Collection of possible decarbonisation barriers (Deliverable D1.5)

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List of acronyms and abbreviations

BF	Blast furnace
BOF	Basic oxygen furnace
CAPEX	Capital expenditure
CBAM	Carbon border adjustment mechanism
CCfD	Carbon contracts for difference
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture and utilisation or storage
CDA	Carbon direct avoidance
CO_2	Carbon dioxide
DR	Direct reduction
DRI	Directly reduced iron
EAF	Electric arc furnace
EEG	German Renewable Energies Act (*Erneuerbare Energien Gesetz*)
EU	European Union
EUA	European Union emission allowances
ETS	Emission trading system
H2-DR	Hydrogen-based direct reduction
IP	Intellectual property
NG	Natural gas
OPEX	Operational expenditure
R&D	Research and development
SR	Smelting reduction
t	Tonne
TRL	Technology readiness level
WP	Work package

Executive summary

This 'Collection of possible decarbonisation barriers' report (D1.5) aims to give a comprehensive overview of all major barriers to the decarbonisation process in the iron and steel industry. It does not assess the specific severity or offer possible solutions to overcome these barriers. Less serious barriers may slow down or limit the development and deployment processes; more serious barriers may block them completely.

The findings of this report are based on desk research evaluating academic and industrial publications, as well as on input provided by EU steelmakers via a scoping questionnaire.

Based on the desk research conducted, four different categories of decarbonisation barriers have been identified:

1. **technical barriers** caused either by the technological development of decarbonisation technologies or by the required mass and energy flows;
2. **organisational barriers** caused by the organisation of technology development or deployment in terms of management, administration or personnel;
3. **regulatory or societal barriers** caused by externally set framework conditions, policies or social acceptability; and
4. **financial barriers** caused by limitations to the economic operation of the iron and steel production.

For each category, four to five specific barriers have been identified and analysed in more detail. Besides the assessment of the barriers themselves, their specific relevance to the stakeholders of the EU iron and steel production is assessed through an evaluation of the consultations with steel producers covering more than 80% of the European steel industry's CO_2 emissions. The definition, background and potential impacts of these barriers can be summarised as follows.

Technical barriers

Within the technical barrier category, four specific barriers affecting the decarbonisation of the EU steel industry have been identified:

- limited availability of raw materials
- limited availability of renewable energy
- limited technical integration potential into existing plants, and
- risk of unsuccessful development.

The **main input materials** for steel production are iron ore as the primary raw material (processed into sinter or pellets), and steel scrap as the secondary raw material. A replacement of the primary raw materials (i.e. ores) by scrap would avoid the energy- and CO_2-intensive step of ironmaking; however, this is strongly limited by scrap availability and product quality issues due to residual impurities from scrap. Additionally, the higher costs of scrap are extremely relevant; the price is expected to further increase as the demand for high quality scrap rises. A shift towards direct reduction plants (to replace the blast furnace-basic oxygen furnace [BF-BOF] route) would result in a high demand for iron ore pellets. The current sintering plants, which allow the use of a wide variety of iron-bearing raw materials and the recycling of most internal residuals, probably have to be replaced in the long-term. This would need new material cycles and new raw material supply chains. New pelletising plants would have to be built on site (causing high investments and space problems for brownfield installations) or an external pellet supply would be necessary (causing a risk of carbon leakage and decreasing flexibility).

The deployment of decarbonisation technologies results in an increased substitution of fossil energy carriers with **renewable energy sources** (including secondary biomass and waste materials). The renewable energy supply will have to be delivered mainly by electricity, which will be consumed either directly (electrification) or indirectly via hydrogen production (e.g. by water electrolysis). Only a smaller part can be supplied by secondary biomass and combustible wastes. The CO_2-free electricity demand of the EU iron and steel industry in 2050 is estimated at 400 TWh per year, corresponding to about half of today's total electricity production from renewable sources. Additionally, fluctuations in renewable electricity production should be considered. These may require, for instance, the implementation of large-scale storage systems (e.g. for electricity or gas) or new approaches to increase demand-response flexibility.

