foundation-cement-and-concrete-decarbonization

[36] Global Cement and Concrete Association (n.d.) *Direct separation indirect calcination*. Available at: https://gccassociation.org/cement-and-concrete-innovation/carbon-capture-and-utilisation/direct-separation-indirect-calcination/

[37]Department for Business, Energy & Industrial Strategy (2018) *Final UK National Carbon Capture and Storage (NCCS) Roadmap*. Available at: https://assets.publishing.service.gov.uk/media/5a7f207340f0b62305b853c1/Final_NCA_Report_for_publication.pdf

Emerging electrification, particularly electrolysis for hydrogen, introduces highly controllable load that may operate dynamically in response to renewable availability. National Grid's Hydrogen Electrolyser Study in 2023 notes electrolysers can ramp to match renewables, offer balancing in industrial sites (limited by onsite demand), and boost capacity factors via flexibility.[38] Any electrolysed hydrogen can then act as an energy store to be used where and when it is needed, although its flexibility value is constrained by storage capacity, safety requirements, compression and transport costs, end-use demand, and conversion losses where hydrogen is subsequently used to generate electricity.[39]Oxygen from electrolysis may also have complementary uses.

Safety considerations, feedstock contracts, and process integration limit the depth of flexibility in some sub-sectors. Moreover, price-driven demand response may not align with emissions reduction if electricity remains partially fossil-based. The sector's decarbonisation trajectory will strongly influence the environmental impact of future flexibility potential.

A.3 Glass

Glass production is constrained by the continuous operation of melting furnaces. The thermal inertia of furnaces allows limited short-term modulation but not frequent shutdown. Electric boosting systems can provide partial load adjustment, while auxiliary systems can offer additional flexibility. On-site battery storage can provide a separate source of short-duration flexibility by charging when electricity is abundant or lower cost and discharging during high-price or system-stress periods. This can reduce the site's net grid demand without requiring a change in furnace operation.

Glass furnaces run continuously for 15-20 years at 1,500-1,600°C, resisting shutdowns; thermal mass allows minor adjustments but not frequent cycling, prioritising process stability.[40] Flexibility in glass is therefore incremental rather than transformational. As electrification of furnaces progresses, potential flexibility may increase, but process stability will remain paramount. Emissions implications depend on whether reduced electricity use is offset by fossil fuel combustion.

A.4 Pulp and Paper

Pulp and paper manufacturing stands out for its integrated energy systems and buffering capacity. Mechanical pulping consumes substantial electricity but can be scheduled around market signals due to storage of intermediate products. CHP systems and steam accumulators allow dynamic balancing between electricity and thermal demand.[41]

Evidence from Sweden demonstrates practical pulp and paper participation in balancing services. Arctic Paper Grycksbo has participated in the Swedish FCR-D Up and Down markets since 2020, using energy-intensive equipment including an electric boiler, pumps, a crusher and pulp-processing equipment. These

[38] National Grid Electricity Distribution (2023) *Hydrogen Electrolyser Study*. Available at: https://commercial.nationalgrid.co.uk/downloads-view-reciteme/639231
[39] National Grid ESO (2023) *Hydrogen as an Electricity System Asset*. Available at: https://www.neso.energy/document/354486/download
[40] British Glass (2024) *Net zero strategy: Progress Update 2024*. Available at: https://www.britglass.org.uk/sites/default/files/2024-12/British%20Glass%20-%20Net%20zero%20strategy%20update%20Nov%202024_0.pdf
[41] Ibn-Mohammed, T., Serrenho, A.C., Fujii, H., Acquaye, A. and Morrison-Saunders, A. (2025) *Decarbonising the UK pulp, paper and printing sector. Energy Economics.* Available at: https://www.sciencedirect.com/science/article/pii/S0140988325006991

services require substantial load changes within five seconds, demonstrating the value of fast automated control and suitable process integration. The UK sector shares similar technical characteristics, though participation levels differ.[42]

Because many pulp and paper facilities already utilise biomass and high-efficiency CHP, their electricity and heat supply arrangements differ from those in sectors relying predominantly on grid electricity. The emissions implications of flexibility participation should therefore be assessed on a site-specific basis, taking account of the carbon intensity of marginal grid generation, changes in CHP output, the need for alternative heat supply, and any associated changes in fuel use.[43]

A.5 Iron and Steel

As mentioned in earlier case study, steel production presents a dichotomy between traditional integrated routes and Electric Arc Furnace routes. EAF facilities are electricity-intensive and batch-oriented, allowing production scheduling flexibility. Load can be aligned with favourable electricity conditions, subject to labour and supply chain coordination.

