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Report

Metallurgical flexibility

Enabling the aluminium and steel sectors for demand response

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Author

This report was written by Fausto Zaccaro, Policy Officer at Sandbag.

About Sandbag

Sandbag is an independent think tank dedicated to advancing data-driven, evidence-based climate policies that drive rapid and effective emissions reductions in Europe and beyond. With deep expertise in carbon markets, industry decarbonization, and energy transitions, we leverage our in-house research capacity, sophisticated data modelling, and visualization tools. We design and advocate for robust climate solutions that ensure everyone can contribute to, and benefit from, the fight against climate change.

contact@sandbag.be

sandbag.be

LinkedIn

@sandbag_eu

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The paradigm shift

Energy-intensive industries have historically operated in a context where their primary energy needs have typically been met without significant competition from other users, enjoying seemingly unlimited access to abundant primary energy. In addition, industry could buy energy at competitive prices and supply could comfortably meet its commercial and technical needs without impacting other users.

Climate change and the dramatic development in Europe's energy landscape in recent years have made industrial decarbonisation all the more urgent. While the continent managed to survive two consecutive winters without heavy reliance on Russian fossil fuels, the energy crisis highlighted the **finite nature of energy resources**. During these periods, price signals and awareness-raising campaigns have been crucial in reducing demand and the EU to rethink its energy consumption and procurement strategies.

Meanwhile, the drive to decarbonise industry through **electrification is likely to strain Europe's electricity grids**. A prime example is the planned deployment of electrolysers to produce hydrogen for the decarbonisation of energy-intensive industries such as fertilisers, refining and steel, which will put further pressure on the electricity grids that host these facilities.

Consider the steel industry: with the planned introduction of hydrogen-based Direct Reduced Iron (DRI) and Electric Arc Furnace (EAF) plants in Europe by 2030, partially replacing the conventional and polluting Blast Furnace (BF) – Basic Oxygen Furnace (BOF) route to make flat products, annual electricity consumption is expected to reach 165 TWh, more than doubling the current consumption of 75 TWh (55 TWh coming from the grid and 20 TWh coming from combusting blast furnace gases). By 2050, this demand is expected to rise to around 400 TWh.[1]

Without concurrent investment in renewable generation capacity to meet the increased electricity demand from electrified industrial processes, the energy transition could be in jeopardy. Many developers of new electrification projects, such as electric kilns, smelters or electrolysers, do not plan to complement these power-hungry investments with additional renewable energy to at least match the capacity of these new facilities. In absence of a commensurate acceleration in the deployment of renewables, recent achievements in the penetration of renewables and the phasing out of coal could

[1] Eurofer (2024) - The European steel industry recommendations on Industrial Demand Side Response

stagnate or even be reversed. At present, Europe's energy transition pace is mainly geared towards the substitution of fossil-based electricity, while efficiency improvements have effectively kept EU-wide electricity consumption stable, offsetting marginal sectoral gains in non-intensive electrification. However, the introduction of electrolysers to support hydrogen-based technologies will increase electricity consumption rates. In the absence of accelerated deployment of renewables, these facilities **operating round the clock risk cannibalising fossil-free electricity deployed for the wider power grid users to benefit from**, leading to a higher average carbon intensity of the grid and a greater need for thermal power capacity to balance demand.

In addition to the generation issue, the **saturation of the electricity infrastructure** is also a serious problem, which is already having an impact on limiting the deployment of renewable capacity. Although the current issue is on the supply side, the introduction of electrolysers and other electro-intensive equipment would further strain grids, requiring investment not only in expansion but also in maintenance to deal with congestions.

Overall, the energy-intensive nature of electrified industrial processes will place an additional burden on the expansion and decarbonisation of electricity grids. While the most straightforward solution to this dual challenge would be to channel more investment into expanding renewable generation capacity and upgrading infrastructure networks to ensure efficient transmission and distribution, there is a more economical alternative that can cost-effectively enhance the integration of renewables into the grid.

Most carbon-intensive industries adjust output to their customer demand and/or market prices, resulting in continuous production or idle periods. **While fossil-based technologies have limited impact on other energy users (operating as ‘energy islands’), electrification would force industries to interact more with other users on the grid and compete for finite resources (i.e. renewables)**. In the traditional business model, where production simply follows customer demand, the transition to electrified assets would put equal pressure on networks regardless of the daily fluctuations between congested and non-congested periods within their 24-hour operating regime.

Unlike buildings and transport, which have more variable electricity consumption patterns, industries typically maintain a stable and consistent energy usage profile throughout their operating cycles. **Production cycles that do not match the availability of renewable electricity create prolonged and**

unnecessary reliance on thermal power plants to provide back-up capacity, potentially increasing the carbon intensity of the grid and the price of electricity.

To prevent the lock-in of avoidable investment in energy infrastructure (both thermal capacity and grid reinforcement) that only addresses a few congested hours of the day, a better strategy is to **shift loads to times when the grid is less congested**. To achieve this, current and future electro-intensive industries will need to **re-evaluate their operating models to become more responsive to grid conditions**, reducing or turning off their loads during ‘peak’ hours, and concentrating their processes during ‘off-peak’ hours.

Demand response

Balancing the grid of the future

Ensuring a real-time balance between supply and demand is a major engineering challenge in the power industry. When demand is low, the grid operator instructs generators to reduce production, but when demand increases, it sometimes exceeds the limits of generation facilities. This fluctuation in consumption throughout the day leads to over- and under-consumption, requiring capital investment in generation capacity and grid infrastructures to prevent blackouts. **To protect against grid failure, thermal capacity is often overbuilt as an insurance policy**, requiring expensive and carbon-intensive system operating reserves to maintain security of supply, creating opportunities for marginal generators to exercise market power and command prices.[2]

The acquisition and maintenance of generation capacity represents a significant proportion of the total costs in the electricity industry. **Generators often operate at partial load** to provide necessary ancillary services (such as frequency regulation, voltage control etc.),[3] which places an additional burden on the economics of electricity generation and distribution. In particular, generators providing regulation services (such as small, continuous adjustments in generation to maintain grid frequency[4] within a specified range) and spinning reserves (additional capacity available to meet sudden surges in demand that takes a few minutes to come online) incur significant costs. These costs include **efficiency losses due to ramping,** environmental costs due to **increased emissions**, and **increased wear and tear** resulting in higher operating and maintenance costs.[5]

Meanwhile, congestion in transmission and distribution networks remains a long-standing problem, requiring costly infrastructure upgrades and reinforcements, with **network expansion typically matching**

[2] Jessoe K. & Rapson D. (2013) – Commercial and industrial demand response under mandatory Time-of-Use electricity pricing.
[3] Ancillary services are support functions traditionally provided by thermal power plants to maintain the stability and reliability of the grid. They also include black start capability, which is the ability of a power plant to start up and operate independently without external power support, enabling it to restore the grid after a complete blackout.
[4] Grid frequency measures the number of cycles per second in alternating current and indicates the balance between electricity supply and demand. Maintaining a constant frequency is critical to the stable operation of the power system. Any deviation, if not corrected promptly, can lead to power quality problems, equipment damage and even blackouts.
[5] Kirby B. & Milligan M. (2009) – Capacity requirements to support inter-balancing area wind delivery.

incremental increases in demand.[6] However, the uncertain nature of long-term load forecasts makes anticipatory network reinforcements **economically inefficient**.[7]

Over the past decade, the development of distributed renewable energy systems has created new challenges for grid stability which involve rapid adaptation to changing generation mixes. While renewable energy sources offer environmental benefits, their output is difficult to predict.[8] Fluctuations in wind and solar generation can disrupt the stability of the electricity system, creating technical and economic hurdles for grid operators.[9] **As the share of renewables increases and the generating units change from a few large ones to many smaller ones, the higher complexity and cost of managing back-up thermal generation, makes the traditional model of supply following demand obsolete**.[10]

The **environmental impact of thermal back-up capacity** has become more apparent with the increasing integration of renewables into grids. When renewables production is high, thermal generation units need to operate at lower levels or cycling baseload units (i.e. frequently starting and stopping a traditionally steady-state, high-output plant in a way that deviates from its intended operation, or operating it at widely varying output levels), which is much less efficient and **can compromise the environmental benefits of renewables**, as fuel consumption and emissions per unit of electrical output tend to increase at lower operating levels.[11]

Dynamize consumption via demand response

Managing wind and solar generation in the traditional way of simply meeting the demand would require large (thermal) generation reserves to manage output fluctuations and ensure system security. To avoid this and, instead, optimise the use of renewable energy, additional non-fossil balancing and ancillary services in the form of storage technologies and demand response programmes will be required.[12]

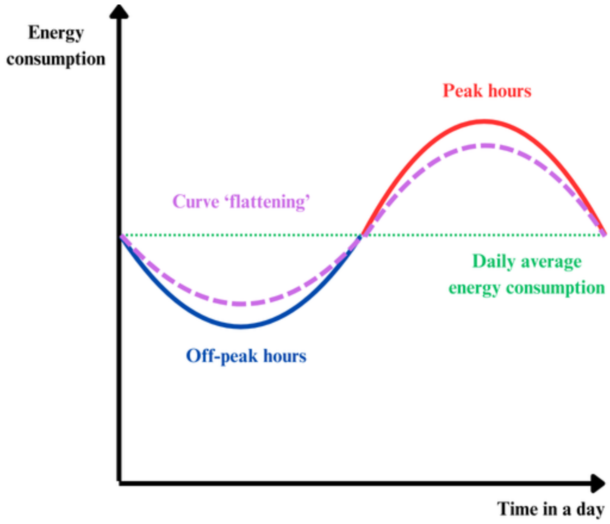
[6] Ea Energy Analyses (2012) – Managing congestion in distribution grids: Market design consideration.
[7] Jamasb T. & Marantes C. (2014) – Electricity distribution networks: Investment and regulation, and uncertain demand.
[8] Eftekharnejad S., Vittal V., Heydt G.D., Keel B. & and Loehr J. (2013) – Impact of increased penetration of photovoltaic generation on power systems.
[9] Finn P., Fitzpatrick C., Connolly D., Leahy M., Relihan L. (2011) – Facilitation of renewable electricity using price based appliance control in Ireland's electricity market.
[10] Strbac G. (2008) – Demand side management: Benefits and challenges.
[11] Paterakisa N. G., Erdinç O. & Catalão J. P.S. (2017) – An overview of demand response: Key-elements and international experience.
[12] Eceee (2017) – Why is demand response not implemented in the EU? Status of demand response and recommendations to allow demand response to be fully integrated in energy markets.

Demand Response (DR) is a type of grid balancing strategy developed during the 1970s oil crisis that involves shifting consumption patterns throughout the day to temporarily reduce or increase normal energy use, unlocking potential energy savings.