The **technical integration of a new technology into pre-existing physical plants** (brownfield sites) at industrial level requires available space for the new equipment and a connection to the existing material and energy flows. In practice, any steelworks would need comprehensive individual planning and to find room for new installations as well as for their servicing within an already limited physical space. Additionally, production would have to stop (at least partially) while the new equipment is incorporated. Longer downtimes of large parts of a plant can cause a loss of production worth several million euros. A further important aspect is the influence of the new technologies on energy flows, as currently heat and power production relies on gases generated by the processes of the plants (BF gas, BOF gas and coke oven gas) as the main energy sources.

The risk of unsuccessful development refers to failures in achieving either the technical objectives itself or in achieving an economically sound and sustainable result. While the technical functionality of a process is developed during the technical development phase, the economical operation and sustainability is developed at a later stage in the industrial deployment phase. Due to this, a risk of unsuccessful development must be considered for all stages of development and for all technologies, as in all R&D activities. In terms of decarbonisation of the iron and steel industry, due to the fluctuating quality of the raw materials and the huge size of steel production plants, the technical risks of unsuccessful development are still very present during the final stages of development.

Organisational barriers

The category of organisational barriers consists of four specific decarbonisation barriers relevant to the EU steel industry:

- limited availability of qualified staff
- administrative requirements
- issues related to the management of industrial transformation
- issues related to intellectual property management (intra- & inter-firm).

As in any large-scale production process, the planning and operation of (integrated) plants for iron and steel production require significant human resources. Thus, the **availability of qualified staff** is a precondition to pushing forward the development of decarbonisation technologies, including the necessary technical development of new technologies. In the first phase, the development and operation of new technologies need more personnel than usual commercial processes. Additional personnel is necessary when the new technology is installed in addition to the existing ones. Challenges arise with regard to the long-term perspective for the workforce, however.

Administrative requirements may also hinder the development and deployment of low-CO_2 technologies. Authorities may demand proof of compliance with relevant standards, which may be lacking at the time of first implementation. Regarding collaborative research and the funding of projects, internal and external bureaucracy could impose an additional burden.

Considering the fundamental changes of process chains, including energy and raw material supply chains, the decarbonisation of industrial production is a revolutionary **transformation process** whose different phases are extremely difficult to **manage**. It starts with the efforts and issues related to the research and demonstration of the new technologies. Managing the deployment of new technologies in the existing brownfield plants while usual production goes on might be even more important. The related effort significantly exceeds 'normal' business since the scope and time pressure of the changes are fundamentally larger than usual.

Intellectual property management refers to the management of intellectual property (IP) rights. Extraordinary intensive research and development (R&D) activities are needed within the coming decades to decarbonise the steel production. In this context, the use of exclusionary rights generates burdens and limitations for the competitors. This might lead to a delayed or altered implementation of decarbonisation technologies, possibly resulting in less CO_2 mitigation achieved or higher costs. Additionally, the information exchanged between competitors outside of the regulated environments may be decreased, leading to slower technological progress overall.

Regulatory/societal barriers

Among the regulatory or societal barriers to the decarbonisation of the EU steel industry are five specific ones:

- limited availability of permanent CO_2 storage
- limitations stemming from emissions-related legislation (e.g. pricing in EU ETS system)
- limitations associated with social acceptability and environmental protection
- burden by local taxes and fees, and
- uncertainty related to carbon contracts for difference.

For the abatement of remaining CO_2 emissions that cannot be mitigated in the process, Carbon Capture and Storage (CCS) is an option, in particular in the medium-term when not enough renewable energy sources are available yet replace all fossil energy sources. The capacities for **CO_2 storage in Europe are limited.** Current cumulative storage resources are in the range of 10,000-30,000 Gt CO_2, including 1,000 Gt in depleted oil and gas reservoirs. The main share of these capacities is restricted by national legislations due to public concern. Thus, the significance of this barrier is highly depending on the national and regional framework conditions related to CCS.

The economic viability and competitiveness of decarbonisation technologies is subject to **emissions-related legislation** as the **carbon pricing in the EU emission trading system (ETS)**. Meanwhile, substantial increases in carbon price and/or changes in mitigation measures could ultimately result in carbon leakage. This is especially true if one considers that production costs for green steel are expected to be substantially higher than costs for conventional steel. Steel imported from third countries with less stringent climate rules than the EU could be sold at a lower price, while generating comparable or often higher carbon emissions than those linked to EU steelmaking.

The magnitude of the carbon leakage challenge is increased by the global overcapacity and heavy competitive pressure from the global steel markets.