Blast furnace operations are less adaptable due to continuous chemical reactions and safety constraints. However, auxiliary systems and oxygen production units offer limited flexibility.

A.6 Data Limitations and Evidence Gaps

Publicly available UK data provide sector-level energy consumption and emissions information but lack detailed operational metrics. Ramp rates, minimum stable load levels, and duration limits are rarely published. Measurement and verification methodologies vary, complicating cross-study comparison.

Industrial flexibility modelling often relies on engineering assumptions rather than empirical operational data. Greater transparency and collaboration between industry, regulators, and researchers would strengthen the evidence base

[42] Sympower (n.d.) *Arctic Paper Grycksbo: Paper Mill's Winning Strategy for Demand Response.* Available at: https://142257164.fs1.hubspotusercontent-eu1.net/hubfs/142257164/Gated%20Content/Sympower%20Case%20Study%20-%20Arctic%20Paper.pdf

[43] Department for Business, Energy & Industrial Strategy and Confederation of Paper Industries (2017) *Pulp and Paper Sector: Joint Industry-Government Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan*. Available at: https://assets.publishing.service.gov.uk/media/5a81fa7f40f0b6230269a302/pulp-paper-decarbonisation-action-plan.pdf

Annex B - Evidence Base: Literature and Global Comparisons

B.1 Methodological Approach

The literature review draws on peer-reviewed journal articles, consultancy analyses, industry association publications, UK Government statistics, and international benchmarking studies. Sources were identified through structured searches covering the period 1990-2025, with emphasis on 2019-2025. Keywords included industrial demand response, process flexibility, load shifting, energy-intensive industry decarbonisation and sector-specific flexibility studies.

The review also considers available datasets on industrial energy use and emissions, including sector-level electricity consumption, process versus combustion emissions, and operational metrics where available. However, a recurring limitation in the evidence base is the scarcity of publicly available data on ramp rates, minimum stable loads, response durations and plant-level operational constraints.

B.2 Industrial Energy Use and the Nature of Flexibility

UK energy-intensive industries account for a substantial share of industrial electricity consumption and direct greenhouse gas emissions. The structure of energy demand varies considerably across sectors. Cement and glass production are thermally dominated but include electricity-intensive grinding and auxiliary systems. Chemicals display heterogeneous energy profiles depending on feedstock and process configuration. Pulp and paper integrate electricity and steam systems extensively, often supported by combined heat and power. Steel production differs markedly between blast furnace–basic oxygen furnace (BF-BOF) routes and Electric Arc Furnace (EAF) routes.

Industrial flexibility operates across multiple temporal and technical scales. Fast response services involve automated modulation of motors or variable speed drives within seconds. Reserve services operate over minutes. Load shifting may involve rescheduling batch processes over hours or days.

Flexibility can be significantly enhanced by the availability of storage or buffers of:

- The fuel being used to drive the process (e.g. hydrogen)
- The heat used within the process (e.g. steam accumulators)
- The end product and/or intermediates (e.g. clinker silos, pulp storage tanks)

The attractiveness of providing flexibility can be encouraged by:

- Price volatility: time shifting to take advantage of periods of low electricity prices and to avoid periods of high prices (arbitrage). Where this is a driver, the larger and more frequent the price swings, the greater the potential value. However, it must be remembered that most industrial users see arbitrage as a secondary or tertiary business driver, and many are more likely to be adversely affected by high volatility due to impacts on core operations.
- Contract structures: arrangements with, for example, the system operator can provide greater clarity and revenue certainty for service provision. Traditionally, providers of fast frequency response services, such as pumped hydro, have been incentivised through contracts rather than price arbitrage.
- Low costs, risks and administrative barriers to participation: particularly the risk of penalties for non-delivery when called upon, which has been identified by industry as a major deterrent.

