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Flexibility options in a decarbonising iron and steel industry

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ABSTRACT

The decarbonisation of the iron and steel industry is expected to significantly increase its electricity consumption due to higher levels of electrification and the partial shift to hydrogen as iron reductant. With its batch processes, this industry offers large potential for the application of demand response strategies to achieve electricity cost savings. Previous research has primarily focused on investigating the demand response potential for currently operating manufacturing processes and partly for future low-carbon processes. This study aims to consolidate this knowledge and apply it to a modelling analysis that investigates the demand response potential of two new low-carbon technologies: the hydrogen-based direct reduction of iron with electric arc furnace technology (H₂-DRI-EAF) and the blast furnace basic oxygen furnace technology retrofitted with carbon capture (BF-BOF-CCUS). A cost optimisation approach is applied to plant configurations with varying parameters relevant for flexibility, such as electrolyser and storage sizes, and in the context of future electricity prices. Multiple price profiles are selected to encompass uncertainties on the development of the power system. The potential for a H₂-DRI-EAF plant is 3–27 times higher than for a BF-BOF-CCUS, with electricity costs savings potentials of 35% and 3%, respectively. The study finds that electricity prices have the most significant impact on the profitability of investing in electrolyser overcapacities, which enable operating costs reduction. Therefore, the profitability of these investments are strongly dependent on future power system configurations.

1. Introduction

The European Union (EU) has set the ambitious target of achieving climate neutrality by 2050 as a critical component of the European Green Deal. This target involves a comprehensive transformation of the European energy system and economy [1]. An increasingly preferred strategy for the decarbonisation of energy consuming sectors is electrification thanks to high efficiencies and the availability of cost-effective, low-carbon power generation options. Various studies foresee large increments of electricity demand by 2050 of up to 750 TWh for the built environment [2], 700 TWh for the transport sector [3] and 2000 TWh for the industrial sector [4], growing from an electricity demand of 2500 TWh in 2021 in the EU [5]. This demand surge, combined with the intermittent nature of many low-carbon power solutions, requires a substantial increase in sources of flexibility within the power system, which is defined as the ability of the power grid to respond to expected or unexpected variations in load or generation [6]. Koolen et al. [7]

estimates a 133%, 160% and 200% increase in flexibility requirements for daily, weekly and monthly needs by 2030 compared to 2021, reaching 13%, 11% and 7% of total power demand by 2050.

Among the flexibility options is demand response (DR), which involves an adjustment of electricity consumption in response to a price signal through load shifting or load shedding [8]. The deployment of DR has the potential to reduce power system costs by decreasing the need for transmission capacities, and for expensive, usually fossil fuel-fed peak power generators [9]. Consumers are encouraged to adopt DR through incentive- or price-based mechanisms. Incentive-based DR indicates an adjustment of the electricity load dispatched by a 3rd-party. This category includes ancillary services and direct participation in day-ahead or intra-day markets, where consumers (and producers) face penalties for failing to meet their commitments. Price-based DR, contrastingly, indicates the adoption of electricity tariffs that stimulate consumption during specific hours of the day. For instance, time-of-use (TOU) tariffs consists of pre-defined price clusters aimed at reducing consumption at peak hours, critical peak pricing (CPP) involves

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Nomenclature		Notations	
Abbreviations		$c(t)$	Day ahead electricity price [€/MWh]
BF	Blast furnace	CAPEX(p)	Capital expenditure [€/MW or €/t]
BOF	Basic oxygen furnace	$e(p,t)$	Electricity consumption/production [MWh]
CCUS	Carbon capture storage and/or utilisation	$E(p)$	Power min/max constraint [MW]
CO ₂	Carbon dioxide	End	Ending
CS	Crude steel	in	Input
DRI	Direct reduction of iron or directly reduced iron	ini	Initial
DR	Demand response	$m(p,t)$	Material flow [t]
EAF	Electric arc furnace	max	Maximum
EU	European Union	min	Minimum
H ₂	Hydrogen	out	Output
I-flex	Incentive-based flexibility	p	Index for process step within processes P
ISI	Iron and steel industry	$s(p,t)$	Storage level [t]
MEA	Monoethanolamine	$S(p)$	Storage level min/max constraint [t]
NPV	Net present value	t	Index for time step within time horizon T
P-flex	Price-based flexibility	ST	Steel production target [t/month]
PEM	Polymer electrolyte membrane	$\eta(p)$	Specific electricity consumption [MWh/t]
RTP	Real-time-pricing	$\theta(p)$	Ratio of output to input material [%]
SEWGS	Sorption enhanced water-gas shift	Units	
TOU	Time-of-use	J	Joule (GJ giga-)
TRL	Technology readiness level	min	Minutes
WAG	Work arising gas (i.e., blast furnace, coke oven and basic-oxygen furnace gases)	Nm ³	Normal cubic meter (at 20 °C and 1 atm)
		t	Tonne (Mt mega-)
		W	Watt (MW mega-, GW giga-)
		Wh	Watt hour (MWh mega-, GWh giga-, TWh tera-)

short-notice prices – minutes to hours – that are implemented on top of TOU tariffs to address short-term grid requirements, and real-time pricing (RTP) reflects very short-term market clearing (5–15 min), exposing consumers directly to wholesale prices fluctuations [10]. The fast interoperability characterising mechanisms such as RTP necessitate the deployment of devices that allow automated DR [11]. This automation holds the potential to maximise flexibility utilisation in response to system requirements [10].

The industrial sector, particularly energy-intensive industries, can attain significant benefits from DR due to their large electricity consumption thus potential cost savings. Some industrial processes can be interrupted without causing financial losses or damage to production facilities [12]. For instance, batch processes such as scrap steel melting in electric arc furnaces (EAFs) can be strategically delayed as intermediate manufacturing products can be stored. This in contrast to, for example, large petrochemical plants that mainly run continuously with limited bandwidth [13]. Gils [14] estimated the load shedding and shifting DR theoretical potential of Europe in 2010 at 93 GW, of which 35% provided by industries. Considering that the decarbonisation of energy-intensive industries involves direct or indirect electrification – i.e., electrolytic H₂, this potential is expected to increase further [15]. Moreover, as electricity prices are expected to exhibit more spiky behaviour with the integration of intermittent power sources [16], stimulating industrial DR can yield even more significant costs savings, especially for the sectors with growing interactions with the power system.

The iron and steel industry (ISI) emerges as an optimal sector to benefit from DR applications. Almost 20% of steel worldwide and over 40% in the EU today [17] employs electric arc furnaces (EAFs) to process recycled scrap steel. EAFs usually exhibit electricity costs of more than 20% of the overall production costs [18], bearing strong incentives for DR. In some countries, e.g., Germany, EAFs are already partially engaged in providing positive reserves capacities in balancing markets through load shedding, despite the fact that the high costs of lost load makes the probability of an energy call negligible [19]. Re-scheduling

production processes to earlier or later times – i.e., load shifting – offers a strategy to offset lost load, which is more favourable than load shedding for balancing purposes. Previous research has investigated the load shifting potential of EAFs through a cost minimisation approach [20,21] or via process simulation [22]. Furthermore, research has focused on assessing price-based DR through RTP [23,24], incentive-based DR [25] or a combination of both [26]. Some studies have explored EAFs with abilities to ramp-up or -down their load [18] and without [27]. Although a wide range of options and methods have been researched, these studies primarily evaluate flexibility strategies based on historical electricity prices. EAF production will remain a relevant technology in a low-carbon economy. Nonetheless, a research gap is found in quantifying the DR potential of EAFs within the context of future power systems.

In contrast to EAFs, the integrated route, producing almost 80% of steel worldwide and almost 60% in the EU27 [17], heavily relies on coal thus standing out as the most CO₂ emitting alternative for steel production [17]. This technology offers limited DR potential as relatively little electricity is used in the manufacturing processes. However, the carbon-rich work arising gases (WAGs) produced are often burned in nearby power plants to produce electricity with some degree of dispatchability. In the context of present-day markets and regulations, Feta et al. [28] evaluate the power plant capacity that can be offered to the Dutch balancing market while He et al. [29], Liu et al. [30] and Zhao et al. [31] investigate the extent to which the power plants fed by WAGs can supply peak-shaving and valley-filling services with TOU tariffs in China. Notably, there is a research gap regarding the participation of these plants in day-ahead markets or their responsiveness to RTP, which are strategies more commonly applied in liberalised electricity markets. Furthermore, integrated steel plants are likely to be decommissioned or retrofitted with carbon capture technologies due to more stringent decarbonisation targets set or expected to be established around the world [17]. The impact of applying carbon capture technologies to the integrated route on the dispatchability of the WAGs-fed power plants remains unknown.

In the coming decades, the integrated route's capacity is expected to be gradually replaced by low-carbon technologies, many of which entails direct or indirect electrification [32]. These options are electro-winning, hydrogen (H₂) plasma smelting or H₂-based direct reduction of iron with electric arc furnace (H₂-DRI-EAF) [33]. The latter has, in recent years, gained the attention of many European steelmakers with major companies such as ArcelorMittal and ThyssenKrupp announcing or beginning the construction of such plants [34]. The electricity demand of steel production using H₂ is strongly influenced by the method of hydrogen production. For instance, utilising electrolytic H₂ produced via electrolysis increases electricity consumption of the H₂-DRI-EAF by approximately four times [35]. In the present-day and near future, H₂ production is economically more attractive via steam methane or ethanol reforming [36]. Nevertheless, to mitigate their environmental impact, these methods require the implementation of carbon capture solutions. Electrolysis currently stands out as the most promising low-carbon H₂ production method, as other low-carbon production methods are in earlier stage of development [37]. This is reflected by the presence of studies that investigate the performances of electrolysis-based H₂-DRI-EAF steelmaking, and to some extent, its flexibility. Vogl et al. [35] qualitatively assess its flexibility through storage of intermediate products and oversizing of the electrolyser. Superchi et al. [38] investigate the potential constant production of green hydrogen by supplying a steel plant with locally produced wind power, but without considering DR options by the plant. Elsheikh et al. [39] assess the decarbonisation performances of steel production by supplying an electrolyser by solar- and grid-electricity, allowing DR strategies by the electrolyser but not by the manufacturing processes.

In summary, there exists a body of literature that analyses DR potential for established steelmaking technologies, but these studies vary widely in terms of technologies assessed, operation strategies, location, historical electricity pricing. Furthermore, they apply a wide range of assumptions, such as plants ramping abilities and batch process duration, overall lacking harmonised conclusions. Moreover, the assessment of this potential in the context of future power system configurations and as a means of comparing various alternatives for steel decarbonisation is missing. By answering to the question “what is the current DR potential of iron and steel manufacturing plants, and how will this potential evolve in the context of low carbon production and energy supply?”, the contribution of this study to the existing research is twofold:

- consolidating existing literature to offer a comprehensive overview of DR potential in the ISI, to provide a clearer understanding of the current status of flexibility in steelmaking processes, identifying potential bottlenecks, the state-of-the-art, and highlight future directions in the context of decarbonisation and the potential electrification of the sector.
- identifying several low-carbon steelmaking technologies that are good candidates for flexible operations, calculating and comparing their flexibility potential through modelling. Furthermore, this study tests these potentials under different power system configurations by varying electricity pricing scenarios.