Technologies that are technically and economically viable may not be successfully implemented due to **limited social acceptability**. Such issues have already occurred to CCS and renewable energy installations (e.g. windmills or power supply lines). Other decarbonisation technologies may suffer from similar issues in the coming years (e.g. pipelines for hydrogen or CO_2).

Decarbonisation actions can be subject to additional or changing **local taxes and fees**. One example is that of feed-in tariff schemes which several member states have unilaterally changed to support renewable energy. However, in doing so, they have generated economic uncertainty and increasing investment risks. Specifically, the German Renewable Energies Act (*Erneuerbare Energien Gesetz*, EEG) plays a significant role in local electricity costs. As a matter of fact, under its provisions steelmakers may have to pay additional taxes and fees if they acquire renewable electricity externally instead of producing it internally.

The current set of **national framework conditions** is not fixed for a longer term but is subject to change in coming years. This may for instance be a barrier with respect to the currently discussed implementation of **carbon contracts for difference** (CCfD): A 'strike price' is agreed upon between a state and a producing company over a defined period which anticipates the expected future increase of certificate prices. The aim of these contracts is to hedge the higher future prices. If the 'strike price' is higher than the market price, the state covers the difference. In the opposite case, the company covers the difference. This would guarantee producers of low-carbon steel a fixed future CO_2 emission price, decrease their investment risks and make their decarbonisation projects financially viable already in short-term. However, if national framework conditions in this respect are unknown, precarious and heterogeneous, this may become a barrier.

Financial barriers

Besides the aforementioned non-financial barriers, five specific financial decarbonisation barriers relevant to the EU steel industry have been identified:

- increased operational expenditure
- additional capital expenditure for demonstration plants
- additional capital expenditure for industrial deployment
- limited access to funding and financing, and
- unknown market conditions for clean steel.

The implementation of a technology is highly dependent on its competitiveness. Therefore, attention must be paid to the **operational expenditure** (OPEX) which includes costs for energy, material, operation and maintenance. The OPEX related to energy and material inputs generally make up over half of the total steel production cost. The price of electrical energy is significantly higher than for thermal energy provided by fossil fuels (e.g. seven times higher for coal). It is expected that the electricity prices will significantly rise in almost every EU member state up to 2050. Additionally, new raw material demand (e.g. high quality scrap for increased scrap usage or pellets for direct reduction [DR] plants) may significantly raise the OPEX.

Most breakthrough decarbonisation technologies currently have technology readiness levels (TRLs) in the range of 7, meaning that the important step of demonstration in an operational environment still has to take place. High **capital expenditure for demonstration plants** is due to the fact that the scale of steel demonstration plants is considerable compared to process industries, with capacities ranging from 10 to 100 t per day. Usual demonstration project budgets are between 100 and 200 million euros.

Additional capital expenditure for the industrial deployment of decarbonisation technologies depends on the extent to which the new technology calls for new asset expenditure. This includes not only the investment in the decarbonisation technologies themselves, but also the effort to adapt the existing assets to integrate the new technologies into the brownfield plants. Generally, the costs must be evaluated in relation to the corresponding mitigation potential and vary among plants depending on the local conditions (e.g. investment cycles, availability of secondary biomass).

The high demand in terms of capital expenditure (CAPEX) clearly shows that the development and deployment of decarbonisation technologies need additional financial investments. Thus, the **limited access to funding** is a concern and does not encourage the desired actions. This applies not only to the high investments in demonstrations plants, but also to the even more expensive industrial deployment of decarbonisation technologies.

The production of clean steel, characterised by zero or low CO_2 emissions, will go along with (significantly) higher costs, at least for the foreseeable future. To cover these additional costs, the implementation of new **markets and business models for clean steel** is a promising option. In such an approach, 'clean steel' would be characterised as a different product than conventionally produced steel (premium product), with higher pricings to cover the higher production costs. If such a market for clean steel were created, it would strongly depend on European and worldwide policies. These may include public support (currently unknown), e.g. for public procurement. Additionally, the customer acceptance of higher prices for clean steel-based end products is unknown and may need support by legislative actions.