- Climate value: this may act as a driver in some cases but depends on the carbon intensity of marginal generation at the time of response and on interactions between electricity use and on-site fuel consumption.
- Industrial demand-side flexibility (DSF) can be monetised through both implicit and explicit mechanisms. Implicit mechanisms rely on exposure to wholesale and retail electricity price signals, while explicit mechanisms involve direct participation in ancillary services, capacity markets, or congestion management schemes; however, access to these markets remains uneven across regions, with more advanced frameworks typically observed in Northern and Western Europe. [44]

B.3 Systematic Literature Review Findings

Our limited study scope points to even greater gaps in documented cluster-scale impacts. Worldwide examples of significant ICLF remain scarce, with few documented cases achieving cluster-scale impact beyond isolated pilots (e.g., steel or chemicals clusters in Europe). This gap underscores the need for targeted data collection on cross-facility coordination and highlights opportunities for UK leadership through policy and demonstration projects.

Literature reveals a persistent gap between the theoretical potential and realised participation in demand-side flexibility (DSF). The three key barriers are: technical process constraints, economic revenue uncertainty and regulatory fragmentation. The UK electricity regime shows path dependency, with wholesale markets and network charging historically favouring supply-side balancing over demand response

[44] ENTSO-E (2021) *ENTSO-E Market Report 2021*. Available at: https://eepublicdownloads.entsoe.eu/clean-documents/nc-tasks/ENTSO_E_Market_report_2021_2e499deda8.pdf

B.4 Global Comparison of Market Mechanisms

International experience demonstrates that larger-scale flexibility is feasible where regulatory frameworks and digital infrastructure converge (Table 2).

Table 2: Comparison of DSF market arrangements in the UK, the United States and France

Feature	UK Context	International Leaders (USA/France)
Market Access	Evolving; historically biased toward supply-side participation, with DSR facing higher entry barriers	More Integrated; DSR is more systematically embedded across market layers
Aggregation	Emerging; limited by high transaction costs.	More established; aggregation is widely used to pool distributed loads and enable market participation.
Revenue Stability	Short-term; volatile balancing markets.	Long-term; stable capacity remuneration mechanisms.
Incentives	Weakened by removal of Triad, which provided strong locational and time-specific price signals for peak demand reduction.	Potentially more diverse; Some schemes (e.g. residential-focused programmes such as OhmConnect in California) use behavioural incentives, including real-time feedback and reward-based participation.[45]

Source: Author synthesis based on Ofgem, FERC, RTE and OhmConnect sources

Success hinges on regulatory clarity for aggregation, low-latency digital dispatch, and volatile price signals.

Delivering large-scale demand-side flexibility (DSF) remains a complex challenge despite its substantial technical potential. The literature consistently identifies the main barrier as the difficulty of capturing and monetising value streams for industry that also benefit customers, aggregators, and grid operators simultaneously.[46] Although regulatory and policy frameworks are evolving, progress remains uneven across regions. However, growing practical experience is enabling distribution and transmission system operators to integrate flexible demand resources with increasing confidence.

B.5 Case Studies in Practice

Within the limited international comparison feasible in this research's timescale, Enel X (an Enel subsidiary managing ~6.3 GW of demand flexibility worldwide) provides a notable example. Its business model focuses on large commercial and industrial consumers, where transaction costs are relatively low compared to

[45] However, these are typically small-scale relative to industrial demand response and should be understood as complementary rather than system-critic.

[46] International Energy Agency (2020) *Global Energy Review 2020*. Available at: https://www.iea.org/reports/global-energy-review-2020

potential value creation. The company identifies suitable customers, assesses operational flexibility, and implements tailored demand response strategies designed to minimise disruption to core operations, often without requiring upfront investment. Nevertheless, challenges persist, including customer scepticism, uncertainty about returns on investment, and complexities in allocating risks and savings. Though notable compared to other programs, Enel X's 6.3 GW capacity is significantly small relative to global flexibility needs.[47]

Case studies illustrate the effectiveness of this approach. For instance, a Kimberly-Clark manufacturing facility in Ontario achieved a 5.3 MW load reduction during demand response events without capital investment, generating roughly $325,000 annually and over $2.3 million since 2011. Similar applications, including the optimisation of distributed energy resources in residential portfolios and critical infrastructure, demonstrate the scalability of low-barrier participation models.[48]

Another first mover is Voltalis, which aggregates residential and small commercial loads, particularly electric heating systems. By exploiting thermal inertia, the company shifts demand without affecting user comfort. Control devices are installed at no cost, enabling customers to achieve electricity bill savings of up to 15 per cent while providing balancing services to the grid. After its reliability was validated by RTE (Réseau de Transport d'Électricité), France's Transmission System Operator (TSO) responsible for real-time grid balancing and procurement of ancillary services, Voltalis secured financial support from the European Investment Bank and expanded into additional distributed energy resources such as photovoltaic systems and electric vehicles. [49] [50]