It must be noted that, for simplicity, the flexibility through dispatchability of WAGs power plants will be henceforth referred to as DR, despite the fact that is implemented by modulating electricity generation rather than demand. The study is structured as follows: Section 2 reports the review and Section 3 the modelling analysis. Discussion and conclusions are reported in Sections 4 and 5, respectively.

2. Review of demand response strategies in the iron and steel industry

2.1. Method

The study collects information and data from case-studies of existing

and potential configurations of iron and steel plants. These case-studies were found by screened the following key words in peer-reviewed articles, conference contributions, and grey literature: *iron and steel industry, demand side management, demand response, flexibility, direct reduction of iron, electric arc furnace, carbon capture usage and/or storage, real-time pricing, time of use tariff, ancillary services*. Studies were selected that assess DR potential for iron and steelmaking through real-cases analysis and modelling. To consolidate the findings of these studies, data that represents the DR potential is harmonised and expressed by two indicators: electricity shifted and electricity costs savings achieved through load shifting. Furthermore, factors influencing the DR potential are gathered, namely, type of steelmaking route, plant size, processes of the steelmaking route that provide DR, the type of DR provided and under which tariff. The type of DR and tariffs are classified according to Morales-España et al. [10], which distinguishes between incentive- and price-based DR. Sections 2.2 and 2.3 report the results of the review for currently operating and new steelmaking technologies, respectively.

2.2. Current status of demand response in the iron and steel industry

Steel is today primarily manufactured with the three type of technologies shown in Fig. 1. Two primary routes – i.e., producing steel from raw material, requiring the reduction of iron ore in the ironmaking process – are the blast furnace with basic oxygen furnace (BF-BOF) and the direct reduction of iron in electric arc furnaces (DRI-EAF). One secondary route – i.e., processing recycling steel in the steelmaking process – feeds scrap steel to an electric arc furnace (scrap-EAF) where it is melted using electricity as the main energy source [33,40].

In the BF-BOF route, coal and derivatives are the main input to most manufacturing processes. They are used as fuel and feedstock in processes that reach temperatures above 1500 °C while electricity is used in much smaller quantities for secondary purposes such as pumping and ventilation, thus DR strategies are usually not applied to the manufacturing processes. However, the WAGs produced are carbon-rich and often used for combustion in local power plants that can provide flexibility to the power system thanks to their dispatchability. Table 1 reports studies found in the literature about BF-BOF providing flexibility to the grid. They identify the power plant running on WAGs as the component to exploit different types of flexibility strategies. Feta et al. [28] assess the potential flexibility in the context of the Dutch frequency restoration reserves markets and find that, out of the 300 MW turbine capacity running on WAGs available, 10 MW of balancing reserve capacity can be ensured for periods of 30 min and 20 MW for periods of 15 min, with availabilities higher than 90%. This capacity sizes could contribute 3% and 6% of the average contracted balancing reserves in the Netherlands in 2023 [41]. The balancing capacities must be able to react to a signal by decreasing or increasing their load within few minutes.

Larger capacities can be made available when other grid services with loosened time constraints are considered. He et al. [29], Liu et al. [30] and Zhao et al. [31] assess price-based flexibility under TOU tariff of electricity for WAGs-fed power plants in China [29–31]. This type of tariff reflects the peak shaving and valley filling requirements of the power grid over a day. He et al. [29] estimates that all WAGs-based power plant in China can potentially reduce the annual peak by 0.9% (5.4 GW) and fill the valleys by 0.5% (2.7 GW) in the national power system. Meanwhile, power plants fed by WAGs can modulate their output to maximise their revenues. Among the studies collected, only Zhao et al. [31] reports specific information regarding the share of capacity that can provide flexibility, that is 70%. With this flexible capacity the electricity profits increase by 29.7%. In contrast, the other studies reports 2.4% and 3.4% increase, with unknown level of flexible capacity. In other geographical areas with more liberalised electricity markets than China, such as the EU and the USA, steel power plants bid on electricity day-ahead markets similarly to conventional power plants, potentially leading to higher profits by exploiting larger price volatility.

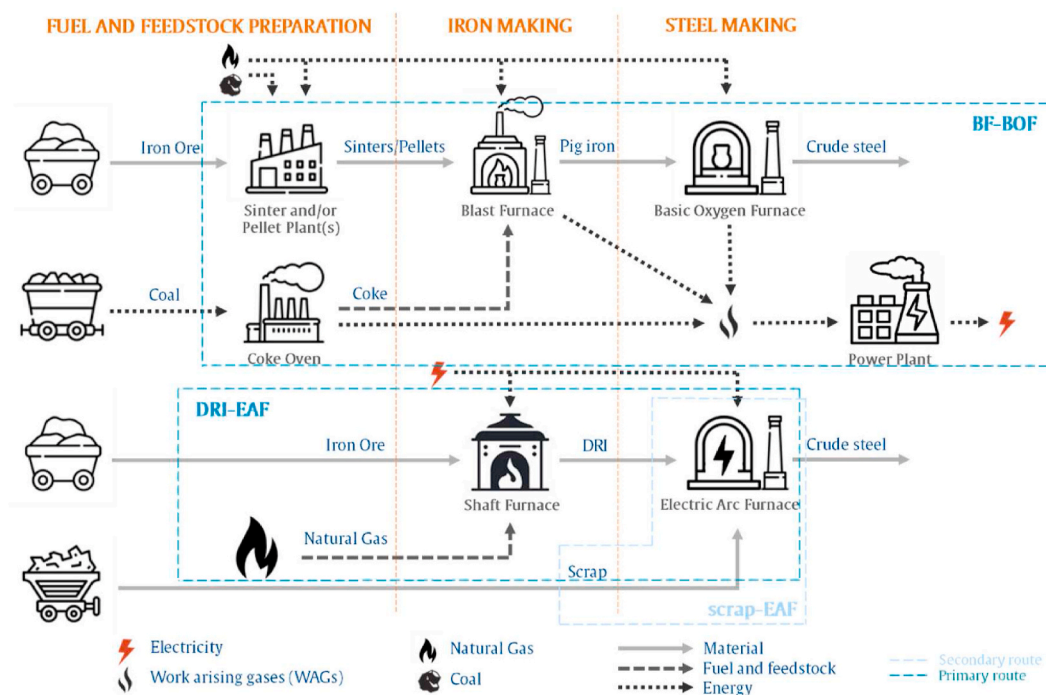


Fig. 1. Schematic overview of the most common steel-making routes with the main energy and material inputs.

Table 1

Collection of literature on flexibility strategies for the BF-BOF route. ‘-’ indicates not applicable. Abbreviations: NA Not available, P-flex price-based flexibility, I-flex incentive-based flexibility, BM balancing markets, TOU time of use tariff.

Study	Type of analysis	Flexible plants		Type of DR		DR results		Notes	
		Plants	Electric capacity	Flexible capacity	Tariffs	Electricity shifted	Annual profit increase		
			[MW _{el}]	[% of electric capacity]		[TWh]			
[28]	Profit maximisation	Power plant fed by WAGs	300	3.3% (30 min) 6.6% (15 min)	I-flex	Dutch BM	-	-	Main constraints are power plant ramp-rates and WAGs storage capacity
[29]	Profit maximisation	Power plants fed by WAGs	NA ^a	(-) 5.4 GW (+) 2.7 GW ^b	P-flex	TOU Four time slots, prices in the range of 80 ± 40 €/MWh	15.8	2.4% (year 2010)	WAGs storage: - typical size per plant: 650,000 m ³ sufficient to store 1 GWh of WAGs - CAPEX storage 25€/m ³ Main constraint is WAGs storage capacity (710,000m ³ /1.1 GWh)
[30]	Profit maximisation	Power plants fed by WAGs	650	NA	P-flex	TOU Four time slots, prices in the range of 70 ± 28 €/MWh	NA	3.4% (year NA)	
[31]	Profit maximisation	Power plants fed by WAGs	48	70%	P-flex	TOU Four time slots, prices in the range of 80 ± 53 €/MWh	NA	29.7% (year 2010)	

Notes: ^aall power plants fired by WAGs in China with steel production of 515 Mt_{CS}; ^bcorresponding to the 0.9% and 0.5% of the maximum and minimum load of the Chinese power grid in 2010, respectively.

Contrarily to conventional power plants, the dispatchability of WAGs-based plants are dependent on the stream of WAGs. WAGs storages are essential to decouple the continuous BF-BOF processes from the potentially flexible operations of the power plants and avoid as much flaring as possible. The studies in Table 1 identify WAGs storages as major constraint to the flexibility of these power plants, thus, investments in larger storage capacities could lead to higher electricity profits. However, it is important to note that the BF-BOF route emits, on average, 1.9 t_{CO2}/t_{CS}, which is more than double the emissions of the primary DRI-EAF route [33]. Therefore, BF-BOFs are expected to be

phased out in favour of low-carbon technologies or retrofitted with carbon capture. As a result, the significance of harnessing flexibility from these plants may diminish or be influenced by the carbon capture application in the future.

The scrap-EAF route melts recycled steel in electric arc furnaces. Small amounts of natural gas or coal are added to provide additional heat but most of the energy input is in the form of electricity [33], making scrap-EAF a potential low-carbon steel production route – i.e., 0.2 to 0.3 t_{CO2}/t_{CS} [33] – and potentially good candidates for DR applications. Table 2 reports a collection of studies that investigate DR

Table 2

Collection of literature on DR strategies on the scrap-EAF route. ‘Ramping abilities’ indicates the possibility to ramp up or down the electricity consumption or production while delivering a flexibility service. ‘–’ indicates not applicable. DR strategy (i) indicates one power rate level option, strategy (ii) indicates multiple power rates levels options, strategy (iii) indicates multiple power rates levels and ramping options. Abbreviations: NA not available, P-flex price-based flexibility, I-flex incentive-based flexibility, BM balancing markets, TOU time of use tariff, RTP real time pricing, DA day-ahead market.