Evaluation of the specific importance of the barriers to stakeholders

To gain insight into the significance of the identified barriers and their impacts on the overall decarbonisation process, the barriers were the subject of a scoping questionnaire in the first step of the stakeholder consultation. Stakeholders were asked to rate on a scale from 1 (not important) to 5 (very important) the importance of pre-selected barriers to the activity of their respective companies in the short term (2020-30) and in the long term (2030-50). The results presented in this report reflect the situation as of 30 August 2020, thus incorporating preliminary names and categorisation of the barriers. The evaluation is based on detailed responses from 15 stakeholders, which together account for 71% of CO_2 emissions (based on 2020 EU ETS allocations).

The results were further assessed in two different ways: as a general **average** rating and as a **CO_2-weighted** average. The CO_2-weighted average takes into account the stakeholders specific CO_2 emissions based on EU ETS data. Thus, stakeholders emitting larger amounts of CO_2 are weighted correspondingly higher. Based on these methods, the barriers were ranked to identify the main barriers to decarbonisation. In Table 1 the rankings are presented based on the short-term average (2020-30). Table 1 displays both the average and the CO_2-weighted importance ratings for both time frames (2020-30 and 2030-50). In this table, the categories were abbreviated as 'TEC' for technical barriers, 'ORG' for organisational barriers, 'FIN' for financial barriers and 'POSO' for policy or societal barriers.

It is striking that six out of the seven most significant barriers are financial ones. The only exception are the framework conditions created by national or local taxes or fees (ranking 6th) which, however, have financial implications too. Most organisational barriers can be found at the bottom of the table due to the low ranking by the stakeholders. Most rankings – for the average evaluation and the CO_2-weighted evaluation – follow the same trend.

Table 1: Ranking of decarbonisation barriers by steel producers (sorted by 2020-30 average)

1	Decarbonisation Barrier	Cat.	2020-2030		2030-2050	
			Avg.	CO_2	Avg.	CO_2
1	Investments for industrial deployment	FIN	4.80	3.76	4.50	4.51
2	Increase in OPEX (energy/renewable energy)	FIN	4.50	4.75	4.30	4.25
3	Unknown market conditions of clean steel	FIN	4.50	3.85	4.30	3.85
4	Investments for demonstration plants	FIN	4.40	4.59	4.11	3.11
5	Limited access to funding opportunities	FIN	4.30	4.65	4.20	4.06
6	Local taxes and fees (e.g. German EEG)	POSO	4.22	4.19	4.00	4.13
7	Other increase in OPEX (materials, CCS, CCU, etc.)	FIN	4.20	4.49	4.00	3.98
8	Availability of renewable energy	TEC	4.00	4.24	3.90	4.79
9	Bureaucracy and other administrative burdens	ORG	4.00	2.98	3.50	2.66
10	Emission-related legislation (e.g. EU ETS)	POSO	4.00	4.59	4.10	4.70
11	National implementation of other framework conditions (e.g. contract for difference)	POSO	3.63	3.17	3.50	3.17
12	Risk of unsuccessful deployment	TEC	3.60	2.00	3.40	1.90
13	Social acceptance of certain technologies	POSO	3.60	3.92	3.30	3.86
14	Integration of new technologies in existing plants	TEC	3.40	2.64	3.30	2.74
15	Information exchange with other parties, collaborative research	ORG	3.20	3.26	2.90	3.00
16	Management of industrial transformation	ORG	3.10	2.22	2.90	2.21
17	Intellectual property management	ORG	3.10	2.99	2.90	2.99
18	Availability of qualified staff	ORG	2.90	2.60	2.60	2.66
19	Issuing of CO_2 storage permits for CCS	POSO	2.89	3.48	2.67	3.48
20	Availability of raw materials	TEC	2.40	3.28	3.10	3.98

Source: authors' own formulation based on stakeholders' consultation.

<u>Concluding remarks regarding decarbonisation barriers</u>

Different plants will be in different starting positions to integrate new technologies (regarding e.g. the availability of space, the possibilities for industrial symbiosis or even government permits). Therefore, it is extremely difficult to identify any single technology that could be fitted into all existing European steelworks as the best solution. Careful consideration of specific and general conditions is needed to enable the transition towards carbon neutrality. In this context, the stakeholders clearly rated the financial aspects as the biggest barrier to decarbonisation.