In such programmes, electricity consumers are encouraged to adjust their consumption in **response to external signals**, which may be prices from day-ahead or intraday markets, or notices from network operators to take measures to reduce or avoid consuming energy.[13] Customers participate by responding to incentives from network or utility operators to adjust their electricity use, shifting it where possible to periods of low demand. This approach requires the provision of **financial incentives to consumers in proportion to their flexibility** in adjusting their energy consumption. [14]

Effective DR programmes can play a key role in **reducing overall electricity generation during peak demand periods**, thereby **reducing reliance on costly and emission-intensive power plants**, while supporting the decarbonisation of electricity grids (commonly known as ‘flattening’ the curve). These programmes achieve this by adjusting energy consumption to benefit both utilities and consumers, taking into account end-user needs and system losses.

Demand response programmes have been developed to **take advantage of the predictable and cyclical nature of electricity demand**. When DR is implemented with a market-based approach, even small amounts of demand response can displace the most expensive peaking units.[15]



[13] Stede, J., Arnold, K., Dufter, C., Holtz, G., von Roon, S., & Richstein, J. C. (2020) – The role of aggregators in facilitating industrial demand response.
[14] Stanelyte, D., Radziukyniene, N., & Radziukynas, V. (2022) – Overview of demand-response services.
[15] O'Connell, N., Pinson, P., Madsen, H., & O'Malley, M. (2014) – Benefits and challenges of electrical demand response: A critical review.

FIGURE 1 – FLATTENING THE CURVE

The interaction between supply and demand, facilitated by the exchange of price and demand information, provides a **cost-effective alternative to indiscriminate grid investments** for balancing the electricity system at the Transmission System Operator (TSO) level and addressing local constraints at the Distribution System Operator (DSO) level.[16,17] DR programmes are useful to **optimise the use of existing power plants** and minimise the need to operate them at inefficient part load (i.e. operating at a reduced capacity compared to its baseload output, allowing it to be available for quick response when needed: spinning reserve), particularly in electricity systems dominated by fossil and nuclear fuels.

Participation in electricity markets through demand response offers many benefits, including reducing supplier and locational market power by allowing demand to respond to price fluctuations. This limits the ability of large generators to manipulate wholesale electricity prices, leading to **lower average wholesale prices and reduced price volatility**, thereby improving the long-term efficiency of capacity planning.

Another advantage of DR programmes is the **absence of major technological barriers**, as much of the necessary communication and monitoring technology is already available through advanced metering infrastructure.[18] However, continuous demand response across all electricity demand sectors will require investment in communication, control and monitoring infrastructure.

Types of demand response

Demand response can take the form of either **incentive-based** or **tariff-based** programmes, commonly referred to as **explicit** and **implicit** DR respectively.

Explicit demand response

In such programmes, customers are offered **payments to deliver a specified amount of load reduction (compared to the usual pattern) over a specified period of time or face financial penalties for non-compliance** to an agreed DR service. On some occasions, the grid operator even has remote access to the

[16] In the electricity network, TSOs maintain the overall stability of the system by managing the supply and demand of centralised energy sources and overseeing power lines across large regions, while DSOs focus on local power lines, delivering electricity to end-users and integrating decentralised energy sources into their networks.
[17] Eurelectric (2015) – Everything you always wanted to know about demand response.
[18] Callaway, D., & Hiskens, I. (2011) – Achieving controllability of electric loads.

machine of the installation providing DR. This type of DR directly competes with supply in wholesale, balancing and ancillary service markets through aggregators[19] or large consumers, providing a resource comparable to generation and earning similar prices.[20] Consumers receive direct payments to adjust their consumption on demand, either by consuming more or less, individually or through an aggregator.

It should be noted that different circumstances of energy use require different response capacities (maximum amount of electricity a participant can reduce or increase), response rates (how quickly a participant can adjust their electricity consumption) and default energy levels (baseline electricity consumption levels). Therefore, rewards and penalties need to be objectively differentiated based on a consumer's responsiveness and the specific conditions in which they operate.[21]

When it comes to individual medium and large consumers, specific DR schemes called **'curtailable load programmes' incentivise participants to turn off specific loads or interrupt their energy use in response to calls from the utility provider**, where the consumer responds to events threatening grid reliability, or trading those load reductions in the market.[22] These programmes can be managed through bidding, allowing consumers to actively participate in the electricity market by submitting bids to load reduction auctions. Large customers can participate directly in the wholesale market, typically using sophisticated load management tools and strategies to assess whether is more profitable to operate in current market conditions or cash in the financial reward for curtailing load (i.e. temporarily reducing or stopping production).[23] Some DR programmes may also include an agreement whereby the grid operator, with the consent of the end-user, can remotely control specific loads and directly reduce demand, bypassing the plant operator.

Implicit demand response

Implicit DR involves consumers **voluntarily reducing load by responding to economic signals**, such as time-varying electricity prices or network tariffs that reflect the value or cost of electricity and transport

[19] Aggregators are service providers that combine the capacity of multiple end-users to create a flexible resource that offers curtailable energy consumption to grid operators for demand response programmes.
[20] Joint Research Centre (2017) – Why is demand response not implemented in the EU? Status of demand response and recommendations to allow demand response to be fully integrated in energy markets.
[21] Stanelyte, D., Radziukyniene, N., & Radziukynas, V. (2022) – Overview of demand-response services.
[22] Rocky Mountain Institute (2006) – Demand Response: An Introduction.
[23] Paterakisa N. G., Erdinç O. & Catalão J. P.S. (2017) – An overview of demand response: Key-elements and international experience.

at different times. These prices are part of the consumer's supply contract and allow consumers to respond to price differences without any formal commitment.[24]

Time-of-use (TOU) tariffs provide an incentive to reduce consumption during peak hours, when electricity demand is highest by charging more expensive rates during this period and cheaper rates during off-peak hours, when electricity demand is lower and the proportion of renewables is often higher in the energy mix, thereby encouraging "night-valley filling" behaviour. The aim of TOU tariffs is to minimise the difference between peak and off-peak demand, thereby reducing the need for generator to operate at lower levels.[25] This pricing structure is typically tiered, reflecting average market conditions based on the time of day electricity is consumed, and does not take into account the day-to-day volatility of supply costs. A typical TOU structure includes peak, off-peak and potentially shoulder-peak rates, each applicable during specific time periods defined by the utility.[26]

Critical peak pricing (CPP) is an event-based tariff scheme aimed at reducing peak loads, typically for larger commercial and industrial consumers. It involves applying higher electricity rates during extraordinary peak demand events, superimposing a time-independent high rate on existing TOU or flat rates. CPP tariffs are triggered by system criteria, such as reserve unavailability (when one or more power plants are unable to provide the reserve capacity they have committed to the grid operator) or extreme weather conditions causing unexpected supply and demand variations. Relevant contracts outline the maximum number of days per year considered critical and the number of periods during which the CPP rate applies.[27]

Real-time pricing (RTP) is a pricing scheme where energy prices are updated hourly or more frequently, exposing customers directly to fluctuations in wholesale energy market costs or changes in locational or zonal marginal prices.

When **comparing explicit and implicit DR programmes**, the former provides a valuable and reliable operational tool for system operators to adjust load and solve operational problems such as congestion management or unexpected generation outages, while the latter encourages consumers to reduce or shift

[24] Eurelectric (2015) – Everything you always wanted to know about demand response.
[25] O'Connell, N., Pinson, P., Madsen, H., & O'Malley, M. (2014) – Benefits and challenges of electrical demand response: A critical review.
[26] Rocky Mountain Institute (2006) – Demand Response: An Introduction.
[27] Wolak, F. A. (2007) – Residential customer response to real-time pricing: The Anaheim critical peak pricing experiment.

their electricity consumption with no predictable impact on the grid.[28]. Implicit DR is also unable to support regional demand-side services for TSOs and DSOs because it lacks geographic targeting, nor does it provide a controllable DR loads for the system as a whole as it is impossible to precisely quantify participating load reductions. However, compared to explicit DR, implicit DR has a much wider market reach, especially in the residential sector, as end-users would be subject to dynamic pricing programmes in the retail market. Therefore, both forms are needed to allow all consumers to fully participate and benefit from its flexibility.[29]

DR as an ancillary service

Loads participating in **DR programmes can often provide ancillary services**, although this requires **much shorter notification times and higher technical requirements** for speed and measurement accuracy compared to planned load reductions. The electrical load needs to be dispatched more frequently and accurately, quickly correcting real-time imbalances, and must be able to change frequency or voltage, not just shut down.[30] In addition, ancillary services are typically required throughout the day, not just at peak times, and requirements vary by location and technology.

A prime example of DR strategy implemented as ancillary services is regulation, which involves the rapid and controlled adjustment of power input by the end-user to maintain a constant grid frequency. This requires loads with special characteristics, such as the ability to switch on and off quickly or large variable speed drives[31], to deviate from their normal operating setpoint without altering their overall power input in the long run. Regulation is the most expensive and financially rewarding ancillary service, where the preferred loads are those that incur in minimal additional costs to be ready to respond, including investment in load preparation, efficiency losses and opportunity costs associated with eventual output adjustments.[32]

[28] Some energy-intensive industries operate on-site power plants to meet their needs. When these facilities reduce their own energy consumption, the surplus is sold to the grid.
[29] Joint Research Centre (2017) – Why is demand response not implemented in the EU? Status of demand response and recommendations to allow demand response to be fully integrated in energy markets.
[30] Shen, B., Ghatikar, G., Lei, Z., Li, J., Wikler, G., & Martin, P. (2014) – The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges.
[31] Some loads are designed to run only at full power or not at all. However, the use of variable speed drives allows machines to run at variable speeds rather than just at full capacity.
[32] Shoreh, M. H., Siano, P., Shafie-khah, M., Loia, V., & Catalão, J. P. S. (2016) – A survey of industrial applications of Demand Response.