Study	Strategy	Flexible plants			Type of DR		Modes of operation			DR results		
		Strategy for DR and type of analysis	Plants	Electric capacity	Flexible capacity	Tariffs		Load as share of Electric capacity	Batch time	Ramping abilities	Electricity shifted	Annual cost saving
				[MW _{el} input]	[% of electric capacity]							
[27]	(i) Cost minimisation	EAF	170 ^a	100%	P/I-flex	DA, TOU Four time slots, prices NA	100%	85	NO	NA	46% (year 2013)	
[20]	(i) Cost minimisation	EAF	170 ^a	100%	P-flex	RTP Prices from 50 to 210 €/MWh	100%	85	NO	NA	12% (year NA)	
[26]	(i) Cost minimisation	EAF	170 ^a	100%	P/I-flex	DA, TOU Four time slots, prices NA	100%	85	NO	NA	33% (year 2013)	
[21]	(ii) Cost minimisation	EAF	170 ^a	100%	P-flex	RTP prices NA	(a) 100% (b) 80% (c) 60% flexible	(a) 85 (b) 106 (c) 142	NO	NA	6–29% (year NA)	
[42]	(iii) Cost minimisation	EAF	70	100%	P-flex	TOU Four time slots, prices NA	flexible	60, 120, 150	YES	NA	5.7% (year 2001)	
[23]	(iii) Cost minimisation	EAF	170 ^a	100%	P-flex	RTP Prices from 22 to 52 €/MWh	(a) 100% (b) 79% (c) 57% (d) flexible	(a) 100% ^b (b) 120% (c) 150% (d) flexible	YES	NA	Compared to (a) (b) 6.5% (c) 35% (d) 37% (year 2017)	
[43]	(iii) Cost minimisation	EAF	170 ^a	100%	P-flex	RTP Prices from 35 to 92 €/MWh	(a) 100% (b) 80% (c) 53% 100%	(a) 45 (b) 54 (c) 76 NA	YES ^c	NA	8% (year NA)	
[18]	(iii) Increasing transmission capacity	EAF	EAF: 60 Transmission: 54	(–)10%	–	–	–	–	–	–	–	
[19]	(iii) Assessment of technical DR potential	EAF	1097 ^d	(–)19% ^e	I-flex	German BM	–	60	YES	–	–	
[22]	(iii) Process simulation	EAF	–	100%	P-flex	RTP prices NA	–	60	YES	NA	5% (year 2016)	
[24]	(iii) Cost minimisation	EAF	170 ^a	50%	P-flex	RTP prices NA	(a) 125% (b) 100% (c) 75%	(a) 64 (b) 85 (c) 106	YES	400	11.4% (year NA)	
[45]	NA Cost minimisation	EAF	NA	50–60 MW (15 min)	P-flex	RTP prices NA	–	–	–	–	–	
[25]	NA Cost minimisation	EAF	170 ^a	(–)37% ^e	I-flex	BM	–	45	YES	–	–	

Notes: ^a2 plants of 85 MW; ^bactual time not available; ^ctransformer level; ^dall German EAFs; ^eload shedding.

strategies applied to scrap-EAFs through load shifting or shedding. The studies assessing load shifting investigate plants of size ranging from 60 to 85 MW_{el}, from where 100% of the capacity is harnessed for flexibility to decrease production costs, with various levels of process constraints: (i) EAFs operate at maximum power input capacity and a predefined duration of the batch [20,26,27]. (ii) EAFs operate at different input power rates and batch durations, but the power rate stays constant for the duration of the batch [21]; (iii) is same as (ii) but the power can ramp-up and -down during the batch [18,19,22–24,42,43]. Studies that apply strategy (i) rely on a capacity utilisation lower than 100% – i.e., 67%–87% – to operate flexibly so that they can shift in time the start of the process. By applying strategies (ii) and (iii) a plant operator can shorten the processing time of a batch by increasing the power rate – up to 125%, assuming equal energy provided to melt a batch – thus making time available for shifting or slowing down other batches and further increasing the DR potential.

The results in Table 2 show no correlation between the type of constraint applied to flexibility – (i), (ii) or (iii) – and the electricity cost savings achieved. Nonetheless, it is clear that plant operators can conveniently exploit the flexibility of EAFs if capacity utilisation rates are lower than 100% – i.e., Castro et al. [20] calculates 12% costs savings with capacity utilisation rate of 87%, by applying the level of constraint (i). To put this into perspective, in the EU27 and the USA, capacity utilisation rates of EAFs have dropped about 20% points on average from the 1990s to the late 2000s and 2010s due to lower steel demand, reaching levels of 65–70% [27,44]. More flexible operation such as varying the power rate levels or ramping abilities – i.e., levels of constraints (ii) and (iii) – can lead to additional complexity in the process scheduling without evident additional cost savings benefits. According to Paulus et al. [19], if the melting in the EAF is disrupted for more than 30 min, the process will have to start again. Furthermore, the increasing of the power rates accelerate the degradation of the EAFs' electrodes. Castro et al. [43] and Ave et al. [23] take into account 20'000 € for electrodes replacement, finding that the benefits of DR are positive regardless. A lack of research was found on the impact of these strategies on the degradation of other equipment.

The pricing scheme applied also does not show correlations to the economic potential for DR of EAFs. Most of the studies investigate RTP price-based DR that achieve savings from 5% to 37% of the electricity costs with historical prices applied [20–24,43,45]. Hadera et al. in two different studies [26,27] identify higher costs savings, of 33% and 46%, by applying a combination of TOU pricing scheme and day-ahead (DA) markets bidding but also relying on the dispatchability of the electricity produced on site. Two other studies investigate the possibility of applying load shedding to the scrap-EAF route through incentive-based DR with participation in balancing reserve markets [19,25]. The studies show that 20%–40% of EAFs electric capacity qualifies for positive balancing reserve in the North American Midwest and the German system markets, respectively. Load shedding applied to these plants is an effective tool to reduce large grid loads while affecting few large consumers. Already in 2011, about 50% of German EAFs pre-qualified their capacity for positive balancing in the tertiary reserve market [46]. However, the cost of missed loads for steel manufacturer is high [46] and the future volatile electricity prices could be more impactful on production costs, thus load shifting stimulated through specific pricing schemes should be preferred over load shedding.

In 2019, EAFs manufactured 28% of the globally produced steel [44]. The deep decarbonisation of the scrap-EAF route is easily achieved by supplying low-carbon electricity thus this technology will stay relevant in the future. The different configurations and assumptions of the studies reported in Table 2 shows that more consistent research is required to assess the most advantageous load shifting strategies for plants' operators and the power system, in terms of flexibility options, additional operational costs incurred, investment costs to provide DR and pricing schemes that are updated for future low-carbon power systems.

Table 3

Summary of primary routes for iron and steelmaking, potential CO₂ emission reduction, technology readiness level (TRL) and electricity consumption. Abbreviations: BF-BOF blast furnace-basic oxygen furnace, DRI-EAF direct reduction of iron-electric arc furnace, H₂-DRI-EAF H₂-based DRI-EAF, TGR-BF top-gas recycling-blast furnace, VPSA vacuum pressure swing adsorption, PP power plant, MEA monoethanolamine, SEWGS sorption enhanced water-gas shift.

Primary technologies	CO ₂ emissions reduction	TRL	Electricity consumption MWh/t _{CS}	Sources
BF-BOF	1.9 t _{CO2} /t _{CS} (reference)	9	0.10	[4,33,50–52]
DRI-EAF	50%	9	0.80	[33,35,50,52]
H ₂ -DRI-EAF	98%	7	3.3–3.7	[4,33,35,52]
H ₂ plasma	95%	5	NA	[4,33,52]
Electrowinning	87%	5	2.5–3.6	[4,33,52]
HIsarna + (cryogenic) ^a	80%	5	0.12	[4,33,52,53]
TGR-BF + VPSA (adsorption)	55–60%	6–7	0.09	[4,33,50,52]
BF-BOF + PP + MEA (absorption)	35–75%	8	0.05–0.12	[33,50,54,55]
BF-BOF + SEWGS + PP (adsorption)	90%	6–7	0.14	[50,52,55]
BF-BOF + PP + DMX (absorption)	90%	5	NA	[56]

Notes: ^acarbon capture is not needed if CO₂ concentration is sufficiently high (>90–95%) and the flue gas has low impurities.

The DRI-EAF technology, with its 0.9 t_{CO2}/t_{CS}, is expected to be operational for a longer time-frame than the BF-BOF route. Various large steel-makers such as ArcelorMittal and Thyssenkrupp have already successfully tested the operations of DRI plants with blends of natural gas and H₂ [47] or plan to build new natural gas-based DRI plants as transitional technologies [34]. No relevant literature is found for DR strategies specific to this technology. However, the steelmaking process of the DRI-EAF occurs in electricity-intensive EAFs, same as for the scrap-EAF routes. Thus, the DRI-EAF route presents the same DR potential in terms of modulating the EAF. More constraints are given by the process of DRI making in the shaft furnace that precedes the EAF, entailing the material flows between the shaft furnace and the EAF should be decoupled by allowing DRI storability to enable full flexibility of the EAF processes.

2.3. New primary steelmaking technologies and their demand response potential

Part or all of the current primary steel production is expected to be replaced by low-carbon technologies in the coming decades. Table 3 reports various low-carbon solutions for primary steelmaking, at different stages of development and with different decarbonisation potential. The CO₂ produced by the BF-BOF route can be captured for storage and/or usage (CCUS). Blast furnaces produce most of the CO₂ emissions of the BF-BOF route, but the largest emitters are usually the power plants fed by the WAGs. Most of CCUS projects focus on carbon capture from these two processes. If carbon capture is retrofitted to the blast furnaces, the power plants burning WAGs become obsolete because most of the combustion gases are in fact blast furnace gases. This strongly decreases the interaction with the power system and nullifies the flexibility potential reported in Section 2.2. To this category belongs the Steelanol project that captures the carbon-rich flue gases from the blast furnaces to be converted into ethanol [48], inaugurated in December 2022 at the ArcelorMittal BF-BOF steel plant in Ghent [49].

Alternatively, pre- and post-combustion technologies capture the CO₂ emissions from the gases entering and exiting of the power plants, respectively. With these applications the power plants remain operative

and their dispatchability limited by the carbon capture element, the extent to which is unknown. These technologies are the post-combustion monoethanolamine (MEA) scrubbing adsorption, a commercially-ready technology with high specific primary energy consumption (3.8–5.2 GJ/tCO₂ [55]) and costs [57]; the post-combustion DMX™ process that can reduce costs of CO₂ capturing up to 30% compared to the MEA technology [56], and with the first industrial unit aims at being operational by 2025 at an ArcelorMittal steel plant in Dunkirk [58]; and the pre-combustion sorption enhanced water-gas shift (SEWGS), considered one of the most promising CCUS technologies for steel applications thanks to its high CO₂-removal potential and low specific primary energy consumption – 1.9 GJ/tCO₂ [52,55]. No research is found on how retrofitting WAGs-based power plants with carbon capture affects dispatchability, as well as on potential DR options for the capturing system. Spitz et al. [59] assesses the latter for a MEA carbon capture system applied to a gas turbine, finding that a delay of 1 h of the CO₂ compression, responsible for 70% of the electricity consumption of the capturing system [55], leads to 20% of electricity output penalty. This penalty potentially increases for WAGs-based power plants that run on gases with higher carbon concentration and lower energy content.

Other new processes include the HIsarna technology, a fossil-fuel-based smelting reduction technology that processes directly iron ore into pig iron thus reducing the overall energy consumption by 20% compared to the BF-BOF technology [53]. The gas stream emitted by HIsarna has a pure CO₂ stream which can be directly compressed for storage and/or usage if the CO₂ concentration is above 90–95% [33]. Similarly to the BF-BOF manufacturing, the HIsarna processes have high thermal inertia and low shares of electricity as energy input, thus have negligible flexibility potential. Electrolytic processes i.e., reduction of iron ore through electrolysis, and smelting reduction of iron ore using H₂ plasma are potential game changers due to their high efficiencies and no fossil fuel utilisation [60]. These technologies are directly or indirectly fuelled by electricity, however, most of them are at early stage of development and their deployment is not expected before 2040–2050 [33]. Only the molten oxide electrolysis (MOE) technology already reached industrial development by Boston Metal [61], however, this technology requires continuous power supply thus limiting DR options [32].