In more detail, especially high investment costs for industrial and demonstration plants, increasing OPEX and unknown market conditions for clean steel in particular were assessed as having the highest impact on decarbonisation for both time periods under investigation (2020-30 and 2030-50). Also limited funding opportunities and local taxes and fees had average ratings between 'high' (4) and 'very high' (5). These findings are used as basis for the more detailed impact analysis and discussion of policy options in work package 3 of the Green Steel for Europe project (refer to the Impact Assessment Report – Deliverable D3.2 of the project).

1. Introduction

The purpose of this deliverable is to identify and assess all relevant possible financial and non-financial barriers (i.e. technical, organisational, regulatory or societal) affecting the development and deployment of decarbonisation technologies in the EU iron and steel industry. The findings of this report are based on desk research evaluating academic and industrial publications, as well as on inputs provided by EU steelmakers via a scoping questionnaire.

The term ‘barrier’ is defined in this context as an obstacle to the technical development and/or the industrial deployment of (certain) decarbonisation technologies. The extent and severity of these barriers may vary depending on the considered timeframe and on the respective technologies. Less severe barriers may slow down or hinder the development and deployment processes, whereas more severe barriers may block them completely. Since barriers are defined as abstract concepts, their severity cannot be quantified.

The decarbonisation barriers identified in this deliverable are usually strongly linked to certain framework conditions, which will also be subject to changes in the future with the adjustments to the iron and steel production system. These barriers will influence the industrial deployment scenarios, which will be elaborated in the following tasks 1.4 and 1.5 (Decarbonisation pathways 2030-2050) of the Green Steel for Europe project. Furthermore, the barriers will be used for the specific technology roadmapping in task 1.2 (see deliverable 1.2) to clarify how their relevance changes over time (as the development and the deployment of the corresponding technique progress).

The objective of this deliverable, and one of the first steps of the Green Steel for Europe project, is to provide a list of barriers stemming from the identified problems. This will be a main input for work package 3 which is a second step and has the objective to analyse the impacts of the technologies and barriers, and to propose and assess possible remedies. The discussion of solutions to improve the framework conditions to support decarbonisation (e.g. in terms of policy options) falls outside the scope of this deliverable.

This report aims to give a comprehensive overview of major barriers to the decarbonisation process of the iron and steel industry, without finally estimating their specific severity or stating possible solutions to overcome them. The analyses focus on barriers affecting the decarbonisation of the EU iron and steel industry. Therefore, the scope of this report is more restricted than other published reports dealing with the entire industrial sector (Wyns et al., 2019; Lytton, 2018).

2. Possible barriers to the development and deployment of decarbonisation technologies

As mentioned above, in this deliverable report and the corresponding work within the Green Steel for Europe research project, the term 'barrier' is defined as an obstacle which may impede the development and/or the deployment of (certain) decarbonisation technologies. As a result of the conducted desk research, four different categories of decarbonisation barriers were identified:

1. **technical barriers**, which are caused either by the technological development of decarbonisation technologies or by the required mass and energy flows;
2. **organisational barriers**, which are caused by the organisation of technology development or deployment in terms of its management, its administration or its personnel;
3. **regulatory or societal barriers**, which are caused by externally set framework conditions, by policies or social acceptability; and
4. **financial barriers**, which are caused by limitations to the economic operation of iron and steel production.

These categories and their related specific barriers are summarised in Table 2 on the following page. In the following chapters, the definitions, the background and the potential impacts of these specific barriers shall be further explained. These are distinguished according to the different technologies and to the different stages of their development until their industrial deployment. This will provide the background for the technology roadmapping in the deliverable D1.2 of work package 1, as well as a basis for the impact assessments in WP3. Possible solutions or remedies to the identified decarbonisation barriers will be investigated and presented in WP3.

In general, the starting position of the different plants will differ when it comes to integrating new technologies, in terms of the available space, the possibilities for industrial symbiosis or the legal permits. Therefore, the authors doubt that any single decarbonisation technology could be successfully fitted into all existing European steelworks. Thus, careful consideration of the conditions of each specific plant is needed.