Overall, evidence suggests that successful aggregation of DSF relies on effective participant recruitment, equitable distribution of value and overcoming barriers related to customer engagement. Although the sector remains at an early stage, advances in digital technologies, such as sensors, communications and data analytics, are enabling more scalable and economically viable models. Consistent and supportive regulatory frameworks will remain essential for sustained growth.[51]

B.6 Industrial Demand-Side Flexibility in the European Union

Energy-intensive industries in the European Union face major challenges in decarbonisation, including high capital expenditure and technological constraints. Demand-side flexibility offers a complementary pathway to enhance the business case for electrification by providing additional revenue streams and reducing emissions, provided there is equitable sharing of risk and reward for those industry participants who can and wish to participate. [52]

[47] Enel (n.d.) *Demand response & energy flexibility*. Available at: https://www.enel.com/company/retail/business-solutions/demand-response-energy-flexibility
[48] Enel X (n.d.) *Kimberly-Clark case study*. Available at: https://www.enelnorthamerica.com/solutions/case-studies/cs-kimberly-clark
[49] Voltalis (n.d.) *Demand response & grid stability*. Available at: https://voltalis.co.uk/blog/demand-response-grid-stability/
[50] European Investment Bank (2020) *EIB finances 150,000 smart boxes for electricity demand management*. Available at: https://www.eib.org/en/press/all/2020-016-eib-with-the-support-of-the-european-commission-is-financing-the-deployment-of-150-000-smart-boxes-to-actively-manage-electricity-demand
[51] International Energy Agency (2020) *Global Energy Review 2020*. Available at: https://www.iea.org/reports/global-energy-review-2020
[52] Council of the European Union (2023) *Commission Staff Working Document: Energy Storage - Underpinning a decarbonised and secure EU energy system (SWD(2023) 57 final)*. Available at: https://data.consilium.europa.eu/doc/document/ST-7390-2023-INIT/en/pdf

Aggregation of distributed energy resources is critical to enable industrial participation by addressing minimum bid size and response time requirements. It also helps spread operational risks across multiple assets. [53]

The technical potential for flexibility differs by industrial sector. Batch processes, such as electric arc furnaces in steelmaking and grinding processes in cement manufacturing offer high flexibility due to their interruptible nature. In contrast, continuous processes like aluminium electrolysis, glass production, and pulp and paper manufacturing require additional investment in storage or process modifications to unlock flexibility.

Beyond financial gains, DSF can contribute to emissions reductions, though impact varies by sector. Aluminium production (primary smelting) is electricity-intensive, so shifting loads to low-carbon grid periods via DSF reduces emissions substantially. In glass manufacturing, flexibility often increases gas use for heat recovery, partially offsetting electric savings.[54]

Despite these opportunities, high participation costs, operational risks and investment requirements remain major barriers. Strategies such as aggregation, integration with storage, and optimisation of non-core processes can improve economic viability. More broadly, strategic use of flexibility can enhance industrial competitiveness and support European decarbonisation objectives.[55]

[53] International Energy Agency (2022) *Unlocking the potential of distributed energy resources*. Available at: https://www.iea.org/reports/unlocking-the-potential-of-distributed-energy-resources

[54] European Aluminium (2023) *Net-Zero by 2050: Science-based Decarbonisation Pathways for the European Aluminium Industry*. Available at: https://european-aluminium.eu/wp-content/uploads/2023/11/23-11-14-Net-Zero-by-2050-Science-based-Decarbonisation-Pathways-for-the-European-Aluminium-Industry_FULL-REPORT.pdf

[55] European Environment Agency and ACER (2023) Flexibility solutions to support a decarbonised and secure EU electricity system. Available at: https://www.acer.europa.eu/sites/default/files/documents/Publications/EEA-ACER_Flexibility_solutions_support_decarbonised_secure_EU_electricity_system.pdf

Annex C: Stakeholder Engagement and Evidence Analysis

C.1 Overview of engagement

Two complementary strands of stakeholder engagement were used, as described below.