A technology that in recent years has gained the interest of steelmakers is the H₂-based DRI-EAF, where H₂ replaces the natural gas as fuel in the shaft furnace [33]. Eighteen projects have been announced globally that foreseen operations by 2030, of which eleven at full scale [34]. This is a highly power intensive manufacturing route if H₂ is produced via electrolysis. Table 3 shows that electricity demand for the this route grows by thirty-five and four times compared to the BF-BOF and DRI-EAF, respectively. DR strategies can mainly be applied to EAFs and to some type of electrolyzers that allows flexible operations – i. e., polymer electrolyte membrane (PEM) [62]. Table 4 reports the studies found that assess DR potential for this technology. Vogl et al.

[35] assesses the techno-economic performances of the H₂-based DRI-EAF route with the option of feeding the EAF with either DRI pellets, scrap steel or a mixture of the two and estimates the balancing market potential. If the EAF is running on DRI with the oversized electrolyser operating at a sufficient level to produce the required H₂, the plant can at any time increase its power load by the size of the additional electrolyser capacity. Whereas feeding scrap to the EAF can contribute to balancing by decreasing the consumption of the electrolyser and shaft capacity. Elsheikh et al. [39] assesses potential CO₂ emissions and costs reductions while operating a H₂-based DRI-EAF plant on grid purchased electricity or on site generated solar power in Spain. The study investigate optimal sizing and operations of solar PV, electrolysis and H₂ storage reaching CO₂ emissions and costs reductions of 41% and 20%, respectively. From the studies it is evident that the DR potential strongly depends on the installed overcapacity of the electrolyzers and the H₂ storage. However, both studies assess systems applying a mixture of scrap and DRI pellets in the EAFs which increases flexibility options, as electrolysis can be fully decoupled by the manufacturing processes, but it hinders the DR potential inherent to the this route. Further research should address how the sizing of the components of this manufacturing route affects its flexibility options. Furthermore, Elsheikh et al. [39] optimises operations by applying historical prices of electricity, while the uncertainty of future prices calls for an extended analysis assessing the impact of these on the DR potential of this power intensive technology.

3. Analysis of demand response potential of low-carbon steelmaking

Section 2 shows there exists a broad range of literature on the application of DR or flexible power generation for the two most common steelmaking routes, and some for emerging low-carbon technologies, mainly the H₂-based DRI-EAF manufacturing route. Overall, there is a lack of harmonised research on flexibility for low-carbon steel plants in the context of future power systems where price development is uncertain, as well as in the assessment of how specific design choices affect flexibility. Therefore, this section presents how these gaps are bridged by selecting relevant low-carbon technologies and assessing the flexibility potential of multiple design options through linear optimisation.

3.1. Technology selection and system definition

The selection of the technologies in Table 3 that are assessed for their DR potential is driven by the following criteria that encompass realistic chances of DR application while driving the decarbonisation of the sector: (1) CO₂ emission reduction of at least 80% compared to the BF-BOF route; (2) realistic chances of commercial viability by 2050, thus including technologies with TRL above six and (3) relevant in the context of flexible electricity consumption or generation. Based on the

Table 4

Collection of literature on flexible operations of ISI with H₂-DRI-EAF technology. Abbreviations: I-flex incentive-based flexibility, BM balancing markets, P-flex price-based flexibility, DA day-ahead market.

Study	Type of analysis	Flexible plants			Type of DR		DR results		
		Plant	Electric capacity	Flexible capacity	Tariff		Balancing potential	Electricity shifted	Annual cost savings
			[MW _{el} input]						
[35]	Assessment of techno-economic performances	Electrolyser	411	100%	I- flex	BM	123 (positive) 468 (negative)	–	–
		Shaft furnace	81	70%					
		EAF	129	100%					
[39]	Operational and investment cost minimisation	Electrolyser	910 ^a	100%	P- flex	DA/on site PV generation	–	NA	20% (year 2019)
		Shaft furnace	NA	NA					
		EAF	NA	NA					

Notes: ^a50% oversized.

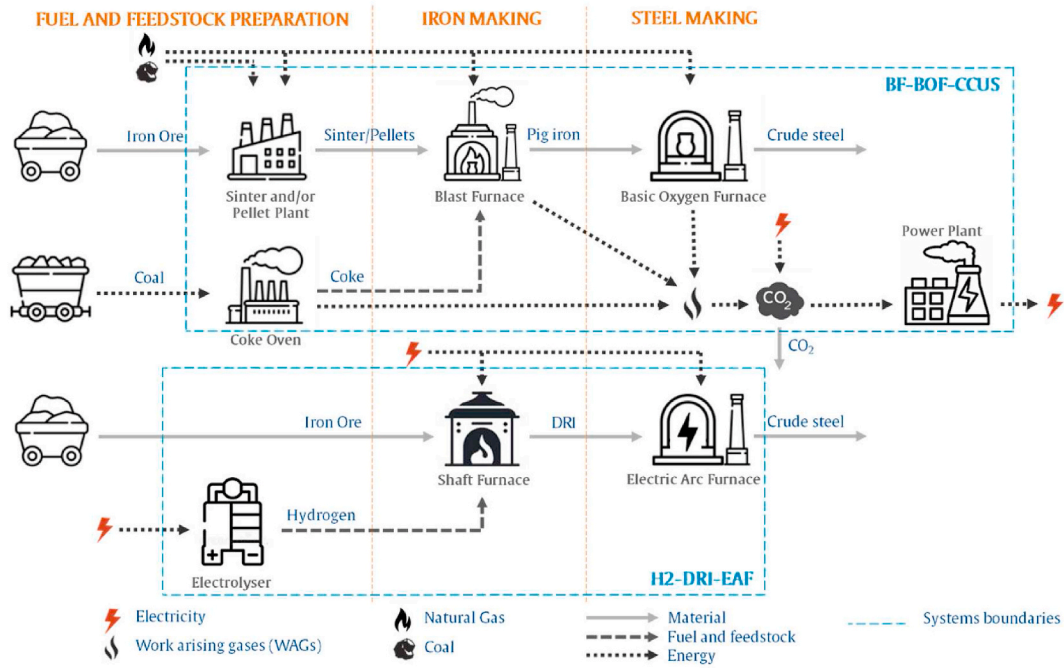


Fig. 2. Schematic representation of the steel-making routes and the boundaries of the systems analysed.

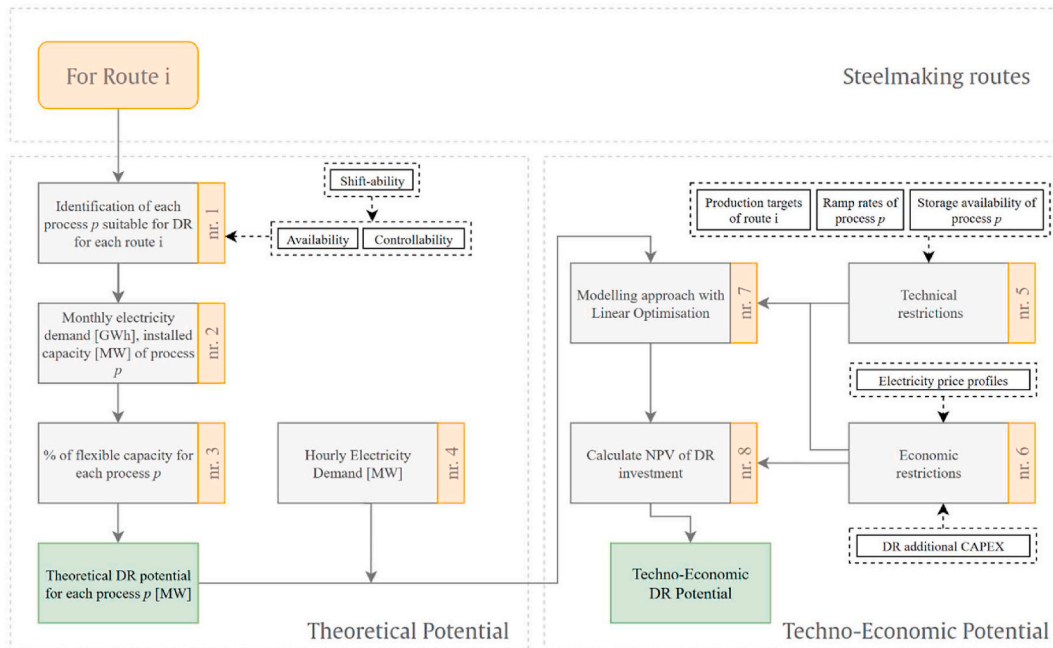


Fig. 3. Activity diagram for calculating DR potential, adapted from Dranka et al. [6].

review of Section 2, these criteria limit the scope of the study to the following technologies: (i) H₂-based direct reduction of iron (H₂-DRI-EAF) and (ii) BF-BOF with pre-combustion SEWGS carbon capture (BF-

BOF-CCUS).

The boundaries of the systems to be modelled are selected based on the processes function. Fig. 2 shows that the core iron and steelmaking

Table 5
Definition of the process steps for each decarbonisation route, as used for the modelling.

Processes steps	Feedstock preparation	Fuel preparation	Ironmaking	Steelmaking	Carbon capture	Power plant
p	p_0	p_1	p_2	p_3	p_4	p_5
H ₂ -DRI-EAF	–	Electrolyser	Shaft furnace	Electric arc furnace	–	–
BF-BOF-CCUS	Sinter/pellet plant	Coke plant	Blast furnace	Basic oxygen furnace	SEWGS carbon capture	Power plant

processes are included – BF, shaft furnace and BOF, EAF, respectively, as well as the fuel and feedstock preparation – i.e., sinter, pellet, coke and H₂. Combustion of WAGs for power production are also included in the boundaries as it can largely influence the DR potential of the BF-BOF-CCUS route. For simplicity, finishing processes are excluded because these vary depending on steel applications.

3.2. Rationale for demand response assessment

This section explains the approach applied to determine the DR potential of the steelmaking routes. The study starts from the definitions of theoretical, technical and economic DR potentials by Dranka et al. [63], as these take into account the body of literature covering DR that has been published in recent years and provide a user-friendly framework for the calculation of DR potentials. The activity diagram adopted in this study, adapted from Dranka et al.'s framework [63] is represented in Fig. 3.

First, the theoretical potential is calculated by: (nrs. 1–2) identifying processes suitable for DR in terms of load shifting and determining their electricity consumption and installed capacity; (nr. 3) identifying the share of flexible capacity, based on the data retrieved from the review in Section 2, to calculate the theoretical potential at process-level. Second, the study assesses the techno-economic potential – i.e., the DR potential limited by technical restriction and driven by electricity prices – by applying a modelling approach (nr. 7) that uses as input data the theoretical potential and: (nr. 4) the electricity load of a reference scenario where no DR is applied, (nr. 5) technical restrictions on ramp-rates, material flows to and from each process and (nr. 6) electricity price profiles. With linear programming, first the potential electricity cost savings are identified (nr. 7) and then, through an ex-post analysis taking into account the CAPEX of the installed technologies, the techno-economic potential of each design is assessed using the net present value (NPV) indicator (nr. 8).