Table 2: List of possible decarbonisation barriers

Technical barriers
• Limited availability of raw materials
• Limited availability of renewable energy
• Limited technical integration potential into existing plants
• Risk of unsuccessful development
Organisational barriers
• Limited availability of qualified staff
• Administrative requirements
• Issues related to the management of industrial transformation
• Issues related to intellectual property management (intra- & inter-firm)
Regulatory/societal barriers
• Limited availability of permanent CO_2 storage
• Limitations stemming from emission-related legislation
• Limitations by social acceptability and environmental protection
• Burden by local taxes and fees
• Uncertainty related to carbon contracts for difference
Financial barriers
• Increased operational expenditure
• Additional capital expenditure for demonstration plants
• Additional capital expenditure for industrial deployment
• Limited access to funding
• Unknown market conditions for clean steel

Source: authors' own composition.

2.1 Technical barriers

A technical barrier is defined as any obstacle to the development or deployment of a specific decarbonisation technology due to its required mass or energy flows or its technological development process. Four specific technical barriers were identified and are presented below.

2.1.1 Limited availability of raw materials

Today, the main input materials for steel production are iron ore as primary raw material (processed into sinter or pellets), as well as steel scrap as secondary raw material. Currently, the primary steel production from virgin ores relies mainly on integrated steel production routes (BF-BOF route), where the BF is used for reduction and melting (ironmaking) and the BOF converts hot metal into steel (steelmaking). The secondary steel production uses an electric arc furnace (EAF) based mainly on smelting steel scrap. In addition, other processes are used on a much smaller scale, such as direct reduction of ores in solid or liquid state. At present, about 80% of iron ore is imported to the EU, whereas steel scrap is exported from the EU (18 Mt in 2016) (Bureau of International Recycling, 2017).

The following figures will give a first overview of the dimensions of the required input materials. The primary steel production (via BF-BOF) consumes 1400 kg of iron ore and 120 kg of recycled steel to produce 1000 kg of crude steel, whereas the secondary steel production (via EAF) consumes an average of 880 kg of recycled steel in combination with different amounts of other iron bearing materials (directly reduced iron [DRI], pig iron or sponge iron) to produce 1000 kg of crude steel.

Replacing the primary raw materials (i.e. ores) with scrap would avoid the energy- and CO_2-intensive step of ironmaking; however, this is strongly limited by scrap availability and product quality issues due to residual impurities from scrap. Hence, some steel grades are typically not produced using certain technologies. Steel produced from scrap is mainly used in the construction industry (reinforcing steel), while steel production for more ambitious products requires primary raw material, i.e. ore. From the technical point of view, several steel grades cannot be produced from scrap because it contains a number of residual and alloying elements, which cannot be removed in the electric steel process, such as Cu, Sn, Sb, As and Bi, but also Cr, Mo and B. However, depending on the origin of the scrap, the concentrations of those impurities strongly vary. The amount of tin (Sn) is higher in scrap of cans, household equipment, electrical equipment and car scrap, whose share is estimated at over 60% of global scrap stocks.

For the above reasons, it is currently not possible to significantly increase the share of the scrap-based electrical process. This barrier is mainly related to the availability of appropriate amounts of scrap whose quality meets the requirements of the target products. The further increase of scrap availability and use in steel production would require increased scrap quality analysis, metal scrap classification, as well as big data technologies to supervise the whole process of steel production from scrap. This barrier to increased scrap usage could be relieved to some extent by the development of technologies for collecting, selecting and processing ferrous scrap.

Besides the technical aspects, the higher prices of scrap compared to ores also have to be taken into account when contrasting the two options (see also Section 2.4.1 Increased operational expenditure). The demand for high quality scrap is expected to further rise while scrap availability remains limited, possibly resulting in higher prices and increasing significance of this barrier.

Alternatives to increased scrap usage are represented by ironmaking decarbonisation technologies, which could also impact the demand for raw materials. Currently, the iron ores for the blast furnace are prepared mainly through the sintering process, which yields an intermediate product called sinter. On the one hand, this is a rather CO_2-intensive process, but, on the other hand, it makes it possible to recycle most iron- and carbon-bearing residues and to provide enough flexibility to produce ironmaking feed on-site with changing ore supplies. Most EU blast furnaces use a mixture of sinter and pellets. Pellets are produced by caking very fine ore materials and result in fewer CO_2 emissions. However, there is only one integrated steel mill in the EU (in the Netherlands) that has a pellet plant. The total pellet consumption in the EU is currently over 40 Mt/y. The demand might rise significantly in the future if the conventional BF-BOF plants have to be replaced, depending on the alternative technologies used. An alternative would be the implementation of DR plants (e.g. Midrex, HyL, Fastmet, Finmet, etc.), which mostly use pellets as iron feed.