IDRIC thematic workshop on Consumer-Led Flexibility potential

- Purpose: To gather real-world evidence, experiences and perspectives on if, how, and where CLF might be implemented by industry and what policy evolution would be required to support adoption across sectors and sites (clusters and dispersed).
- Format and timing: In-person, half-day thematic workshop in January in Birmingham.
- Structure: Facilitated sessions structured around:
    - Welcome and scene-setting on CLF in the industrial context.
    - Discussion of current practice, incentives, regulations and barriers (operational, technical, commercial, financial).
    - Exploration of best practices, practical support and policy shifts needed to enable CLF.
    - Wrap-up summarising insights and next steps.
    - The workshop built on previous roundtables/forums and reflected on the implications of the Modern Industrial Strategy.
- Participants: 27 individuals from 23 organisations
    - Industry associations and representative bodies
    - Research and innovation organisations
    - Government and regulators
    - Regional and cluster bodies
    - Policy and consultancy organisations

Targeted case studies and in-depth conversations

- Purpose: To explore specific sectoral and organisational perspectives in more detail, test emerging findings from the workshop and understand operational, technical and policy constraints relevant to CLF and broader industrial flexibility.
- Approach: Semi-structured one-to-one interviews conducted online and case-study discussions. These conversations built on workshop insights and allowed deeper exploration of sector-specific issues.

C.2 Selection of participants

Workshop participants

Participants were selected through a purposive sampling approach to ensure:

- Sectoral coverage: Representation from major energy-intensive sectors, either directly or via their trade associations.
- Stakeholder type diversity: Inclusion of industry, government, regulators, researchers, regional bodies and policy/consultancy organisations with an interest in CLF and industrial flexibility.
- Geographic spread: Representation from key industrial regions and clusters, covering both cluster and dispersed sites.

Initial invitations were issued by the IDRIC policy workshop team, drawing on:

- Existing networks from prior IDRIC activities, roundtables and forums on industrial decarbonisation and flexibility.
- Recommendations from core industry bodies.
- Prior engagement in related policy processes.

Potential participants were screened to avoid over-representation from any single organisation or sector and to ensure a balance of technical, operational, commercial and policy expertise relevant to CLF.

Case study and in-depth interview participants

Case study partners were selected to:

- Represent strategically important sectors for UK industrial decarbonisation and flexibility (steel and minerals/cement).

Within each organisation, interviewees were identified based on their role and expertise in industrial decarbonisation, energy policy, operations and/or flexibility.

C.3 Data collection and analysis

Workshop data

- Data collected:

- Facilitated discussions (audio-recorded where consent was given, plus detailed written notes).
- Live note-taking of key points, examples and policy suggestions raised during each agenda item.

- Analysis approach:
  - Thematic analysis of discussion notes and transcripts to identify recurring themes, points of consensus and areas of disagreement on:
    - Current flexible actions and practices.
    - Drivers and barriers (operational, technical, commercial, financial).
    - Incentives, regulations and policy shifts needed to enable CLF.
  - Mapping of issues by:
    - Sector (e.g. steel, minerals, chemicals, glass, etc.)
    - Site type (cluster vs dispersed)
    - Theme (e.g. market design, network charges, metering and data, operational constraints, risk and finance).
    - Triangulation with existing literature and policy documents: workshop findings were cross-checked against published evidence on industrial flexibility and decarbonisation. Where discrepancies arose (e.g. on barrier severity or policy impacts), we examined whether differences reflected site-level experience vs. national assumptions and retained stakeholder evidence where it highlighted current practice or emerging constraints not yet captured in the literature, while flagging topics requiring further analysis.

Case study and interview data

- Data collected:
  - Semi-structured one-to-one interviews conducted online (detailed notes).
  - Any supplementary materials provided by participants (e.g. briefing notes, public reports).
- Analysis approach:
  - Thematic coding of interview content, aligned with the workshop-derived framework on CLF drivers, barriers and policy needs.
  - Cross-case comparison to identify:
    - Common barriers and enablers across sectors.

        - Sector-specific constraints or opportunities for CLF.
        - Divergent views on policy priorities, market mechanisms, or technology pathways.
    - Integration with workshop findings to refine overall conclusions and policy recommendations on CLF.