3.3. Modelling of energy flows and demand response strategies

This section reports the methods used to apply the activity diagram in Fig. 3. Table 5 reports the processes p of each steelmaking route enumerated in sequential order – nr. 1 of the activity diagram. Specifying the sequence of the processes is relevant for the application of the model in step – nr. 7 of the activity diagram. Furthermore, the section reports the data required for determining the theoretical potential and the techno-economic input data to the model – nrs. 1 to 6 of the activity diagram. The various system configurations are then described. The input parameters to the modelling that are varied in the different configurations are the ones providing the largest constraint to the exploitation of DR, as highlighted by the research gaps in Section 2.

3.3.1. Linear programming model formulation

To assess the techno-economic DR potential by minimising electricity-related operating costs taking into account technical constraints, energy and material flows are optimised between the processes p of H₂-DRI-EAF and BF-BOF-CCUS routes, as represented in Fig. 2 and Table 5. The linear programming model applied is developed with the open source software PuLP written in Python and solved using Gurobi.

For each steelmaking route, the cost minimisation problem is given by Eq. (1):

$$\min \sum_t^T \sum_p^P c_t \bullet e_{p,t} \quad (1)$$

with c_t the day-ahead electricity price at hour t in the monthly time-horizon T and $e_{p,t}$ the decision variable representing the electricity consumption of process p at hour t .

The optimisation problem is subject to a number of constraints. First, the relation between electricity consumption and material production of

each process are ensured by introducing the specific electricity consumption in Eq. (2):

$$e_{p,t} = \eta_p \bullet m_{p,t}^{in} \bullet \theta_p \forall p, t \quad (2)$$

with η_p the specific electricity consumption of process p , $m_{p,t}^{in}$ the decision variable representing the material flow input of process p at hour t and θ_p the parameter representing the material efficiency – i.e., the ratio of output to input material for each process. The electricity consumption of each process is constrained between a minimum and a maximum operating electric capacity, as in Eq. (3):

$$E_p^{min} \leq e_{p,t} \leq E_p^{max} \forall p, t \quad (3)$$

with E_p^{min} the minimum and E_p^{max} the maximum capacity of process p . Second, Eq. (4) ensures that the steel production of each route reaches at least the predetermined manufacturing target:

$$\sum_t^T m_{p,t}^{out} \geq ST \quad \text{for } p=3 \quad (4)$$

with $\sum_t^T m_{p,t}^{out}$ the sum of the material flow exiting the steelmaking process within the time-frame T and ST the steel production target. Third, Eqs. (5)–(8) ensure the flow of materials within and between processes taking into account storage availability. Constrains the material flow within a process:

$$m_{p,t}^{out} = m_{p,t}^{in} \bullet \theta_p - \Delta s_{p,t} \forall p, t \quad (5)$$

with $m_{p,t}^{out}$ and $m_{p,t}^{in}$ the material flows output and input of process p at time t , respectively, θ_p the material efficiency of process p and $\Delta s_{p,t}$ the decision variable representing the storage level variation between time t and $t - 1$. Storage levels are constrained within minimum and maximum capacities by Eq. (6):

$$S_p^{min} \leq s_{p,t} \leq S_p^{max} \forall p, t \quad (6)$$

with S_p^{min} and S_p^{max} the minimum and maximum storage level capacities, respectively. Furthermore, the initial and final storage level s_p^{ini} and s_p^{end} have to be equal so that a whole storage cycle is taken into account, as in Eq. (7):

$$s_{p,t} = s_p^{ini} = s_p^{end} \forall p, t = 0, T \quad (7)$$

Lastly, Eq. (8) ensures the flow of materials between processes, where $p + 1$ is the process subsequent to p , following the order described in Table 5.

$$m_{p+1,t}^{in} = m_{p,t}^{out} \forall p, t \quad (8)$$

3.3.2. Techno-economic parameters

The study assumes all steelmaking plants to have a production capacity of 2.1 Mt_{CS}/year, based on the average European plant for primary steelmaking [44]. Each process is designed accordingly, assuming a capacity factor utilisation of 95%. Table 6 reports techno-economic parameters of the processes categorised by steelmaking route and by the function performed. Technical parameters are size of the electrical equipment, specific electricity consumption and flexible capacity. With these, the DR theoretical potentials are calculated at process-level. The potentials at plant-level are calculated by including ramp-rates, steel production targets and CAPEX of plants and storages, if these resulted relevant according to the review. All CAPEX are estimated for the year 2030, which is realistic time frame for the operations of these plants. The method to assess storage sizes is reported in Section 3.3.3. After the modelling simulations, the NPV of the additional investments required for DR strategies is calculated, assuming a discount rate of 5%.

Multiple electricity price profiles are selected for the modelling to

Table 6

Techno-economic parameters of the steelmaking routes for the Baseline system. “t.b.d.”: to be defined in the following sections; “-”: not relevant or applicable; “%FL/h”: share of full load per hour. Sources: own review, Gazzani et al. [55], Dolci [64], Rechberger et al. [65], Somers [33], Bellotti et al. [66], Gorre et al. [67], Xi et al. [54], De Vita et al. [68], Toktarova et al. [77].

Process step	Units	Feedstock preparation	Fuel preparation	Ironmaking	Steelmaking	Carbon capture	Power generation
Steelmaking route	H₂-DRI-EAF						
Component		–	Electrolyser	Shaft furnace	EAF	–	–
Material input		–	Water	Iron ore, H ₂	DRI, Scrap steel	–	–
Material output		–	H ₂	Sponge iron (DRI)	Crude steel	–	–
Installed electrical capacity input	MW _{el}	–	t.b.d.	75	135	–	–
Specific electricity consumption	MWh/t _{CS}	–	2.70 ^a	0.30	0.50	–	–
Share of flexible capacity	%	–	100%	70%	100%	–	–
Theoretical DR	MW _{el}	–	650	53	135	–	–
Ramp-rates	%FL/h	–	100%	100%	100%	–	–
Storage capacity	t _{H₂} ^b	–	t.b.d.	–	–	–	–
Component CAPEX	€/kW _{el}	–	880	–	–	–	–
Lifetime	years	–	10	–	–	–	–
Storage CAPEX	€/t _{H₂}	–	160,000	–	–	–	–
Lifetime	years	–	20	–	–	–	–
Steel production target	Mt _{CS} /y	2					
Steelmaking route	BF-BOF-CCUS						
Component		Sinter plant	Coking plant	Blast furnace	Basic oxygen furnace	SEWGS	Power plant
Material input		Iron ore	Coal	Sinter, Coke	Pig iron	WAGs	WAGs
Material output		sinter	Coke, WAG	Pig iron, WAG	Crude steel, WAG	Compressed CO ₂ , WAGs	Combustion gas
Installed electric capacity input	MW _{el}	–	–	–	–	40	160 ^c
Specific electricity consumption	MWh/t _{CS}	–	–	–	–	0.14	0.65 ^c
Share of flexible capacity	%	–	–	–	–	93% ^d	60% ^e
Theoretical DR	MW _{el}	–	–	–	–	37.2	96
Ramp-rates	%FL/h	–	–	–	–	100%	35%
Storage capacity	Nm ^{3f}	–	–	–	t.b.d. ^g	–	–
Storage CAPEX	€/Nm ³	–	–	–	25	–	–
Lifetime	years	–	–	–	20	–	–
Steel production target	Mt _{CS} /y	2					

Notes: ^aassuming H₂ demand of 60 kg_{H₂}/t_{CS} and an efficiency of PEM electrolyser of 74%; ^bassuming that H₂ is stored at 200 bar and 25 °C, energy content of 33.3 kWh/kg_{H₂}; ^cpower output; ^dassuming only the CO₂ compressor is flexible; ^eassuming the power plant has a minimum operating load of 40% of the installed electric capacity; ^fassuming WAGs energy content of 1.56 kWh/Nm³ and production of 1035 Nm³/t_{CS}; ^gWAGs storage.

Table 7

Sources and derivation of the electricity price profiles applied in the modelling.

Name	Model and source	Power system year	Weather year	Country	Characteristics
MIX-H2 (1)	MIX-H2 [69]	2030	1987	Germany	Over two third of the generation capacity installed is wind and solar power, the remaining capacity is equally distributed among hydropower, coal, natural gas and biomass power plants.
MIX-H2 (2)			1998		
MIX-H2 (3)			2005		
Sens-high	PLEXOS [71]	2050	2010	Germany	Almost half of the generation capacity is wind and solar power, most of the remaining generation is provided by expansive biomass power plants.
Sens-low	Wuijts et al. [72]	2040	1982	Sweden	A large implementation of storage and transmission capacities are foreseen.

capture the uncertainty of future electricity prices, by varying weather years and generation portfolios. The main characteristics of these profiles are reported in Table 7. Three price profiles are retrieved from the MIX-H2 scenarios [69] derived with the model METIS [69,70], for weather years that capture a wide range of intermittent renewable generation. Whereas to assess the robustness of the results, a sensitivity analysis is performed with two additional price profiles which capture different mix-generation portfolios resulting in wither high and low average prices and variability – i.e., Sens-high, Sens-low. To capture seasonal variabilities a month for each season is selected and shown in Fig. 4. The profiles have monthly time-horizon and hourly resolution. The study assumes that the steelmaking plants have perfect forecast of

day-ahead prices and voluntarily increase or decrease the electricity consumption without any pre-agreed binding contracts – i.e., P-flex. Furthermore, it is assumed that the steelmaking plants are not price setters but only price takers – i.e., the increase or decrease of the plants’ electricity consumption does not affect the price of electricity. This assumption may increase the DR potential because a load change on the grid affects the electricity price to a certain extent.