At present, there is only one industrial DR installation in the EU with a total production capacity of approx. 0.7 Mt/y (World Steel Association, 2019). Replacing ironmaking with DR plants would mean that the more integrated plants will either have to replace their sintering plants with new pellet plants (which would require high investments and may cause space issues for brownfield installations) or they will have to rely on external pellet supplies, causing a risk of carbon leakage and decreasing the flexibility of raw material supply. If hydrogen-based direct reduction were implemented on an industrial scale in the future, hydrogen would need to be produced using, for instance, water electrolysis. This means water would become an additional raw material required for iron and steel production, which could pose challenges in water-stressed regions (e.g. Central and Southern Europe [European Environment Agency, 2018]). Furthermore, the demand for iron ore pellets would significantly increase, which could present challenges with respect to pellet availability and prices or might require the construction of additional pellet plants. An alternative to direct reduction plants are smelting reduction (SR) plants (e.g. COREX, FINEX process), which use fine-grained iron ores.

Overall, the substitution of primary raw materials, like iron ore, with secondary materials, like scrap, is limited by the amount of scrap available and by the fact that certain higher-quality steel products still require the use of primary raw materials. In conclusion, this barrier should be evaluated for each specific technology, and the requirements regarding raw material supply should be considered when assessing the possible EU market shares of different technologies.

2.1.2 Limited availability of renewable energy

The implementation of breakthrough decarbonisation technologies results in an increased substitution of fossil energy carriers by renewable clean energy, which includes also secondary biomass and waste materials. The renewable energy supply will probably have to be delivered mostly by clean electricity, which will be consumed either directly (electrification) or indirectly, e.g. for hydrogen production (by electrolysis). A smaller part shall be supplied via mass flows of secondary biomass and waste. The barrier 'limited availability of renewable energy' considers two aspects:

1. the amount of energy needed; and
2. the infrastructure needed to supply the energy to the steelworks (e.g. high capacity electricity network, hydrogen pipelines, locally available secondary biomass sources and upgrading technologies).

The extent to which the amount of renewable energy needed can affect the implementation of the breakthrough technologies can be illustrated by comparing the current demand for electricity for the EU steel production with the electricity production from renewable sources. In 2019 the total electricity demand from the EU steel producers accounted for ca. 80 TWh/y, of which ca. 55 TWh/y are taken from the electricity grid and the remaining part is generated from process gases of the steel industry (see Figure 3) (EUROFER, 2019a; Fischedick et al., 2014; Dahlmann, 2019). The total annual electricity production from renewable sources within the EU was ca. 994 TWh in 2020 (EUROSTAT, 2020). The CO_2-free electricity demand from the iron and steel industry in 2050 is estimated at 400 TWh/y by EUROFER (EUROFER, 2020b). This means that the future steel production alone may require about half of today's electricity production from renewable sources. Currently, the share of electricity produced from renewable sources is increasing too slowly to meet this demand.

In addition to the total amount of renewable energy needed, the fluctuation of the renewable electricity production should also be considered. This may require the implementation of large-scale electricity storage systems. Power-to-X technologies may help solve this problem, allowing the production and storage of secondary energy sources such as hydrogen, methanol or ammonia.

Also, additional new technologies for demand-side management may be developed, aiming to stabilise the grid by adapting the industrial production to the fluctuating energy supply. However, most measures to ensure a stable energy supply have to be taken outside of the iron and steel industry. This may lead to a dependency on external changes, possibly impeding the decarbonisation process of the iron and steel production.

Besides the availability of renewable energy in form of electricity, especially the decarbonisation via carbon direct avoidance, and the corresponding substitution of carbon by hydrogen, require an industrial-sized hydrogen provision. This will result in an increased demand for renewable energy, (ideally) in terms of CO_2-free hydrogen at a price level which is economically viable for the iron and steel industry. The demand for clean hydrogen will require a significant expansion and integration of the renewable energy system (possibly through global partnerships), as well as the strengthening of comprehensive sector coupling.