C.4 Limitations

The engagement and analysis have several important limitations:

- Sample size and coverage:
    - While the workshop included a broad range of organisations, it does not represent all UK energy-intensive industries or all relevant stakeholders.
    - Case studies focus on a small number of strategic sectors and organisations; findings are illustrative rather than statistically representative.
- Temporal context:
    - Engagement took place in January-February 2026, during a period of rapid policy and market change
    - Views expressed may have shifted since the engagement period.

These limitations are acknowledged in interpreting the findings and formulating recommendations. Further engagement, particularly with under-represented sectors and regions, would be valuable in future work.

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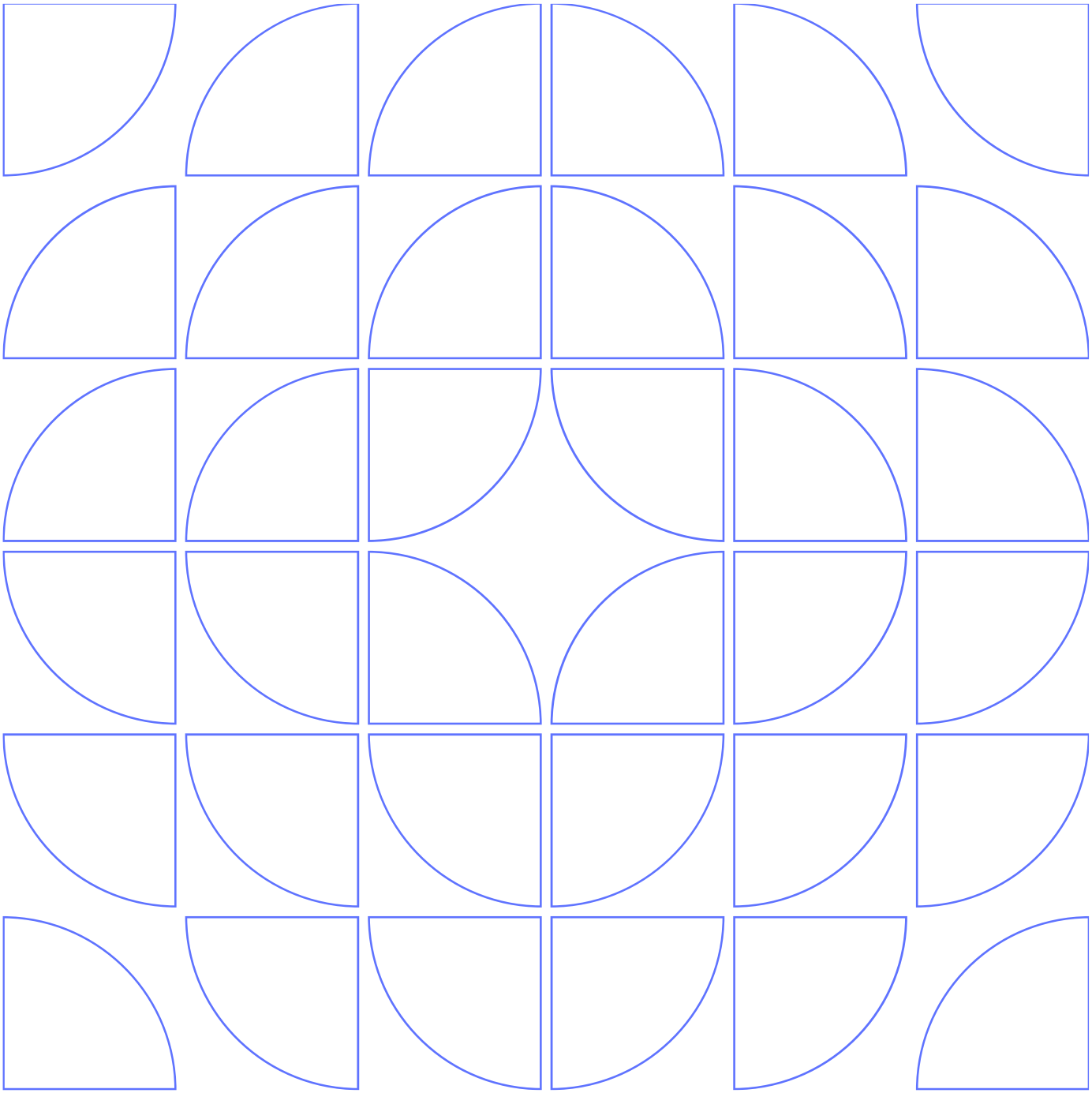
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