3.3.3. Scenarios development

The study develops two sets of scenarios to assess the impact of varying the parameters that may affect the DR potential the most, which are selected according to the review. For both steelmaking routes, our

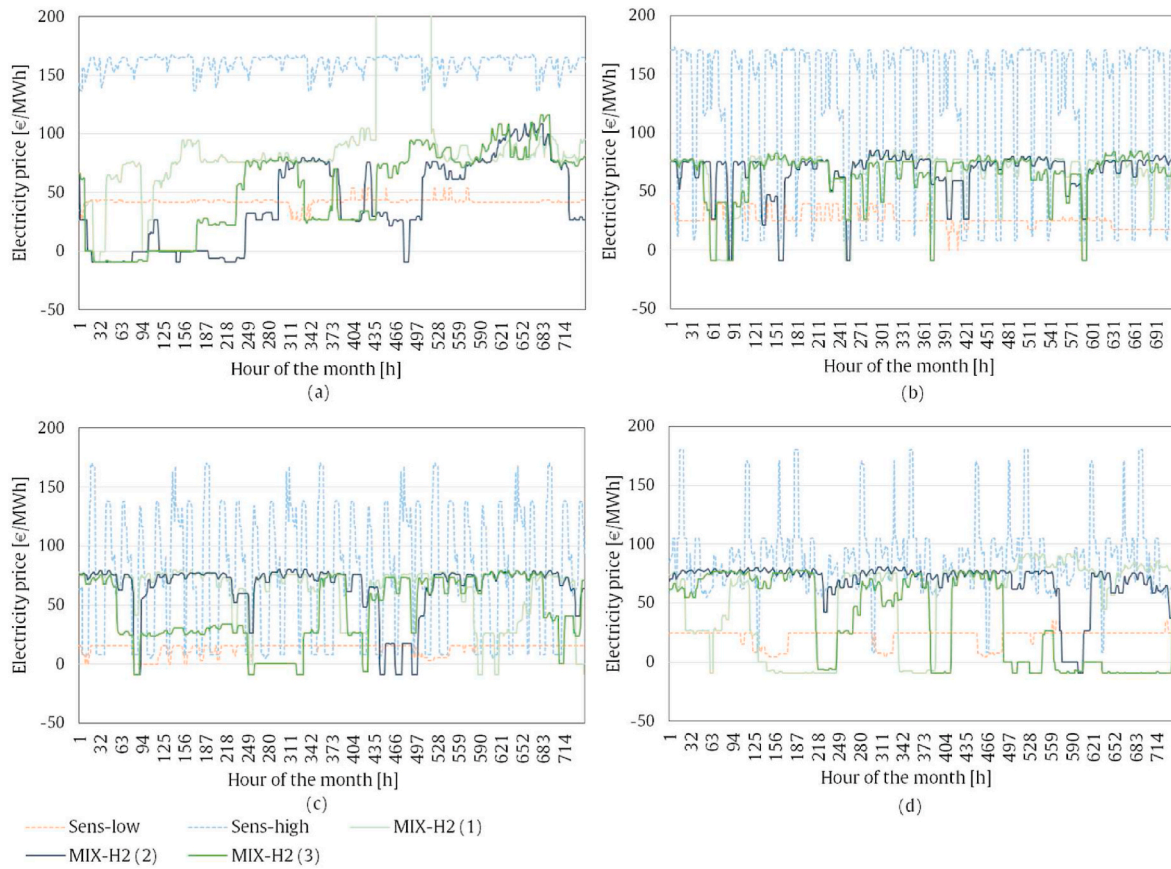


Fig. 4. Electricity price profiles applied for all optimisations – MIX-H2 (1), MIX-H2 (2), MIX-H2 (3) – and for the sensitivity analysis – Sens-low, Sens-high – for (a) January, (b) April, (c) July and (d) October. MIX-H2 (1) has a peak from hour 435 to 500 during January (a) that reaches prices of 900 €/MWh.

Table 8

Technical parameters of first set of scenarios. Abbreviations: CF capacity factor, DR demand response.

Scenarios	Electrolyser capacity MW _{el}	Electrolyser CF	DR strategies
Reference	650.0	95%	NO
Baseline	650.0	95%	YES
Electro25	812.5	75%	YES
Electro50	975.0	63%	YES
Electro75	1137.5	54%	YES
Electro100	1300.0	47%	YES

starting point is the computation of the Reference scenario, characterised by the systems in Table 6 with no DR strategies applied, and the Baseline scenario, characterised by the system in Table 6 where DR strategies are applied.

Table 8 reports the first set of scenarios. The electricity costs of the H₂-DRI-EAF route are optimised while increasing the size of the electrolyser by 25%, 50%, 75%, and 100% compared to the Baseline scenario that runs the electrolyser at 95% capacity factor. Electro25, Electro50, Electro75 and Electro100 scenarios run their electrolysers at lower capacity factor thus enabling operations at times of lower electricity prices. The size of storages are left unconstrained in this first set of scenarios, to determine their optimal size in the context of minimisation of electricity costs.

The second set of scenarios optimise the steelmaking routes by varying the storage sizes of H₂ and WAGs. Storage sizes are relevant parameters because they decouple the operations of the processes within a steelmaking route, allowing the processes to exploit to a higher degree their theoretical DR potential. Storage sizes are left unconstrained in the

first set of scenarios and these determine the starting point for this second set of scenarios. Therefore, the variation of storage sizes are provided in Section 3.4, after assessing the results from the first set of scenarios.

3.4. Results

Fig. 5 shows two aspects of the techno-economic potential of the Reference and Baseline scenarios: (a) electricity cost variation and (b) amount of electricity shifted within the month. With both H₂-DRI-EAF and BF-BOF-CCUS operating with 95% capacity factor, in Baseline, 5% and 7% of consumption is shifted leading to a decrease of electricity costs – or an increase in profits for BF-BOF-CCUS – of 5% and 7%, respectively. In absolute terms, Fig. 6 shows that the advantages of load shifting are more pronounced for the H₂-DRI-EAF route due to a higher electricity consumption than the BF-BOF-CCUS route leading to electricity costs savings of 17 €/t_{CS} by shifting 30 GWh/month against 2 €/t_{CS} by shifting 9 GWh/month. The average monthly variation follows the same decreasing trend, although this is on average more pronounced for January and less pronounced for April.

3.4.1. First set of scenarios – increasing electrolyser capacity

In the first set of scenarios, the Baseline is calculated for the H₂-DRI-EAF and the BF-BOF-CCUS routes and electrolyser size is increased for the H₂-DRI-EAF route. Fig. 6 shows that the Baseline theoretical potential of H₂-DRI-EAF is more than six times the potential of BF-BOF-CCUS and, although almost 10% of this can be harnessed in the latter as opposite to 5% in the H₂-DRI-EAF route, the techno-economic DR potential of the BF-BOF-CCUS route is inherently smaller than the H₂-DRI-EAF route. When increasing the electrolyser size, the theoretical potential of H₂-DRI-EAF expands, as shown by the blue columns in

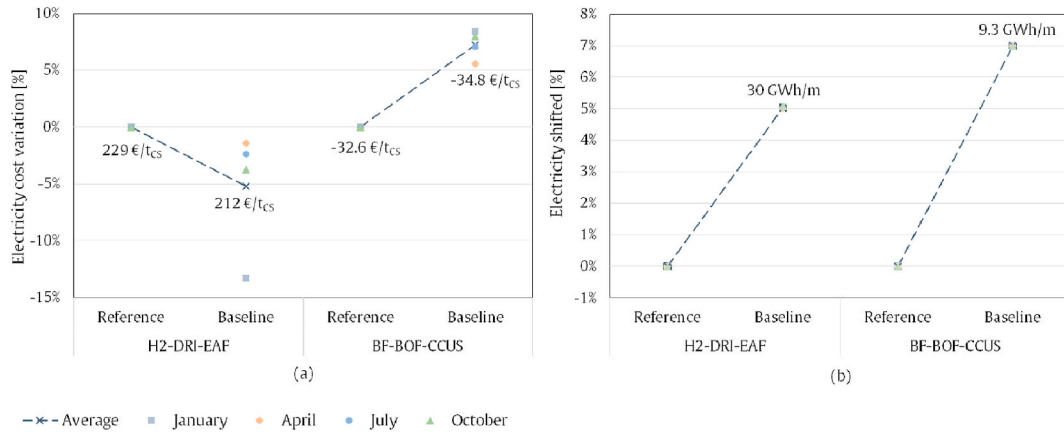


Fig. 5. Techno-economic DR potential of H₂-DRI-EAF and BF-BOF-CCUS routes, shown as electricity cost per tonne of crude steel and its variation (a), and electricity shifted per month (b).

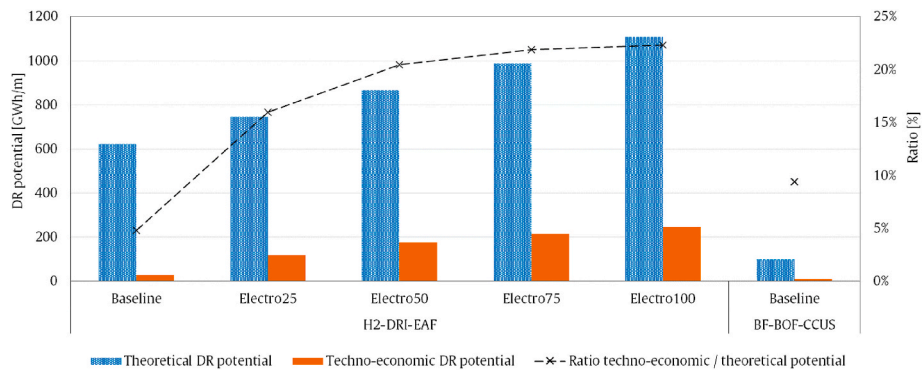


Fig. 6. Comparison of theoretical and techno-economic DR potential, the latter shown as the average electricity shifted over a month as in Fig. 5(b).

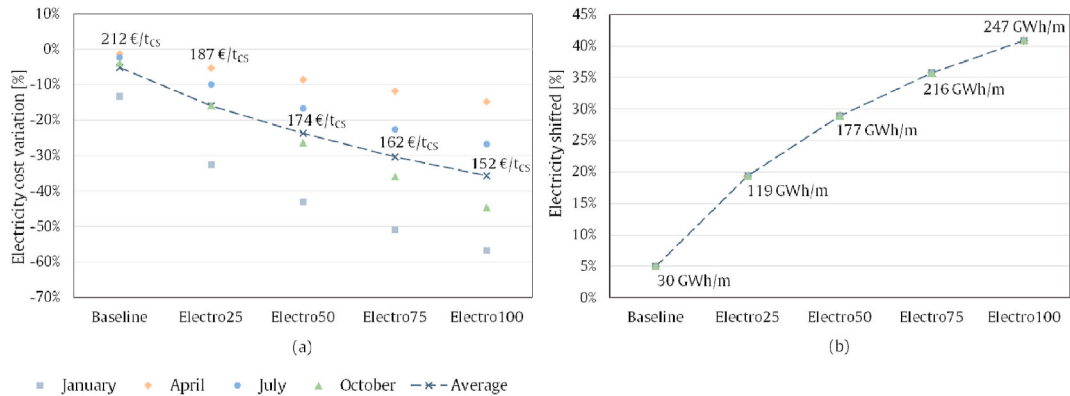


Fig. 7. Techno-economic DR potential of H₂-DRI-EAF with the first set of scenarios, shown as electricity cost per tonne of crude steel and its variation (a), and electricity shifted per month (b).

Fig. 6. The techno-economic potential, represented by the orange columns as the electricity shifted during the simulated months, also rises. By expanding the electrolyser size, and H₂ storage sizes accordingly, the share of theoretical potential that can be exploited increases, as shown by the black dotted line. The biggest growth of this ratio occurs when oversizing the electrolyser capacity by 25%, then the curve flattens off.

Fig. 7 focuses on the techno-economic DR potential showing electricity cost variations in Fig. 7(a) and electricity shifted in Fig. 7(b). Fig. 7(a) shows that there is an average reduction of electricity costs going from 212 €/t_{CS} to 152 €/t_{CS} for Baseline to Electro100 scenarios with relative cost variation of up to almost 60% for January, on average,

compared to the Reference. Fig. 7(b) shows that from the inflexible consumption of the Reference scenario, the electricity shifted increases up to 40% of total consumption, or 247 GWh/month. The amount of electricity shifted per month does not vary according to the electricity price input because it is always limited by the technical constraints of the plant.