Caveats for industries

Industrial consumers offer significant potential for DR strategies to better integrate renewables and efficiently invest in grid infrastructure. **Energy-intensive industries operate power-hungry loads and offer significant balancing potential for grid operators, who in turn would benefit from being able to develop significant sources of flexibility while negotiating with fewer customers**. The high energy component of operating costs drives operators to optimise efficiency and automate industrial processes by default, meaning that these assets often already have an energy management system in place,[33] including sensors, metering technologies and dedicated operators, making them **virtually ready to participate in DR programmes**.[34]

In addition, **energy-intensive industries typically participate in wholesale** rather than retail electricity markets and often have **direct contacts with TSOs** due to their significant electricity consumption.[35] This enables them to negotiate flexibility solutions tailored to their specific processes and markets. These direct contacts can also help to **tailor the financial incentives**, whether through direct payments or discounts during less congested hours, in a way that the industrial consumer can consider in its plant design to adapt to RES intermittency, justifying the **inclusion of flexibility at plant design stage**.[36]

However, **industrial applications are often designed for peak efficiency**, with machines typically operating at high – if not maximum – capacity and maintaining constant loads throughout their operating hours.[37] This leaves operators with **limited scope to adjust power consumption** without violating operational constraints. In addition, the unique processes of each sector make it difficult for grid operators to develop a universal method for assessing their DR potential.[38]

In addition, a huge challenge for TSOs in engaging industry to include them in DR strategies is the **variability of their activities throughout the year**. The flexibility margins industry can offer fluctuates based on **annual production cycles**. Industrial production, especially of basic materials, is not constant

[33] Under the revised Energy Efficiency Directive, large EU energy users with an annual consumption of more than 85 TJ are required to implement an energy management system.
[34] Shafie-Khah, M., Siano, P., Aghaei, J., Masoum, M. A. S., Li, F., & others. (2019) – Comprehensive review of the recent advances in industrial and commercial DR.
[35] Paterakis, N. G., Erdinç, O., & Catalão, J. P. S. (2017) – An overview of Demand Response: Key-elements and international experience.
[36] O'Connell, N., Pinson, P., Madsen, H., & O'Malley, M. (2014) – Benefits and challenges of electrical demand response: A critical review.
[37] Paulus, M., & Borggrefe, F. (2011) – The potential of demand-side management in energy-intensive industries for electricity markets in Germany.
[38] Stanelyte, D., Radziukyniene, N., & Radziukynas, V. (2022) – Overview of Demand-Response Services: A Review.

throughout the year but varies due to factors such as economic cycles, demand shifts, inventory management, weather conditions, climate disasters and geopolitical events. Production can also experience longer cycles influenced by wider economic trends, and if the output is a globally traded commodity, changes in one region can affect production decisions elsewhere. This cyclical and unpredictable nature makes it difficult for industrial producers to operate consistently at full capacity throughout the year and provide reliable sources of flexibility.

To participate in DR programmes, industrial operators would need to modify production schedules to shift power consumption to periods of low demand. However, implementing DR in some industrial facilities is more complex than for other non-integrated loads, such as in the residential or commercial sector, due to the complex reliability management required. While temporary interruption of one or more processes can result in significant load reductions, **technical constraints specific to the industrial process may affect long-term efficiency** (i.e. see the example of primary aluminium in the next section), making DR economically inefficient in some cases. Service interruptions can lead to production stoppages or violate daily operational constraints such as process criticality[39], number of available production lines, production targets and inventory limits. In addition, **some processes are interdependent and difficult to isolate**, interrupt or shut down separately (e.g. in steelmaking, basic oxygen furnaces cannot operate without charging iron in its molten form).[40]

Determining the financial rewards for industrial operators to participate in DR programmes can be complex, as the costs of interrupting production may outweigh the financial benefits of these programmes.[41] The **components of a cost-benefit analysis** are often vague and not clearly agreed, making it difficult to calculate the benefits of DR.[42] There are uncertainties and challenges in valuing the avoided thermal power generation, where inadequate compensation can limit profitability and discourage the development of industrial DR.[43]

In practice, the **need for advance planning in industrial schedules** introduces uncertainty into the real-time capabilities of DR. The need for industry to prepare ahead of adjustment events can limit the effective flexibility of DR, making its response time uncompetitive vis-à-vis flexible thermal generation.

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[39] Process criticalities determine the priority levels assigned to different processes, taking into account factors such as safety, environmental impact, production output or financial impact.

[40] Shoreha, M. H., Siano, P., Shafie-khah, M., Loia, V., & Catalão, J. P. S. (2016) – A survey of industrial applications of Demand Response.

[41] Lunt, P., Ball, P., & Levers, A. (2014) – Barriers to industrial energy efficiency.

[42] Shoreha, M. H., Siano, P., Shafie-khah, M., Loia, V., & Catalão, J. P. S. (2016) – A survey of industrial applications of Demand Response.

[43] Paterakis, N. G., Erdinç, O., & Catalão, J. P. S. (2017) – An overview of Demand Response: Key-elements and international experience.

For example, a load theoretically capable of instantaneous adjustment may not be considered as such if it requires a notice period of a few hours.[44]

Another constraint on industrial participation in flexibility programmes is the priority given to maintaining stable **relationships with off-takers**. Industry must ensure that product quality is not affected by DR participation and that delivery schedules are met. Depending on the operational status of the plant, industries participating in DR programmes could veto the activation of flexibility. In such cases, not only will the industrial operator be penalised, but the TSO will also have to find replacement capacity to ensure grid stability.

Finally, from an **asset ownership perspective**, industrial customers may be reluctant to relinquish control of their production processes to external entities for fear of compromising sensitive data, and management may fail to choose the most rational options, resisting changes in behaviour or organisational structures.[45]

All in all, large-scale, energy-intensive operations based on a single electro-intensive process (e.g. an electrolyser or an electric kiln) are still generally best suited for DR, although many processes are critically dependent on precise scheduling and timing. To adjust energy use profitably, industrial consumers would typically need to be equipped with **automated decision-making systems** that take into account the technical constraints of their processes and the alternative energy sources available to assess whether to participate in each DR event and calculate the reward required to trigger the response.[46]

[44] O'Connell, N., Pinson, P., Madsen, H., & O'Malley, M. (2014) – Benefits and challenges of electrical demand response: A critical review.
[45] Stede, J., Arnold, K., Dufter, C., Holtz, G., von Roon, S., & Richstein, J. C. (2020). The role of aggregators in facilitating industrial demand response: Evidence from Germany.
[46] Ding, Y. M., Hong, S. H., & Li, X. H. (2014) – A demand response energy management scheme for industrial facilities in smart grid.

The case of aluminium

Technology

To explore the interaction between the aluminium sector and DR strategies, we focus on primary aluminium smelting. Unlike other energy-intensive upstream processes, such as alumina refining and carbon anode baking, which are fossil-based and not yet commercially electrified, **primary aluminium smelting is highly electro-intensive**. Secondary aluminium production from pre- and post-consumer scrap is mostly gas-based, with only a few instances of electricity-based induction furnaces.

Before testing configuration scenarios, it is important to understand how aluminium is extracted from alumina and the critical role electricity plays in this process.

Primary aluminium among the most electro-intensive basic material, with **the electrolysis required to produce one tonne consuming between 13 and 16 MWh**, making electricity the largest single operating cost in aluminium production. The century-old Hall-Héroult process, the standard method for smelting aluminium, has been improved and made more efficient over the decades. However, there is limited scope to further reduce the raw cost of electrical components in existing plants, which already operate at peak design efficiency. Even with the advent of new, more efficient plants that can reduce electricity consumption to 12.3 MWh per tonne of aluminium,[47] the chemical process remains inherently energy intensive, with the theoretical minimum energy requirement for electrolysis, according to the rules of thermodynamics, still a substantial 9.03 MWh per tonne.[48]

The core principle of aluminium smelting remains the same: the electrolysis of alumina (aluminium oxide refined from bauxite) in a bath of molten salt (cryolite) using a carbon anode. Aluminium is smelted in ‘pots’ where a direct current is passed through the carbon anode in the molten salt bath, which contains alumina and other elements that facilitate the conductivity of the electrolysis process. The electric current separates the aluminium from the oxygen, depositing the molten metal at the bottom of the pot. Alumina and electricity are continuously added, the aluminium metal is periodically tapped, and the carbon anodes

[47] Hydro (2019) – The world's most energy-efficient aluminium production technology.

[48] Choate, W. T., & Green, J. A. S. (2003) – U.S. Aluminum Production Energy Requirements: Historical Perspective, Theoretical Limits, and New Opportunities.

are periodically replaced as they are consumed to keep the process going. The pots are usually connected in series to form a 'potline' of tens or even hundreds of pots. The total power consumption for a potline can be hundreds of MWh and a smelter may have several potlines. Current controlled at the potline level flows through the pots, and the voltage set for each pot balances the current to efficiently separate aluminium from alumina while minimising energy waste.

The constraint of a controlled electricity feed

Aluminium smelters operate with a specific energy consumption per tonne of aluminium produced, controlled by both current and voltage, together with a design heat loss that is critical to maintaining the thermal balance of the pots. **Approximately half of the energy consumed in an aluminium reduction cell is used to produce metal, while the other half must be lost as waste heat to maintain the delicate balance of the cell**. **Operation must remain within a very narrow window around a setpoint; any deviation from this requires compensatory action to avoid potentially catastrophic damage to the process**. Any period of energy use below the setpoint will result in an energy deficit, as the heat loss rate remains unchanged and the cell is no longer thermally balanced.

Each pot is monitored for chemical and thermal balance and operation, and can be individually controlled by adjusting the gap between the carbon anode and the bottom of the pot. This adjustment controls the immersion of the anode in the molten aluminium, which in turn controls the incoming voltage in the molten salt bath and the smelting rate of alumina. Maintaining thermal balance is critical and two methods of maintaining or restoring it:

1. Modulate the current above or below the setpoint (while maintaining the setpoint voltage);
2. Modulate the voltage above or below the setpoint (while returning to the setpoint current).[49]

Because cryolite is corrosive in its molten form, maintaining thermal balance means that the cryolite must remain liquid in the centre but frozen at the pot walls. A frozen layer of cryolite protects the walls of the pot from corrosion. If the cryolite melts at the pot wall, it would corrode the pot; if it freezes at the centre, it would crush the anode and also damage the pot. It is therefore essential to be able to adjust the incoming voltage by varying the depth of the anode in the molten aluminium.

[49] Enpot - Energy modulation of aluminium smelters

The pots operate at temperatures in excess of 900°C to maintain the aluminium and cryolite around the anode in a molten state, requiring continuous operation to prevent power loss and solidification of the cryolite in the pots. **Perturbations in the thermal balance caused by variations in electrical power input can lead to flaring of molten metal, increased emissions of PFCs and increased power requirements per smelted unit**. Although not inherently dangerous, these disturbances increase the carbon and electricity intensity of the primary aluminium produced until peak efficiency is restored, which can take up to a week, increasing operating costs during the recovery period.

The smelting process uses electricity throughout, with the equipment typically operating at 95% or more efficiency with minimal disruption to the electrical system.

The **production of aluminium is directly linked to the amount of electricity used**, meaning that any reduction in electrical power will result in a reduction in metal output. Furthermore, any change in current at the potline level will result in a directly correlated increase or decrease in production. On the other hand, an increase in voltage will restore heat but will not increase production. However, if the power input is reduced by more than 10% for a short period of time, electrolysis stops and so does production. As smelters are usually designed to operate at full capacity, if the power input is reduced, the plant would not normally be able to compensate for the loss of output in a hypothetical subsequent recovery period.

The options available to traditional smelters for varying power input

Historically, the electrolytic process in aluminium production has focused on maintaining a stable load profile with minimal hourly or daily variation to maximise efficiency and stability. While annual consumption varies with global aluminium market demand, resulting in the addition or removal of pots, hourly process variation remains minimal. Although the addition/removal of pots can change the output level of a smelter, it is a long process and should be ruled out as DR measure. However, occasional adjustments, reductions or interruptions are required due to process problems or equipment maintenance. The frequency and necessity of these interruptions depends on the potline design and specific operating conditions, with some interruptions planned hours in advance and others requiring only a few minutes' notice. Although immediate curtailment is rarely required, these natural process interruptions could be coordinated with the power system during peak load periods to improve reliability.