3.4.2. Second set of scenarios – decreasing storage sizes

In the second set of scenarios storage sizes are decreased from a starting value. For each scenario, the starting value is defined as the average unconstrained storage size of each month and price profile.

Table 9

Results of storage sizes from some unrestrained cases of the first set of scenarios and definition of second set of scenarios by decreasing the storage sizes.

Steelmaking route	Scenario	Storage type	Storage size (first set scenarios)	Scenarios name	Storage size relative to first set of scenarios	Storage size	Volume	
			t_{H_2}/Nm^3_{WAGs}		%	t_{H_2}/Nm^3_{WAGs}	$m^3_{H_2}$ ^a	
<i>H₂-DRI-EAF</i>	Electro25	H ₂	1126	H2S 75	75%	845	59,912	
				H2S 50	50%	563	39,918	
				H2S 25	25%	282	19,994	
				H2S 00	0%	0	0	
	Electro75			2093	H2S 75	75%	1570	111,316
					H2S 50	50%	1047	74,234
					H2S 25	25%	523	37,801
					H2S 00	0%	0	0
<i>BF-BOF-CCUS</i>	Baseline	WAGs	$8.3 \cdot 10^6$	WAGS10	10%	$8.3 \cdot 10^5$	–	
				WAGS100	1%	$8.3 \cdot 10^4$	–	
				WAGS1000	0.1%	$8.3 \cdot 10^3$	–	

^a At pressure of 200 bar and temperature of 25 °C [73].

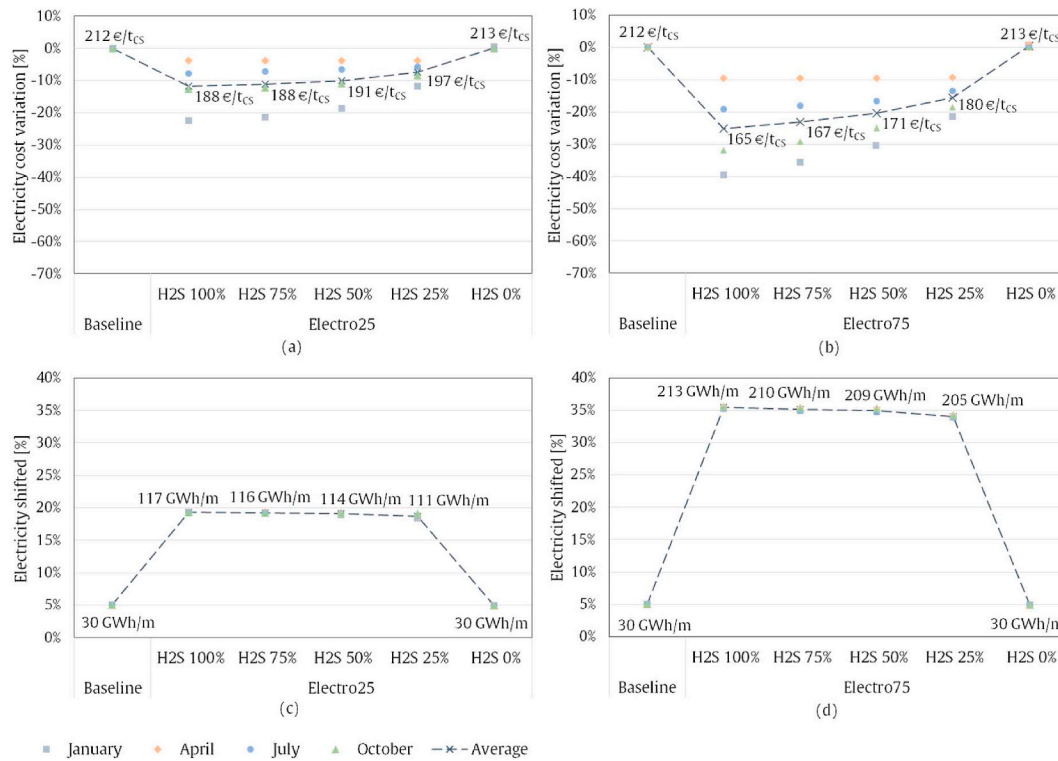


Fig. 8. Techno-economic DR potential of H₂-DRI-EAF with the second set of scenarios, shown as electricity cost per tonne of crude steel and its variation (a–c), and electricity shifted per month (b–d), for Electro25 (a–b) and Electro75 (c–d).

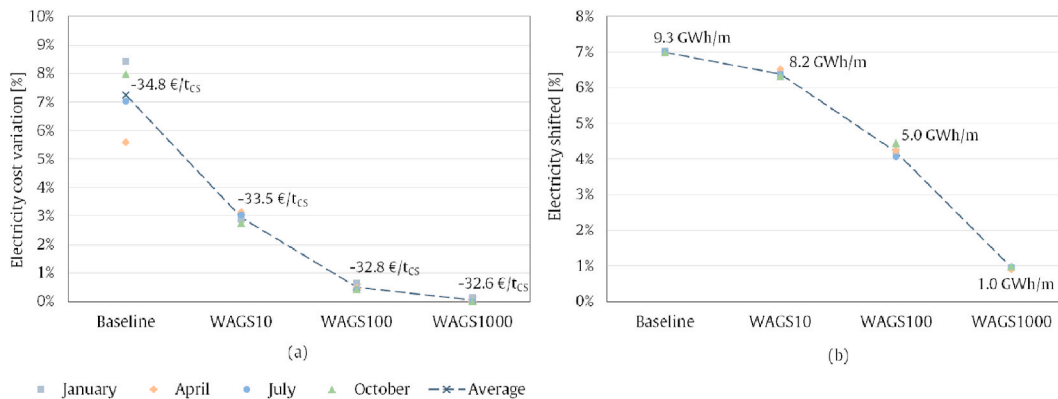


Fig. 9. Techno-economic DR potential of BF-BOF-CCUS with the second set of scenarios, shown as electricity cost per tonne of crude steel and its variation (a), and electricity shifted per month (b).

Table 9 reports these values and the decreased storage sizes that are chosen to ensure feasibility of deployment in regards of volume and investment costs. Electro25 and Electro75 are chosen as exemplary cases among the first set of scenarios for the H₂-DRI-EAF route and optimised with 75%, 50%, 25%, 0% of H₂ storage capacity. These factors are chosen to assess specific configurations that show the impact of discrete variations of H₂ storage size relatively to the oversized electrolyser capacity, from the optimal size to zero. Fig. 8(a and b) shows that decreasing the storage size up to 50% lowers electricity costs savings by less than 4% points compared to unconstrained storage size (H₂S 100%). In other words, decreasing the H₂ storage size of 50% increases electricity costs by 2 €/t_{CS} and 7 €/t_{CS} in the Electro25 and Electro75 scenarios, respectively. Using no H₂ storage leads to a slightly higher cost variation than the Baseline. If no H₂ storage is deployed, the additional electrolyser capacity is unexploited because the shaft furnace cannot decouple its operations from the electrolyser, thus the two processes must be modulated simultaneously. For the BF-BOF-CCUS route, the storage capacity is exponentially reduced to 10%, 1% and 0.1% of WAGs unconstrained storage size. These major reductions are justified by an extremely large optimal storage size resulted from the electricity costs minimisation of the first set of scenarios, which does not take into account the costs of investment nor spatial constraints. The unconstrained storage size results over eight millions Nm³WAGs, which, to put it into perspective, is over 27 times the WAGs storage size of the Tata Steel BF-BOF plant located in Ijmuiden that has over three times the steel production capacity than the BF-BOF-CCUS under analysis [50]. Thus, more realistic configurations are captured by the logarithmic scale chosen to reduce WAGs storage. Fig. 9 shows that decreasing the storage size by 10, 100 and 1000 times reduces the electricity shifted by 12%, 46% and 91%, however, the impact on the electricity costs is maximum 2 €/t_{CS}.

3.4.3. Scenarios comparison and sensitivity analysis

Fig. 10 shows the profitability of the investments for all scenarios in terms of NPV per tonne of crude steel and how this changes in relation to varying electrolyser and H₂ storage CAPEX. The CAPEX of WAGs storage is not varied as a price reduction is not expected. Almost all H₂-DRI-EAF configurations have positive NPV thanks to the high electricity costs savings achievable by applying DR strategies with MIX-H2 prices. For each set of scenario, an optimal configuration is found that maximises the NPV, as shown by the black line Normal CAPEX. However, the results depend on uncertain parameters such as electrolyser and H₂ storage CAPEX in 2030. Therefore, the NPV is also calculated with electrolyser and storages CAPEX varied by ±50% [39,67], which influences the optimal sizes of electrolyser and storage, resulting in no specific configuration that maximises the benefits of applying DR strategies. Nonetheless, it can be noted that electrolyser CAPEX has the largest influence on the NPV, as shown by the blue and orange lines

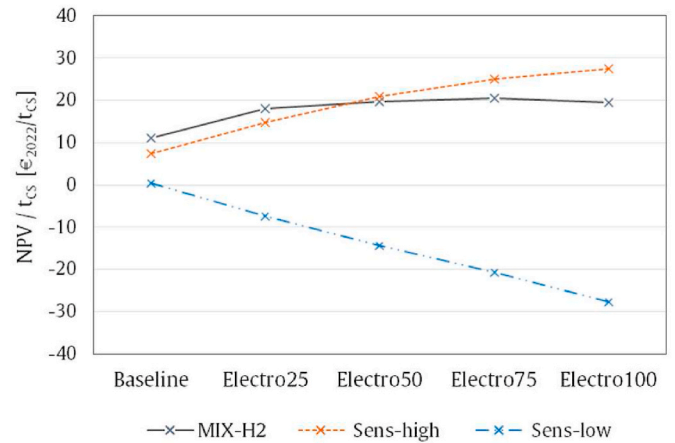


Fig. 11. Net present value per tonne of crude steel [NPV/t_{CS}] of H₂-DRI-EAF system with increasing electrolyser sizes for MIX-H2, Sens-high and Sens-low, considering additional investments compared to the Reference scenario.

delimiting this range of variability. Whereas for the BF-BOF-CCUS route, the NPV is negative for the Baseline scenario, which deploys an extremely large WAGs storage, and it is just above zero for the other scenarios. The low or unprofitability is caused by lower electricity costs savings achievable compared to the H₂-DRI-EAF route as the BF-BOF-CCUS route presents over six times lower electricity demand and larger processes' technical constraints.

Furthermore, various electricity prices profiles are applied to the first set of scenarios to assess the robustness of the results. Fig. 11 shows a great dependency of the profitability of investing in additional electrolyser capacity to electricity prices. Sens-high, that has a price profile derived from a highly renewable power system with 113 €/MWh of average and 39 €/MWh of standard deviation, observes an increasing specific NPV with higher electrolyser capacities thanks to the higher cost savings achieved, with the optimal point found with Electro100. However, Sens-low, with 26 €/MWh of average and 6 €/MWh of standard deviation, observes a merely positive NPV for Baseline and negative for the other scenarios. The low prices and variability of Sens-low do not justify the cost of 143 M€ for the additional electrolyser capacity of Electro25 compared to Baseline.