Effective communication between the aluminium plant and power system operators is essential to avoid dramatic shifts in baseload generation due to short-term load interruptions.

Existing smelters, without the need to retrofit specific technologies, can provide DR in two ways. Firstly, as long as the process is stable, small reductions can be achieved by reducing the potline input voltage, thereby reducing power consumption. This reduction can be achieved in a matter of seconds without shutting down the production line, although a recovery period may be required to return to normal or above normal operation. Secondly, shutting down the entire potline can significantly reduce power consumption. However, the duration of this shutdown is critical and can typically only be maintained for a short period of time, in the order of 30 minutes maximum, depending on the specific limitations of the plant. Plants with multiple potlines can rotate these interruptions, allowing a longer total reduction in power consumption.

A study prepared by Alcoa for the US Department of Energy[50] summarised the following technical limitations that apply to the amount and variability of electrical power supplied to a pot:

- The power supplied to the smelting process should not exceed the capacity of the electrical equipment. Similarly, the power used in the process should not fall below the minimum level that the electrical supply equipment can effectively handle.
- Changes in power should not be too rapid or dramatic as this could disrupt the stability of the smelting reaction. The system needs time to adjust to variations in heat input to prevent chemical imbalances, equipment stress and safety hazards.

The average power input must be kept constant over several hours to avoid complete melting or freezing of the cryolite.

For a primary aluminium smelter to participate in flexibility programmes, it would inevitably have to reduce production during the curtailment periods. Whether these volumes could be recovered later depends on the technology used.

Traditional smelters typically operate close to maximum capacity, meaning that any reduction during curtailment is permanently lost. This loss would need to be compensated to incentivise operator

[50] U.S. Department of Energy. (2009) – Providing reliability services through demand response: A preliminary evaluation of the demand response capabilities of Alcoa Inc.

participation. Conservative scenarios reflect this with configurations that either curtail both potlines simultaneously or rotate curtailment between them. While both approaches result in the same output loss and require similar compensation, potline rotation allows for a less drastic but longer reduction period.

Deeper modulation technologies

Recent technological developments suggest that more flexible production management is now possible. Systems such as the METRIC power control system, developed by the German aluminium company Trimets, and technologies from Enpot claim to achieve much higher levels of flexibility. These have been demonstrated at sites in Essen, Germany and Tiwai Point, New Zealand.

Enpot's technologies, which are specifically designed to retrofit pots, enable smelters to interact more efficiently with grid operators. These technologies enable significant, sustainable reductions in power consumption without completely shutting down production, while ensuring that any lost production can be recovered later, preventing permanent output losses. In addition, as the pots operate in a balanced energy mode, no energy deficit is built up during periods of reduced output. This eliminates the need for a recharging phase when returning to the setpoint, and the specific energy consumption per tonne of aluminium remains unaffected after modulation down. Enpot's system maintains thermal equilibrium during power reductions, allowing smelters to operate indefinitely at lower power levels or to adjust power up and down multiple times depending on energy availability.[51]

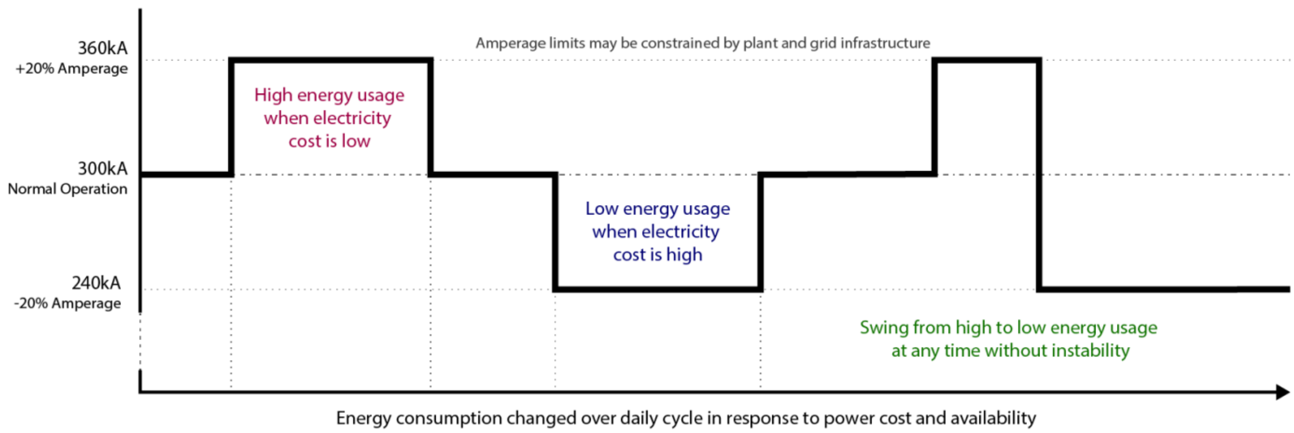

FIGURE 2 – DAILY MODULATION OF POWER CONSUMPTION USING ENPOT TECHNOLOGY
SOURCE – ENPOT

[51] Enpot - Energy modulation of aluminium smelters

Findings

General assumptions

Smelter's annual capacity (2 potlines)		**200,000 t (100,000 per potline)**
Smelter's hourly output (95% capacity, 8322 hours per year)		**24t/h (12t/h per potline)**
Electricity consumption to produce one tonne of primary aluminium	Direct electricity consumption (smelting)	14 MWh/t
	Indirect electricity consumption (rectification from AC to DC, auxiliary equipment, tapping etc…)	1 MWh/t
	Casting into billets	0.125 MWh/t
	Total	**15.125 MWh/t**
Smelter's hourly electricity consumption		**363 MWh (181.5 MWh per potline)**

Scenarios

The scenarios are categorised as follows:

- **Conservative**: This category represents traditional smelters operating close to 100% capacity, meaning that any production loss due to energy curtailment cannot be recovered. Such smelters have fragile systems that are slow to recover to peak efficiency, meaning that in addition to production losses, the operator would incur in increased energy and carbon intensity during the recovery period.
- **Enpot's assumptions for a traditional smelter**: Enpot's assumption is that a traditional smelter operates at 95% capacity, allowing any production loss due to energy curtailment to be recovered by temporarily increasing capacity to 100%. Similar to the conservative category, these smelters experience a fragile, slow recovery of peak efficiency, resulting in higher energy and carbon intensity during the recovery period
- **Enpot's application**: In this category, Enpot technologies are applied in a traditional smelter (although Enpot notes that some overhaul may be required to achieve optimal results for the retrofit). In this scenario, the smelter can increase or decrease the energy input to the pots without affecting the thermal balance or production efficiency, allowing allegedly undiscriminating flexibility in energy use.

Conservative – 10% power reduction for 1 hour

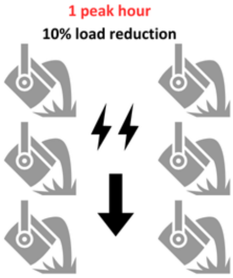

FIGURE 3 – 10% LOAD REDUCTION BELOW THE SETPOINT TO BOTH POTLINES FOR 1 HOUR

In this conservative scenario, the power input to both potlines is reduced by 10% for **1 hour**, avoiding the consumption of **36.3 MWh**.

As a result of the power curtailment, primary aluminium production would not stop, but the hourly output would be reduced by 10%, resulting in a loss of **2.4 tonnes** of output during the power curtailment period that would not be recovered.

Conservative – 5% power reduction for 2 hours via potline rotation

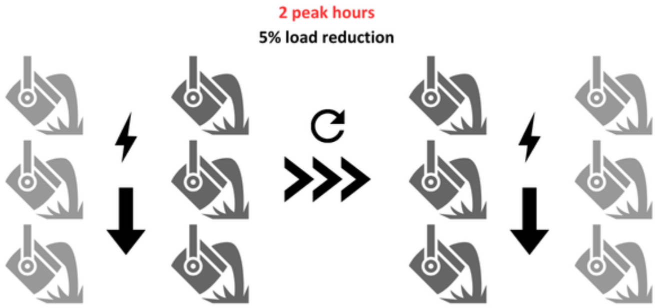

FIGURE 4 – 5% LOAD REDUCTION BELOW THE SETPOINT FOR 2 HOURS VIA POTLINE ROTATION

In this scenario, the power input to just one potline is reduced by 10% for 1 hour (5% total load reduction). This reduction would avoid the consumption of 18.15 MWh per hour. At the end of this hour, the operator resumes normal power to the curtailed potline and reduces power to the second potline by 10% for a further hour, avoiding the consumption of a further 18.15 MWh per hour. Over the course of the entire **2 hour** curtailment period, the operator would have saved a total of **36.3 MWh**, which is the same energy savings as the previous scenario, but less intense and twice as long.

As a result of the curtailment, primary aluminium production would not stop, but the hourly output would be reduced by 5% over the two hour period, again resulting in a loss of **2.4 tonnes** of output during the curtailment period that would not be recovered.

Enpot's assumption of a traditional smelter – 20% of power reduction

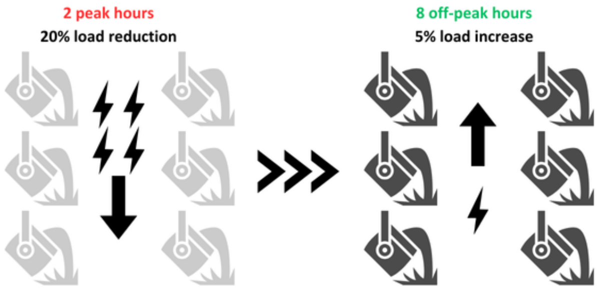

FIGURE 5 – 20% LOAD REDUCTION BELOW THE SETPOINT TO BOTH POTLINES FOR 2 HOURS. 5% LOAD INCREASE ABOVE THE SETPOINT FOR 8 HOURS TO RECOUP OUTPUT LOSSES

In this scenario, the power input to both potlines is reduced by 20% for **2 hours**, avoiding **145.2 MWh** of power consumption (72.6 MWh per hour). Despite this reduction, aluminium production continues, but at a 20% lower rate, resulting in a total production loss of **9.6 tonnes** over the curtailment period (4.8 tonnes per hour).

Since Enpot assumes that a traditional smelter without retrofitted flexibility technologies can recover the lost aluminium production by increasing output by 5% above the normal setpoint, by doing so over **8 hours**, the smelter can recover the unproduced tonnes. This recovery process would increase the hourly electricity consumption from 363 MWh to 381.15 MWh, an increase of 145.2 MWh over the 8 hour period.

Enpot's assumption of a traditional smelter – 10% power reduction for 4 hours via potline rotation

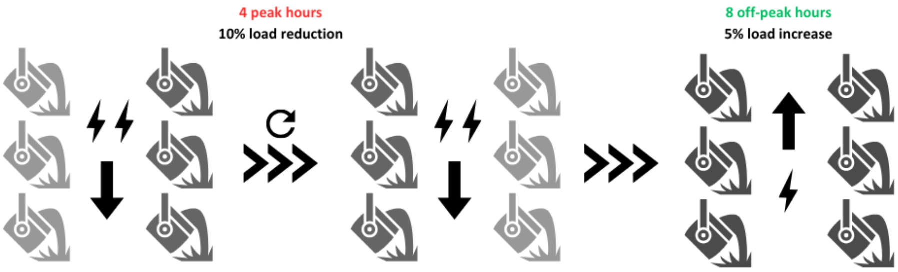

FIGURE 6 – 10% LOAD REDUCTION BELOW THE SETPOINT FOR 4 HOURS VIA POTLINE ROTATION. 5% LOAD INCREASE ABOVE THE SETPOINT FOR 8 HOURS TO RECOUP OUTPUT LOSSES

In this scenario, the power input to one potline is reduced by 20% for 2 hours, avoiding 72.6 MWh of power consumption (36.3 MWh per hour). By alternating which potline is reduced, through potline rotation, the smelter avoids a total of **145.2 MWh** over **4 hours** (36.3 MWh per hour). This achieves the same energy savings as the previous scenario, but is spread over twice the time and at a lower intensity.

The smelter's primary aluminium output would decrease by 10%, resulting in a total loss of **9.6 tonnes** over the 4 hours of curtailment (2.4 tonnes per hour). To recover this lost output, the smelter could overload both potlines by 5% above setpoint during the off-peak hours for **8 hours**. This would increase the hourly electricity consumption from 363 MWh to 381.15 MWh, an additional 145.2 MWh over the 8 hour period.

Enpot's application – 20% power reduction for 8 hours

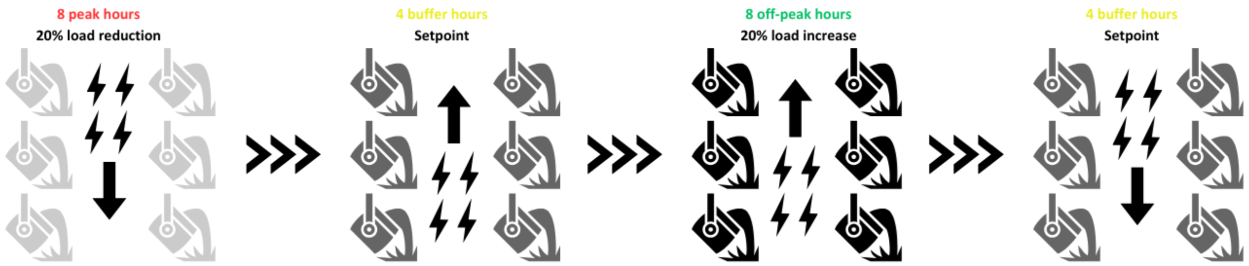

FIGURE 7 – 20% LOAD REDUCTION BELOW THE SETPOINT TO BOTH POTLINES FOR 8 HOURS. LOAD BACK TO SETPOINT FOR 4 HOURS. 20% LOAD INCREASE ABOVE THE SETPOINT TO BOTH POTLINES TO RECOUP OUTPUT LOSSES. LOAD BACK TO SETPOINT FOR 4 HOURS

In this scenario, the full capabilities of Enpot technologies are utilised, allowing a smelter to adjust its electricity consumption by ±20%, which directly affects primary aluminium production by the same percentage over a daily cycle. This flexibility can be driven by factors such as energy prices, grid carbon intensity or even a flexibility agreement with the grid operator. However, as Enpot notes that it is unclear how long a smelter can operate above or below the setpoint, the day is divided into three cycles to maintain some degree of feasibility: 8 hours with energy consumption 20% below the setpoint, 8 hours at the setpoint and 8 hours 20% above the setpoint.

During peak hours, the smelter could reduce energy input to both potlines by 20% for **8 hours**, avoiding **580.8 MWh** of electricity consumption (72.6 MWh per hour) and reducing primary aluminium output by **38.4 tonnes** (4.8 tonnes per hour). To compensate for the lost output, the operator could increase energy input by 20% above the setpoint during off-peak hours for **8 hours**, increasing hourly consumption from 363 MWh to 435.6 MWh and using the 580.8 MWh previously saved.

The remaining 8 hours when the smelter is operating at setpoint could be split into two 4-hour blocks. These hours would act as a buffer between peak and off-peak hours, allowing the smelter to find an interim equilibrium and operate under conditions that are less costly, congested and carbon intensive than peak hours, but not as cheap, decongested or renewable as off-peak hours.

Summary of the results

	Conservative		Enpot's assumptions		Enpot's application
	Both potlines	*Potline rotation*	*Both potlines*	*Potline rotation*	*Both potlines*
Energy saved	36.3 MWh	36.3 MWh (18.15 MWh per hour)	145.2 MWh (72.6 MWh per hour)	145.2 MWh (36.3 MWh per hour)	580.8 MWh (72.6 MWh per hour)
Curtailment period	1 hour	2 hours	2 hours	4 hours	8 hours
Loss of output (no recoup)	2.4 tonnes	2.4 tonnes	/	/	/

Considerations

As smelters have traditionally been designed for flat and stable operation at constant output levels, adaptation of existing equipment requires working within the unique characteristics of each smelter in terms of the occurrence and persistence of thermal balance perturbations, and may require capital upgrades to increase responsiveness (e.g. Enpot or METRIC technologies).

In balancing markets, **smelters are considered a last resort because potlines take time to return to peak efficiency after load curtailment**. Although thermal balance can be quickly restored, energy efficiency cannot, and the timeframe for achieving peak efficiency varies from plant to plant. During this recovery period, a smelter may be able to maintain the same volume output, but, as noted, with higher electricity consumption and higher emission intensity per tonne.

Therefore, primary aluminium production using traditional smelters cannot participate in daily load shifting programmes, but it could participate in occasional load curtailment events throughout the year, conservatively around five events per year. For this participation to be viable, the **compensation from the grid operator must exceed the profit associated with the amount of primary aluminium otherwise produced and offset the additional operating costs incurred while the potlines recover peak energy efficiency**.

Instead of providing regular balancing services, traditional smelter operators could still participate in ancillary services by rapidly varying electrical power consumption to provide regulation services to the power system. This can be done without significantly reducing aluminium production, as long as the average power input remains constant over several hours. However, there are risks associated with providing regulation services, including reduced process efficiency, stability and increased maintenance costs.

That being said, while traditional smelter operators may lack day-to-day flexibility, what they do already today is to adjust volume outputs based on primary aluminium demand by phasing out pots or integrating them into production lines. However, this adjustment cannot interact with day-to-day electricity fluctuations. In theory, a smelter operator could deliberately phase out pots to reduce power consumption ahead of seasons of high electricity consumption and potential higher demand for thermal power plants to provide back-up capacity. To achieve this, however, they would have to be compensated by the grid operator for the volumes not produced during this period, and the compensation required would still be very high due to the costs involved.

Ultimately, it is **impossible to generalise a compensation scheme for DR that would be fair and equitable to all smelter operators**. While market prices for primary aluminium and electricity are known, other operating costs and profit margins are specific to each plant. Although electricity represents the largest component of operating costs, variables such as feedstock procurement, labour and maintenance costs make it difficult to estimate profit margins. Even if operating costs were standardised, efficiencies vary from plant to plant. Therefore, establishing financial compensation for systematic load reductions that offset losses – as an alternative to bidding for each event – **requires bilateral negotiations between smelter and grid operators, which should not be too difficult as only a handful of smelters remain in operation in Europe**.

The case of steel

Technology

For the steel sector, the focus is on the Direct Reduced Iron (DRI) - Electric Arc Furnace (EAF) route using hydrogen from electrolysis as the reducing agent for ironmaking. While natural gas-fired shaft furnaces for ironmaking and arc furnaces for steelmaking are, on their own, well-established technologies with decades of commercial use, their combination as the hydrogen-based (or 'hydrogen-ready', waiting for H2 to become cheaper) DRI – EAF route has emerged as the main alternative to the conventional, carbon-intensive Blast Furnace (BF) – Basic Oxygen Furnace (BOF) route. While replacing the BF - BOF route with the DRI - EAF route, using hydrogen produced from renewable energy, can dramatically reduce GHG emissions and, according to the IEA's emissions threshold, potentially produce near-zero emission steel (<0.4 tCO2 per tonne of steel), questions arise about its operability vis-à-vis the power grid and its impact on carbon intensity.

Installing electrolysers that virtually operate 24/7 into the grid to supply hydrogen to steelmakers – or other industries for that matter – would not be compatible with the transformation of electricity systems, as these machines would draw huge amounts of electricity at all times. Although hydrogen will have to meet strict regulations certified as 'renewable' according to the EU's RFNBO[52] standard (at least from 2030[53]), operators could still produce 'low-carbon' or 'not-so-low-carbon' hydrogen with varying levels of thermal power as long as there is guaranteed demand or direct use.

Although there is no industrial experience of direct reduction with more than 80% hydrogen in the reducing agent, there are significant risks associated with integrating new H2-based DRI-EAF routes into the grid. These machines could divert RES intended for domestic and commercial use, requiring more thermal generators to provide baseload capacity. This cannibalisation could undermine efforts to deploy the RES needed to decarbonise the grid and complicate efforts to phase out thermal plants, which would become increasingly important to ensure grid stability in scenarios of higher electricity demand.

[52] Renewable Fuels from Non-Biological Origin
[53] Sandbag (2023) – EU criteria for green hydrogen: How they could increase reliance on thermal power and hijack the energy transition.

Fortunately, **the DRI-EAF route offers greater flexibility in the feedstock ratio between virgin iron ore and ferrous scrap**, overcoming the technical limitation of the BF-BOF route of 15-20% scrap in the charge. This flexibility allows DRI-EAF operators to use higher proportions of scrap – pre- and post-consumer – reducing the need for virgin iron ore, which **not only reduces resource intensity and is in line with circular economy principles, but also offers potential electrical flexibility**. **By operating the electrolyser and shaft furnace to produce DRI only during off-peak hours, steelmakers can stockpile cold DRI for use during peak hours when only the EAF and secondary metallurgy equipment are operating**. In this way, steelmakers can incorporate varying proportions of DRI and scrap depending on stock levels and impurity tolerances of the steel grades required by customers, providing some flexibility to the power system.[54]

Unlike primary aluminium smelting, which requires maintaining a delicate balance of temperature and chemical composition in the molten bath, EAF steelmaking is generally less complex. In EAF steelmaking, the anodes are not immersed in the feedstock and melting takes place in a confined high-heat zone, allowing easier process control and restarts. This is in contrast to aluminium smelting, where anodes are continuously consumed and the molten bath requires precise control. Although EAFs require careful management of power, oxygen, coke and lime injection and slag control to achieve the desired steel properties, **the overall process is less sensitive to abrupt changes in power supply**.

[54] A more detailed description of the operation of the DRI-EAF route and the flexibility provided by the technologies is provided in the Annex.