4. Discussion

The analysis of this study starts with the selection of two new low-carbon steelmaking technologies based on the criteria of CO₂ emissions reduction, TRL and relevance for flexibility options. While the first

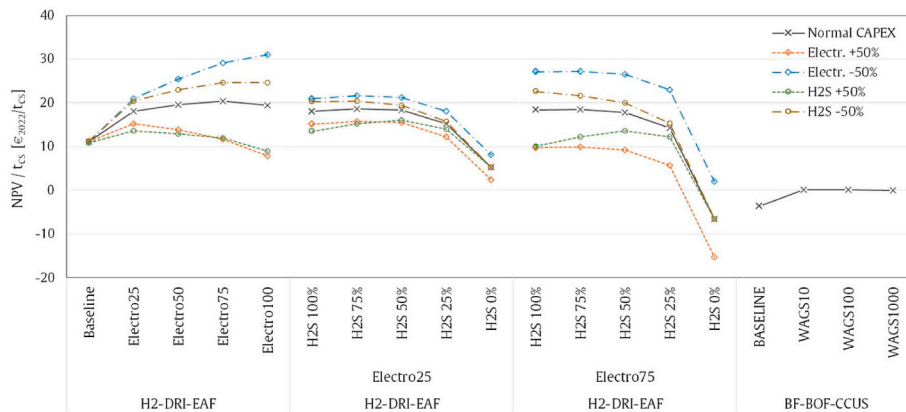


Fig. 10. Net present value per tonne of crude steel [NPV/t_{CS}] of all systems and scenarios, considering additional investments – i.e., electrolyser and storage capacities surplus compared to the Reference scenario. Abbreviations: Electr.: electrolyser CAPEX, H2S: H₂ storage CAPEX.

two criteria are supported by a large body of literature, as shown by the review, research on flexibility options for low-carbon technologies is limited due to the still uncertain development of the steel sector. Therefore, this study may omit potentially relevant low-carbon technologies for flexible operations. Furthermore, this study focuses on the core energy-intensive processes of the industry thus excluding finishing processes. However, the relatively simple decarbonisation of these processes at low-medium temperature through electrification also presents DR potential that should be further explored. This study also excludes costs of operations, potential nightshift labour, other fuels costs, energy penalties of H₂ compression for storage and investment costs of devices that allow automated DR, which leads to an additional overestimation of the DR potential. Furthermore, process duration is not considered, which could delay the material flows from one plant to another by a few hours. Actual operations may impose constraints on DR by, for example, limiting the availability of the processes to be ramped-up or -down at specific times. Nonetheless, steelmakers often have configurations with multiple furnaces working in parallel thus allowing multiple combinations and perhaps increased operational flexibility, thus this assumption possibly does not affect the results to a large extent. Many of these limitations require detailed modelling of an industrial site, although it must be noted that modelling of industrial processes inherently simplifies the complexities of real production processes.

Despite these limitations, this study emphasises the dependency of the DR potential and of optimal plants' design on external uncertain factors such as future electricity prices. The study assumes that steel plants have perfect forecast of electricity prices and that these prices are unaffected by demand shifting. However, higher consumers' participation in DR strategies leads to reduced price peaks, negatively affecting the costs saving potential. Especially for electricity intensive technologies such as the H₂-DRI-EAF, optimal plant configuration not only depends on the specific industrial site but also on the local power system configuration. Elsheikh et al. [39] finds a reduction of electricity costs of over 100 €/t_{CS} by feeding a 50% oversized electrolyser with solar locally generated and grid electricity. This is double the cost savings achieved in this analysis when applying Sens-high prices and triple the average assessed with the MIX-H2 prices. The price profile applied by Elsheikh et al. [39] has lower average and variability than Sens-high. However, the system assessed also employed locally produced solar power and supports greater flexibility by allowing the use of scrap to replace DRI, thus including the electrolyser load shedding option. Storing H₂ locally in salt caverns is another approach to greatly reduce H₂ storage costs while maintaining the same DR potential, although constrained by geographical limitations [74]. The option for steelmakers to purchase H₂ instead of locally producing it, either electrolytic or not, strongly decreases the potential calculated in the study as electricity consumption would be reduced by over 75%. Nonetheless, DR strategies could still be applied to the EAFs and the shaft furnace, although more research should focus on the realistic flexibility of the latter.

The less electricity-intensive BF-BOF-CCUS route inherently offers less flexibility potential due to the smaller electric capacity than H₂-DRI-EAF. Retrofitting a pre-combustion carbon capture technology such as SEWGS on the power plant does not influence its dispatchability and the results of 3% additional profits of this study are in line with the results of the review for the BF-BOF route. However, the carbon capture application comes with an energy penalty. Manzolini et al. [75] calculates a 17% percentage points decrease of the plant electric output if supplying electricity to the carbon capture system. Overall, this study finds null or negative profitability of investing in additional WAGs storage size to exploit larger dispatchability of the power plants. However, the potential for retrofitting existing BF-BOF plants with carbon capture and pre-existing WAGs storage might limit additional investments.

Introducing the concept of achievable potential by Dranka et al. [63] is important to place the results in a practical context. The achievable potential goes beyond the theoretical and techno-economic potential calculated in this analysis by considering consumer acceptance to load

intervention. Assessing this potential is complex due to factors influencing it such as social behaviour and market design. Integrating considerations of consumers acceptance in the analysis involves the examination of qualitative variables and barriers and their implementation in the modelling. It worth noting that, as iron and steel plants are large enterprises primarily driven by profit, their willingness to load adjust in favour of economic remuneration increases the higher the compensation. Therefore, electricity market stakeholders and policy makers should encourage economic compensations for flexibility services by these large consumers.

5. Conclusion

This study aims at consolidating knowledge on demand response (DR) options within present-day iron and steelmaking technologies through a literature review, and at identifying and comparing the DR potential of selected low-carbon technologies under various components and power system configurations. Starting from the literature review, the study has examined the DR potential of scrap-based electric arc furnaces (scrap-EAFs) and blast furnace-basic oxygen furnace (BF-BOF). Scrap-EAF exhibits high potential for flexibility thanks to its batch and electricity-intensive processes, featuring electric capacities on the scale of 60–170 MW. In today's applications, DR is exploited by EAFs mainly in the form of load shedding, despite presenting high cost for missed load. Modelling studies have shown that load shifting, i.e., delaying the start of batch melting, can reduce electricity operating costs by 5%–46% without compromising steel production. The main constraint limiting load shifting is the capacity utilisation factor of the plant. The study shows that even a capacity factor of 95% present some degree of flexibility and, for reference, scrap-EAFs in the EU operated at an average capacity factor of 83% in the last twenty years [76]. BF-BOF provides flexibility to the power system by dispatching the power plants where work arising gases (WAGs) are combusted, whose size can vary from tens of megawatt to almost 1 GW. WAGs storage size is a crucial factor to decouple the continuous high temperature manufacturing processes from the power plants operations. The dispatchability allowed by present-day typical sizes of WAGs storage, i.e., WAGs production of a few hours, can increase electricity profits by 3%–6%. Contrastingly to scrap-EAF plants, BF-BOF has highly polluting processes that are expected to be decommissioned or retrofitted with carbon capture technologies in the coming decades.

This study also evaluated the development of DR potential within the steel sector by focusing on two technologies for primary steelmaking expected to be operationally ready before 2050 and capable of some degree of flexibility: the hydrogen-based direct reduction or iron with EAFs (H₂-DRI-EAF) and BF-BOF retrofitted with the pre-combustion SEWGS carbon capture technology (BF-BOF-CCUS). In addition to comparing different technologies, the novelty of the study lies in the modelling input of electricity marginal price profiles derived from future power system configurations and for multiple weather years. The optimisation of electricity costs (or profit) considered various sizes of electrolyser, H₂ and WAGs storages while maintaining constant steel production. For a H₂-DRI-EAF plant, it was found that between 5% and 40% of electricity consumption can be shifted with electrolyser capacity factor ranging from 95% to 47%. This leads to monthly average cost saving between 5% and 35% of electricity costs, with monthly variations reaching up to 60%. For a BF-BOF-CCUS plant, it was found that 3 to 27 times less electricity can be shifted by dispatching the power plants, leading to a profit increase of about 3% if WAGs storage is in place with typical sizes as today's BF-BOF plants, thus requiring minimum investments to apply flexibility strategies.

On the contrary, additional investments are required to harness larger levels of flexibility from the H₂-DRI-EAF technology. The optimal H₂ storage size was found to vary with different electrolyser configurations, but in all cases that size corresponds to a few hours of production in a medium-sized steel plant. The profitability of investing in

electrolyser overcapacity exhibits significant variability with respect to electrolyser CAPEX and electricity prices. Under electricity prices with medium average and standard deviation – i.e., 64 €/MWh and 75 €/MWh, respectively – the optimal electrolyser capacity factor is 54% with a net present value (NPV) of additional capacity investment of 20 €/t_{CS} for a medium-sized steel plant. Increasing or decreasing the electrolyser CAPEX by 50% from 880 €/kW_{EL} affects the NPV by almost 50% and changes the optimal design to 75% and 47% capacity factors, with higher and lower CAPEX respectively. Nonetheless, the largest impact on the profitability of investing in electrolyser overcapacity is given by electricity prices. A sensitivity analysis shows that electricity prices with either low or high averages and standard deviations change the optimal electrolyser capacity factor to 95% and well under 47%.

Electricity price profiles are highly influenced by power system configurations, which in turn depends on geographical conditions impacting the deployment of low-carbon power generators, market design and the availability of other sources of flexibility, such as electric storage or transmission capacities. Overall, the results of this study are particularly relevant for steelmakers using highly electrified industrial processes in countries expected to rely on non-dispatchable power sources in the future. As the transition towards a low-carbon power sector and iron and steel production takes shape, it is crucial to implement the right mechanisms to incentivise the exploitation of DR strategies where flexibility is needed. In fact, industrial DR can offer benefits to both the power system and industrial stakeholders. From a power system perspective, DR offers advantages such as peak shaving, valley filling, frequency regulation, reduction in CO₂ emissions and reduced investments in other flexibility sources. Therefore, it becomes important for countries with existing or projected high flexibility demands to foster collaborations among policy makers, industrial and electricity market stakeholders. This cooperation should establish effective data communication, financial incentives and regulatory framework to allow the active involvement of this highly energy-intensive industry in cost-effective operations of low-carbon power systems. Further research should focus on detailed modelling of actual low-carbon plants considering costs and specific characteristics of steel plants and local power systems. From a system perspective, further research should assess the benefits for the iron and steel sector to exploit its flexibility within a system harnessing multiple flexibility sources.

CRedit authorship contribution statement

Annika Boldrini: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Derck Koolen:** Supervision, Validation, Writing – review & editing. **Wina Crijsns-Graus:** Supervision, Validation, Writing – review & editing. **Ernst Worrell:** Supervision. **Machteld van den Broek:** Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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