Findings

General assumptions

Tonnes of DRI output per hour (shaft furnace of 1 million tonnes annual capacity)		125t/h[55]
Tonnes of crude steel output per hour (EAF hourly capacity matching the shaft furnace)		125t/h
Electricity consumption	Electrolyser to produce 60 Kg of hydrogen required to produce 1 tonne of DRI	3.18 MWh
	Shaft furnace to produce 1 tonne of DRI (indirect consumption)	0.1 MWh
	Electrolyser + Shaft furnace	3.28 MWh/t
	EAF to produce 1 tonne of crude steel	0.45 MWh/t
	Hot-roll one tonne of crude steel	0.12 MWh/t
	EAF + Rolling	0.57 MWh/t
	Total	3.85 MWh/t
	Electrolyser + Shaft furnace hourly electricity consumption	410 MWh
	EAF + Rolling hourly electricity consumption	71.25 MWh
Assumed time after the restart before regular output volumes are restored	DRI (residence time)[56]	30 minutes
	EAF (tap-to-tap time)[57]	

Scenarios

For a steel plant using a hydrogen-based DRI-EAF route, altering the scrap – both pre- and post-consumer – content to participate in flexibility programmes departs from a baseline scenario where 1 tonne of DRI is required to produce 1 tonne of Hot-Rolled Coil (HRC). In this scenario, the steel production process includes 0.17 tonnes of scrap per tonne of steel, representing 15% of the total feedstock. This results in 1.17 tonnes of feedstock, not including alloying elements, lime, oxygen or any additional coke.

The simulated scenarios include three **static configurations (30;50;80% scrap)** where the feedstock proportions in the finished steel product remain constant over a 24-hour period. In addition, there is also **a dynamic configuration (30+50% scrap)** where the scrap content is increased during the hours when the electrolyser and shaft furnace are offline. This allows the stored cold DRI to be used to produce more steel, delaying the need to restart the electrolyser and shaft furnace.

[55] Teri (2021) – Green steel through hydrogen direct reduction: A study on the role of hydrogen in the Indian iron and steel sector.
[56] US Department of Energy (2000) – Ironmaking processes: Alternatives screening study.
[57] Primetals Technologies (2023) – Remarkable performance figures from Primetals Technologies' electric steelmaking plants in China.

EAFs can be shut down and restarted relatively quickly without compromising the equipment. However, the shutdown would result in a loss of steel production and financial compensation would be required to offset the resulting loss of revenue. Therefore, **a more extreme scenario considers the shutdown of the EAF and post-EAF processes in addition to the electrolyser and shaft furnace**. It shows minimal energy savings that can be achieved in addition to the feedstock flexibility option, but these are outweighed by the significant loss of revenue from reduced output.

To simplify the scenarios, it is assumed that the electrolyser and shaft furnace are located in close proximity, minimising the need for energy to compress, transport, store or decompress the hydrogen before it is fed into the shaft furnace. In addition, storage options such as hydrogen storage to extend the operating time of the shaft furnace or batteries to extend the operation of both the electrolyser and the shaft furnace when not drawing energy from the grid are not considered.

Static – 30% scrap

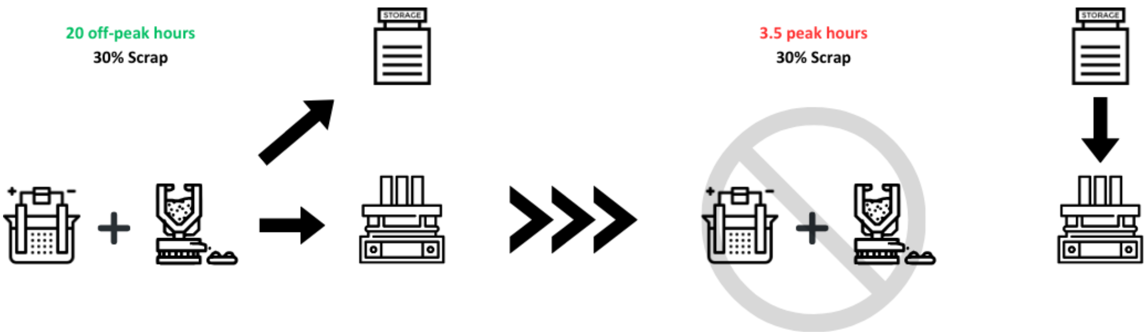

FIGURE 8 – THE STEEL PLANT RUNS FOR 20 HOURS WITH 30% SCRAP IN FINISHED PRODUCT WHILE STORING COLD DRI, ALLOWING THE ELECTROLYSER AND SHAFT FURNACE TO BE SHUT DOWN FOR 3.5 HOURS

When steel contains 30% recycled content, the feedstock to produce 1 tonne of HRC consists of approximately 0.83 tonnes of DRI and 0.34 tonnes of scrap. In this scenario, the shaft furnace would need to produce 103.75 tonnes of DRI per hour to meet the EAF demand and ensure continuous crude steel production followed by uninterrupted HRC rolling.

At full capacity, the shaft furnace would produce a surplus of 21.25 tonnes of DRI per hour, which could be stored cold for future use. Over 20 hours of operation, at 30% scrap content, this surplus would amount to 425 tonnes of DRI.

Maintaining the same recycled content, shutting down the electrolyser and shaft furnace would allow the EAF to continue producing crude steel for 4 hours, using the excess DRI accumulated over the previous

20 hours. As both the electrolyser and the shaft furnace require 30 minutes to return to normal output after start-up, they could be shut down for approximately **3 hours and 30 minutes**. During this time the equipment could be cooled, purged and sealed in preparation for restart.

When the electrolyser and shaft furnace are restarted after 3 hours and 30 minutes, the shaft furnace would resume DRI production just before the stored cold DRI is exhausted. This approach would allow uninterrupted steel production while saving **1.44 GWh** of energy during the shutdown period (410 MWh per hour).

Static – 50% Scrap

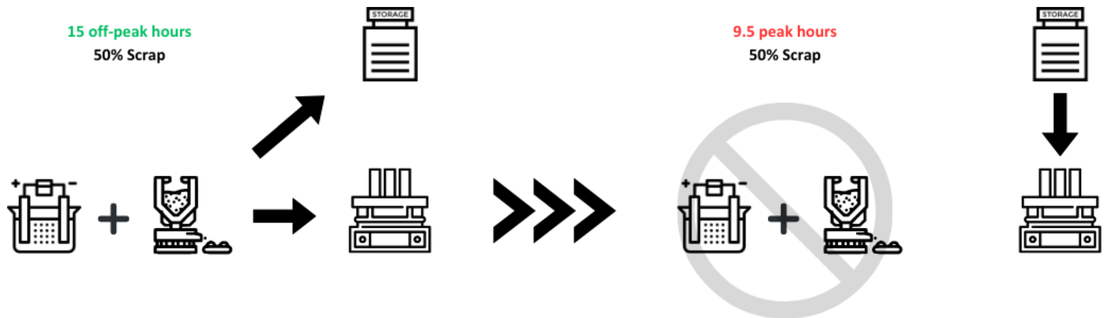

FIGURE 9 – THE STEEL PLANT RUNS FOR 15 HOURS WITH 50% SCRAP IN FINISHED PRODUCT WHILE STORING COLD DRI, ALLOWING THE ELECTROLYSER AND SHAFT FURNACE TO BE SHUT DOWN FOR 9.5 HOURS

When steel contains 50% recycled content, the feedstock to produce 1 tonne of HRC consists of approximately 0.6 tonnes of DRI and 0.57 tonnes of scrap. In this scenario, the shaft furnace must produce 75 tonnes of DRI per hour to meet the EAF's requirements for continuous crude steel production and uninterrupted rolling of HRC.

At full capacity, the shaft furnace would produce a surplus of 50 tonnes of DRI per hour, which could be stored for future use. Over 15 hours of operation at 50% scrap content, this surplus would accumulate to 750 tonnes of DRI.

Maintaining the same recycled content, shutting down the electrolyser and shaft furnace would allow the EAF to continue producing crude steel for 10 hours, using the excess DRI stored during the previous 15 hours. As the shaft furnace and electrolyser require 30 minutes to return to normal output after start-up, they could be shut down for approximately **9 hours and 30 minutes**, which would be used to cool, seal and purge the equipment in preparation for restart.

When the electrolyser and shaft furnace are restarted, the shaft furnace would resume DRI production just before the stored DRI is exhausted. This approach would allow the steel plant to maintain uninterrupted production while saving **3.9 GWh** of energy during the shutdown period (410 MWh per hour).

Static – 80% Scrap

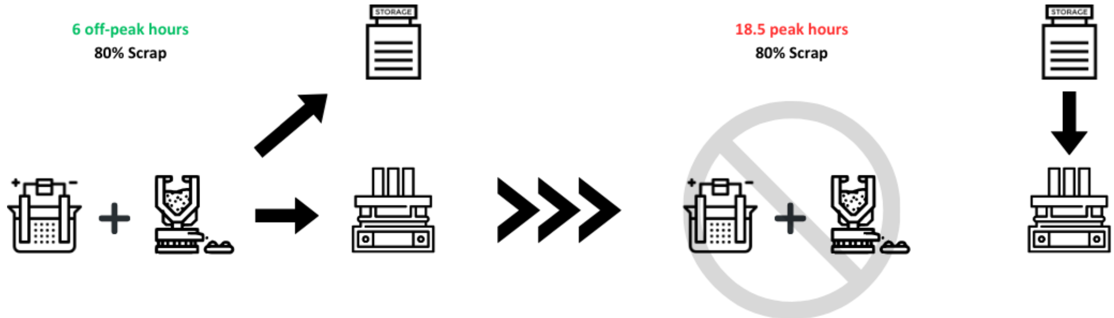

FIGURE 10 – THE STEEL PLANT RUNS FOR 6 HOURS WITH 80% SCRAP IN FINISHED PRODUCT WHILE STORING COLD DRI, ALLOWING THE ELECTROLYSER AND SHAFT FURNACE TO BE SHUT DOWN FOR 18.5 HOURS

For steel containing 80% recycled content, the feedstock to produce 1 tonne of HRC includes approximately 0.23 tonnes of DRI and 0.94 tonnes of scrap. In this scenario, the shaft furnace would need to produce 28.75 tonnes of DRI per hour to meet the EAF requirements for continuous crude steel production and uninterrupted HRC rolling.

At full capacity, the shaft furnace would produce a surplus of 96.25 tonnes of DRI per hour, which could be stored for future use. After 6 hours of continuous operation at 80% scrap, this surplus would be 553.5 tonnes of DRI.

Maintaining the same recycled content, shutting down the electrolyser and shaft furnace would allow the EAF to continue producing crude steel for approximately 19 hours, using the excess DRI accumulated over the previous 6 hours. As the shaft furnace and electrolyser require 30 minutes to return to normal output after start-up, they could remain shut down for approximately **18 hours and 30 minutes**, during which time the equipment could be cooled, purged and sealed for restart.

Once restarted after 18 hours and 30 minutes, the shaft furnace would resume DRI production just before the stored DRI is exhausted. This process allows the steel plant to maintain uninterrupted production while saving **7.59 GWh** of energy during the shutdown period (410 MWh per hour).

Dynamic – 30/50% scrap

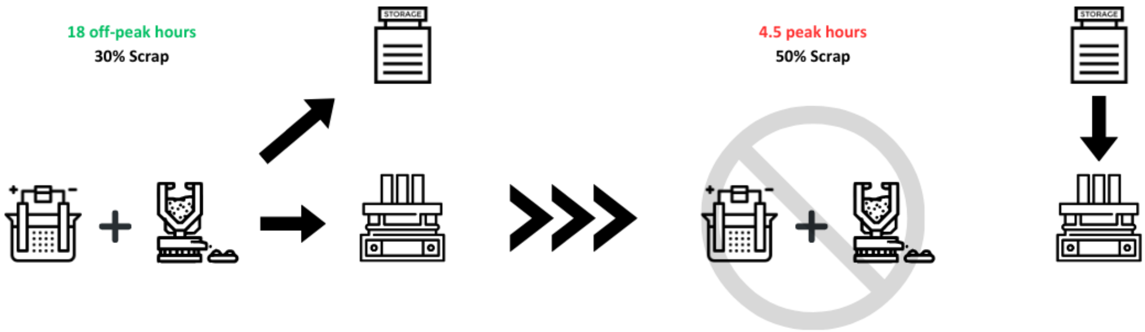

FIGURE 11 – THE STEEL PLANT RUNS FOR 18 HOURS WITH 30% SCRAP IN FINISHED PRODUCT WHILE STORING COLD DRI, ALLOWING THE ELECTROLYSER AND SHAFT FURNACE TO BE SHUT DOWN FOR 4.5 HOURS IF THE SCRAP RATIO IN THE FINISHED PRODUCT IS INCREASED TO 50%

Feedstock ratios can be adjusted between peak and off-peak hours to optimise production. During peak hours, a plant operator could increase the scrap proportion to extend the operating hours of the EAF and rolling mills, delaying the need for the shaft furnace to replenish the DRI stock. For example, if the shaft furnace runs for 18 hours producing crude steel with 30% scrap, the plant would store 382.5 tonnes of cold DRI (with a surplus of 21.25 tonnes of DRI per hour).

At the time of shutdown of the electrolyser and shaft furnace, the operator could increase the scrap content of the EAF from 30% to 50%, further delaying the need to restart the electrolyser and shaft furnace. With the stored DRI from the 30% scrap operation, the EAF could continue to operate for approximately 5 hours at 50% scrap, compared to 3 hours and 30 minutes at 30% scrap.

As the shaft furnace and electrolyser require 30 minutes to return to full output after start-up, they could be shut down for approximately **4 hours and 30 minutes**, during which time the equipment could be cooled, purged and sealed. When restarted, the shaft furnace would start producing DRI just before the stored DRI is exhausted. This strategy allows uninterrupted steel production while avoiding the consumption of **1.85 GWh** over 4 hours and 30 minutes (compared to 1.23 GWh over 3 hours with static 30% scrap).

Complete shutdown

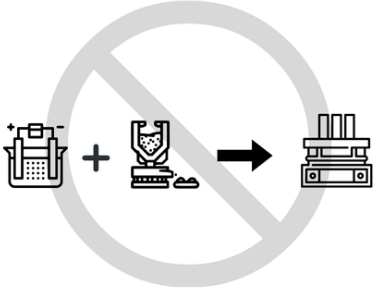

FIGURE 12 – FOR EVERY HOUR OF COMPLETE EQUIPMENT SHUTDOWN, THE STEEL PLANT LOSES 125 TONNES OF PRODUCTION

Previous scenarios only considered the temporary shutdown of the electrolyser and the shaft furnace, while the primary (EAF), secondary (refining) and tertiary (rolling) steelmaking operations were kept running continuously to avoid any impact on production. However, if the EAF and post-EAF facilities were also shut down to maximise energy savings, the outcome would be different.

For comparison with previous scenarios, it is assumed that the electrolyser, shaft furnace, EAF and post-EAF facilities are all shut down for **3 hours and 30 minutes**, as in the static 30% scrap scenario. This would result in **1.68 GWh** of energy consumption being avoided. If sufficient cold DRI is available to allow the plant to resume production without waiting for the shaft furnace to reach full capacity, and considering that the EAF takes about 30 minutes to return to full capacity after restarting, production would resume 4 hours after the shutdown. During the 3 hours and 30 minutes of avoided energy consumption, the operator would incur a non-recoverable loss of **500 tonnes** of HRC output.

While a complete mill shutdown would result in additional energy savings of 14% compared to the static 30% scrap scenario, it would also result in production losses. Any financial compensation scheme to incentivise DR would thus need to take these losses into account, making a complete shutdown more costly and only marginally more effective than balancing feedstock ratios throughout the day.

Summary of the results

	Static 30% scrap	Static 50% scrap	Static 80% scrap	Dynamic 30/50% scrap	Complete shutdown
Energy saved	1.44 GWh	3.9 GWh	7.59 GWh	1.85 GWh	1.68 GWh
Curtailment period	3.5 hours	9.5 hours	18.5 hours	4.5 hours	3.5 hours
Loss of output (no recoup)	/	/	/	/	500 tonnes

Considerations

The H2-based DRI-EAF route offers significant flexibility compared to the traditional BF-BOF route. Unlike blast furnaces, which require a minimum of 24 hours before the first molten iron can be tapped, shaft furnaces and EAFs can quickly resume operation after planned shutdowns, although recovery times may vary from model to model. Even better, an EAF can adapt to varying scrap to DRI ratios, allowing it to operate independently of the ironmaking components (electrolyser + shaft furnace). This means that the EAF, together with secondary and tertiary metallurgy, can continue to produce finished products using only temporarily stored feedstock.

However, it is important to remember that **not all steel mills may have the space to store hundreds of tonnes of cold DRI**, especially on existing brownfield sites that are attempting to decommission their BF-BOF fleets, where the land is already densely used. Installing a mechanical press to produce Hot Briquetted Iron (HBI) and save space may offset the marginal savings in feedstock storage, unless the quantities of HBI saved are well in excess of the daily flexibility requirements.

Although a complete mill shutdown can be achieved and resumed relatively quickly, it would result in only a marginal reduction in power consumption compared to shutting down only the ironmaking components. **The additional cost of compensating for lost output makes a complete mill shutdown an economically difficult decision** and as such should be considered as a last resort, similar to load reduction in primary aluminium smelting.

The power intensity of electrolysers and the hydrogen requirements of a DRI plant pose a challenge to the future stability of the power grid. Unlike primary aluminium smelters, which are few in number in Europe and are already integrated into the grid with their power requirements accounted for, **the future use of electrolysers for steel production and other applications presents new risks to the grid**. As the steel industry moves from carbon-intensive to power-intensive processes, **more than 80% of this power demand will be concentrated in the electrolysers**. Allowing plant operators to use electrolysers only during off-peak hours can result in significant cost savings in hydrogen production by purchasing and using electricity at lower rates, potentially reducing the need for output-based subsidies. While there is a risk of overloading the grid, high utilisation rates reduce production costs by **spreading the initial investment (CAPEX) over a longer period of operation**, and could potentially benefit from economies of scale with prolonged and continuous use. A middle ground could be an approach where electrolysers adapt to grid conditions while energy storage solutions, such as batteries, capture and use excess renewable electricity during off-peak hours to extend hydrogen production during peak hours.

Contaminants in post-consumer scrap pose a challenge to flexibility in steelmaking. The scenarios present scrap as an equivalent alternative to DRI with perfect substitutability, but the reality is quite different. The **scrap available to steelmakers is far from a perfect substitute** unless it undergoes additional processing at the recycling stage, which increases costs. For flat products, copper content is a major issue, as levels above 0.1% per batch can make slabs brittle, leading to cracks in the finished product. In addition, other non-ferrous metal impurities such as nickel, tin and zinc can adversely affect the formability and weldability of finished products. These impurities must be carefully monitored when a plant operator sorts available scrap on site.

In addition, **some high steel grades**, such as Advanced High Strength Steel (AHSS) and Grain-Oriented Electrical Steel (GOES), have an even **lower tolerance for impurities in order to achieve specific properties and therefore require a higher proportion of virgin iron ore**. Consequently, while balancing pre- and post-consumer scrap is a partially valid alternative feedstock to DRI, steel plants specialising in niche steel grades or specific customer requirements may struggle to achieve even 30% scrap content in the finished product. Conversely, achieving 80% scrap content, even for less demanding steel grades, could be challenging both in terms of contamination and availability of post-consumer scrap.

However, the ability to change feedstock proportions between batches provides significant operational flexibility. By increasing the proportion of scrap, operators can extend the downtime of the ironmaking components. To maximise this advantage, operators could sort scrap by reserving batches with the lowest impurity levels for EAF charges with higher scrap content, and using higher impurity batches when DRI makes up the majority of the EAF charge. Alternatively, operators could choose to produce high quality steel grades with lower scrap content during off-peak hours – possibly favouring pre-consumer scrap – and other grades with higher impurity tolerance during peak hours. Ultimately, **unlocking flexibility in the DRI-EAF route depends on improving post-consumer scrap quality, which in turn may require steelmakers to pay a premium for improved treatment processes**.

Oversizing

The near totality of the announced low-carbon steel projects in the EU that are expected to use the DRI-EAF route have annual capacities for sponge iron and steel that are closely matched. In a typical feedstock balance, one tonne of sponge iron is required to produce one tonne of steel only if the finished product contains 15% scrap. However, for plants producing steel with a higher scrap content, **the shaft furnace does not need to have the same annual capacity as the EAF**.

The simulated DRI-EAF configuration, which reflects this capacity matching, can effectively provide grid flexibility by balancing feedstock in the EAF, largely due to the oversized shaft furnace. This configuration is similar to the capacity ratios seen in existing BF-BOF setups, suggesting that **EU steelmakers may have underestimated the capacity of the EAF to handle more than the 15-20% scrap limit typical of BOFs, leading to an overestimation of the need for sponge iron from shaft furnaces**. While certain niche steel grades require minimal scrap due to low impurity tolerance, this is not the case for the full range of finished steel products.

On paper, these new DRI-EAF routes could perpetuate the low scrap rates of the BF-BOF route if they were to operate 24/7. To avoid this, they should be encouraged to apply feedstock flexibility not only from an energy intensity perspective, but also to promote a more circular economy. That being said, the annual capacity of industrial machineries typically represents the maximum possible output, not the expected production. Factors such as planned downtime for maintenance and repairs reduce actual production time, while market fluctuations and variations in operational efficiency can further affect output, resulting in lower production levels that reflect real-world constraints and challenges.

In a similar fashion, the strategy of oversizing shaft furnace capacities could be extended to include EAFs in plant designs, with the aim of operating them both exclusively during off-peak hours. **Rather than adapting existing industrial models to participate in DR, plants could be designed to operate only under favourable conditions, such as low energy prices and low carbon intensity of the grid**. Although building an oversized equipment requires a higher capital investment and spreads the amortisation over fewer operating hours, running it only during less congested periods when fewer or no thermal generation units are active, would result in lower operating costs per unit of output compared to running the same load 24/7. In addition, operating when the carbon intensity of the grid is lower would help to achieve lower embodied carbon emissions per finished product, allowing the plant to secure more profitable premiums and reduce exposure to carbon pricing. Alternatively, oversized equipment could be designed to operate only when sufficient energy is available from associated renewables, either through self-generation or Power Purchase Agreements (PPAs), to supply all or part of the load.

Conclusions

As electrification strengthens the interaction between industries and electricity systems, decarbonising both sectors simultaneously will require energy demand to adapt to supply, reversing the traditional approach of supply following demand. Therefore, to maximise the integration of renewable energy and to cost-efficiently upgrade grids, **non-fossil flexibility instruments are needed to replace traditional capacity mechanisms**.

DR has the potential to significantly reduce the reliance on fossil fuels used to maintain system reliability. To make DR programmes attractive and credible, they need to offer transparent and meaningful financial rewards to encourage end-user participation and effectively decongest grids.

Electrified energy-intensive industries will increasingly represent a huge tappable resource for flexibility, as their power-hungry loads have the potential to make or break power grids. By taking into account the intensity, frequency and impact on volume output, financial compensation can be structured as a profit stream, incentivising widespread participation in DR and increasing its overall effectiveness.

Despite the widespread use of energy management systems and smart meters, energy-intensive industries face significant challenges in achieving flexibility. **Industrial production, particularly of basic materials, fluctuates throughout the year due to factors such as economic cycles, demand shifts and external influences**. These fluctuations make it **difficult for manufacturers to consistently operate at full capacity and provide reliable flexibility**. Adding to the complexity is the **intricate reliability management** required for industrial processes, which is far more demanding than that typically required in the residential or commercial sectors.

While temporary process interruptions can immediately reduce energy consumption, they can also **undermine long-term efficiency, disrupt production schedules and violate operational constraints, leading to potential economic inefficiencies**. In addition, **the need for advance planning in industrial operations introduces uncertainty into the real-time effectiveness of DR**. The required notice periods for adjustments can limit the flexibility of industrial DR and make response times less competitive compared to more on-call thermal generation.

From a financial perspective, flexibility can come at a higher operating cost for industrial operators. **With fewer annual operating hours, the CAPEX invested in the equipment must be recouped over fewer operating hours, increasing the OPEX**. Although fewer operating hours may extend the life of equipment before it requires a complete overhaul, the **increased wear and tear from frequent load reductions or shutdowns to achieve flexibility can accelerate the need for repairs and component replacements**, ultimately increasing overall operating costs.

The challenge of embedding flexibility into electro-intensive loads extends beyond single industrial processes to the spaces in which they take place. Both new greenfield projects and redeveloped existing sites will require **tailored plant designs that can accommodate intermittent production schedules**, allowing the stockpiling of excess production to offset downtime and the storage of excess feedstock from curtailable loads. **One strategy is to oversize machineries**, increasing theoretical annual capacity and enabling plants to operate only during less congested periods, taking advantage of lower energy prices and reduced indirect emissions. However, **while energy storage technologies can help mitigate the intermittency of renewables, minimising disruptions in the value chain will also require new inventory management strategies for producers and flexible delivery schedules for off-takers**. Distributors and wholesalers could act as a buffer in the value chain, bridging the gap between producers and consumers by mitigating supply disruptions caused by production downtimes and ensuring timely delivery to customers.

Of the two sectors studied, steelmaking via the hydrogen-based DRI-EAF route and aluminium smelting through emerging deep-modulation technologies suggest significant potential for improving network flexibility **without incurring volume production losses, unless drastic shutdowns are pursued**. In contrast, conventional aluminium smelting is less suitable for DR programmes.

High-capacity electrolysers, especially those designed for energy-intensive industries, are extremely electro-intensive and pose a significant risk of single-handedly triggering thermal generation and overloading the grid if their operating hours are not carefully monitored and the grid is not adequately reinforced. When investing in such assets, as well as electric kiln, smelters and other heavy equipment, **investors should also commit to installing renewables with a capacity at least equal to that of these electro-intensive loads**. Without these concurrent investments and the integration of flexibility into operating models, it will become increasingly difficult to phase out thermal power plants.

Finally, industry participation in DR programmes should be seen as the first step in aligning manufacturing activities with the availability of renewable energy. This process begins by adjusting loads to help decongest grids and minimise reliance on thermal peaking units, which would otherwise drive up electricity prices and carbon intensity during periods of high demand. However, achieving a fossil-free electricity system will require more than simply operating during fixed periods of average or low energy demand. **To be truly flexible, industries of the future will need to synchronise their operating hours with the availability of renewable energy to ensure they can meet their energy needs without compromising the wider societal benefits of a fossil-free electricity system**.

Annex

The DRI-EAF route[58]

In an integrated DRI-EAF route, DRI, or sponge iron, is a solid granular material produced by reacting iron ores (mainly iron oxides) with a reducing gas (natural gas, hydrogen or a mixture of the two) at high temperatures (900°C to 1100°C) in a shaft furnace. This DRI is then melted in an EAF to produce molten iron, which is then converted into liquid steel.

In terms of the energy intensity of the hydrogen-based steelmaking process, it takes between 3.5 and 4.2 MWh to produce one tonne of hot-rolled coil (HRC) with 15% scrap. Over 80% of this energy is consumed in the electrolysis stage to produce the hydrogen required to reduce one tonne of DRI, approximately 60 kg of it.

In a shaft furnace, iron ore in the form of lumps, pellets or a mixture of the two is fed into the top of the reactor. The iron ore falls through the reduction zone of the reactor where it reacts in counter-current contact with the reducing agent, which must be first brought to temperature by heat exchangers before being introduced at a lower point in the shaft furnace and discharged at an upper point in the reduction zone. Much of this gas is then recovered, as only a small proportion reacts with the iron ore, and is then returned to the reactor.

Generally, in the industrial design of a DRI-EAF route, shaft furnaces have a continuous moving bed at the bottom that discharges either 'hot' or 'cold' DRI. Cold DRI is discharged at temperatures below 100°C, while hot DRI is discharged at temperatures above 700°C without being cooled. The lower part of the reactor has a conical discharge section converging on at least one outlet through which the DRI is discharged either hot or cold. The discharge rate is controlled and can be selectively diverted to one line if the DRI is hot or to another if it is cold, depending on whether the sponge iron is to be charged directly into the EAF or stored for later use.

[58] These technical details are the result of the summary of two patents: Integrated steel plant with production of hot or cold DRI and Electric arc furnace operation

The ability to choose between cold and hot DRI, or to cycle between them, is critical. This design flexibility allows a DRI-EAF route to function both as an integrated ecosystem and as two separate, unconnected ironmaking and steelmaking units, breaking the dependency seen in the conventional BF-BOF route, where the BOF can only produce steel if iron is fed in molten form, typically tapped directly from a BF.

When DRI is discharged hot from the lower cone of the shaft furnace, it is transferred to an EAF using heated pneumatic transport tubes with a carrier gas system, closed metal conveyors/pipes, or a combination of both. These methods are designed to retain heat and exclude oxygen and moisture to prevent oxidation, using nitrogen or other non-oxidising gases. Before entering the EAF, the DRI is separated from the non-oxidising gases and fed into a lock hopper, which then discharges it into the EAF at atmospheric pressure while other lock hoppers are used to feed alloys and ferrous scrap into the EAF. The discharge rate of these lock hoppers are controlled by metering devices.

When DRI is discharged cold, the lower part of the shaft furnace can act as a cooling zone. A non-oxidising, inert or reducing gas is circulated to cool the hot DRI. This cooling gas is introduced cold through a tube at the bottom of the conical zone, removed hot at the top and then returned in a closed circuit, mirroring the path of the reducing gas used to react with the iron oxide. Once cooled, the DRI is discharged through an outlet to a cold DRI conveyor, knowing that sponge iron is less prone to oxidation below 100°C. Alternatively, hot DRI can be cooled in an external vessel to minimise holding times and allow continuous DRI production. DRI is generally discharged cold for sampling purposes, but can be stored in dedicated warehouses for later charge into the EAF. To overcome potential storage space issues, hot DRI can be compacted into Hot Briquetted Iron (HBI) using a mechanical press to convert it from a loose, sponge-like material into denser, pillow-shaped briquettes.

In EAF steelmaking, sponge iron (hot or cold), scrap and alloying elements are fed into the furnace chamber from above via lock hoppers. The furnace roof is then lowered, bringing graphite electrodes, usually two or three, close to the charge without physically touching it. When current is applied, an electric arc – a high-intensity, very hot channel of electricity – forms between the electrodes and the charge. This arc generates intense heat which is concentrated in a limited melting zone around the electrodes, minimising heat loss to the furnace walls and reducing wear. The intense heat rapidly melts the particles closest to the arc, forming a molten pool at the bottom of the furnace. The molten pool plays a critical role in melting the remaining solid charge, which is periodically added to the pool by pausing the arc and reopening the furnace roof. After the initial melting, additional refining processes may be applied depending on the desired steel grade.

To reduce the carbon content of the finished product, oxygen can be injected into the molten metal through lances. Oxygen reacts primarily with carbon, but also with silicon and manganese in the DRI and scrap, which may be considered impurities depending on the steel grade being produced, to form oxides that rise to the surface. Meanwhile, lime is also injected into the EAF via lances to provide precise quantities to react with the oxides for optimum slag chemistry and efficiency. The furnace is then tilted to remove the slag, separating the less dense slag layer from the molten steel. The slag, a complex mixture of these oxides, fluxes such as lime and non-oxidised materials, helps to clean the molten steel. As an alternative to oxygen, finely crushed coke can be injected through lances to increase the carbon content of the molten steel.

Meanwhile, the solid feedstock continues to melt, with the molten steel settling to the bottom and the slag floating to the top. The remaining solid material near the melting zone of the arc is mixed and moved around the furnace by the action of the arc forces and additional stirring mechanisms, ensuring a continuous supply of feedstock for melting. This creates a continuous cycle of melting, refining and slag removal, ultimately producing steel with the desired properties. Finally, by tilting the furnace and opening a controlled taphole at the bottom, the molten steel flows by gravity into a ladle for further refining in secondary metallurgy, where it would undergo further refining processes to achieve the desired final steel composition.

The power distribution in the furnace is controlled to optimise the heat generated by the arc. This is achieved by maintaining a shallow molten steel bath, using a high voltage power supply and adjusting the distance between the anodes and the charge to maintain high resistance and voltage, resulting in a stable arc. This configuration generates heat at high rates, melting the steel efficiently and achieving much higher output factors than primary aluminium smelters, with relatively lower power consumption.

After exiting the EAF, the molten steel is transferred to a ladle furnace for final adjustments to composition and temperature to ensure that the steel meets specific grade requirements. The molten steel is then either extruded into long products or cast into hot slabs. For the latter, it is then hot rolled, where it is squeezed and stretched between powerful rollers to produce flat products.

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