It can be expected that overcoming this barrier will take a long time and that progress will differ throughout Europe. Thus, the decarbonisation of the steel production may be hindered by insufficient CO_2-lean energy supply during this transition phase. Decarbonisation is therefore limited by the pace of the increase in the renewable energy share in the EU. Hence, intermediate technologies, including natural gas, may play an important short-term role at local level to significantly decrease CO_2 emissions. Furthermore, local differences in infrastructure and energy supply will provide different framework conditions for different steelworks. Accordingly, the choice of technology as well as the timing of the industrial decarbonisation is expected to differ due to this barrier.

2.1.3 Limited technical integration potential into existing plants

Integration of a new technology into a pre-existing physical plant (brownfield site) on an industrial scale may be challenging. For those brownfield installations, available space is needed for the new equipment and the connection to the existing material flows has to be well established. As most iron and steel plants in Europe were built decades ago, the new decarbonisation technologies will have to be integrated into mostly crowded plants, containing previous add-ons. Very few steelmaking greenfield plants have been constructed in Europe in recent decades. Therefore, major brownfield installations will have to be part of an industrial decarbonisation process (Wyns et al., 2019).

In practice, all steelworks would have to develop a comprehensive individual plan to find room for new installations within their limited physical space. For example, a blast furnace (BF) in which more equipment and probably higher loads need to be accommodated may require structural reinforcement, even if there is enough space for the new equipment.

Moreover, there should be enough space for servicing the new equipment, and production would have to stop while incorporating the new equipment. For example, carbon capture and utilisation technologies (CCU) also require additional space to install new equipment to capture and convert CO_2 and refine the resulting products.

Material and energy flows in the steelworks are almost completely integrated and have been thoroughly optimised in the last decades to maximise energy and material efficiency. The implementation of decarbonisation technologies does not only impose requirements with regard to material and energy flows, but it may also make other units obsolete, resulting in further changes to the optimised flow integration. In 2019, ca. 60% of steel production occurred in 'integrated plants' using the BF-BOF route, including a BF for the production of hot metal (ironmaking) and a BOF to convert hot metal into steel (steelmaking). The remaining 40% use the EAF route (World Steel Association, 2019). In particular in the dominant BF-BOF route, the material and energy flows are highly integrated. In these plants, heat and power production currently strongly rely on gases generated within the plants (BF gas, BOF gas and coke oven gas) as main energy sources. Thus, replacing the BF and the corresponding gas sources would affect the complete production and supply chain, leaving high demands for energy and material flows open.

Apart from space, material and energy flows, it should also be considered that the plants need to produce almost continuously with minimum downtimes to prevent the loss of production and the corresponding significant revenue losses. Thus, such downtimes need to be aligned with technically caused investment cycles (e.g. refurbishment). Thus, longer downtimes of large parts of a plant can be a severe barrier for the industrial deployment of the new technologies.

Therefore, a technology that allows for a stepwise, flexible transformation of the plant would offer an important strategic advantage. This is the case for many technologies, which rely on limited modifications to existing technologies. However, the substitution of conventional energy carriers with clean ones (e.g. secondary biomass), as well as the higher use of secondary raw materials, such as scrap, may create additional demand for warehousing space. The warehouses need to be reasonably close to the existing installations and very capacious. In the case of gas injection into the BF, gases should be safely fed into existing vessels, thus demanding the construction of new infrastructure at the sites.

2.1.4 Risk of unsuccessful development

There are two main risks stemming from the development of new technologies: failure to achieve the targeted technical objectives (failing during technological development), and failure to achieve those objectives in an economically sound and sustainable way (failing during industrial deployment). Consequently, the validation in a large-scale demonstrator would be a necessary precondition for the deployment of any breakthrough technology available for CO_2-lean steel production. This requirement is essential in the light of the considerable size and financial impact of steel production plants, which are much bigger than in most other industries. Failure during any stage of the process would result in substantial loss of income.

Thus, the risk of unsuccessful development has to be considered for all stages of development and for all technologies. Considering the fluctuating quality of the raw materials (whether ores, scrap or residues) and the huge size of steel production plants, the technical risks of unsuccessful development are still very present until the first industrial-scale deployment, and even afterwards the risks and the need for further development are usually significantly higher than for techniques which profit from decades-long industrial experience.

Since the effort and the costs of development increase with the TRL, this barrier becomes increasingly important as the TRL of the corresponding technology rises. Although pilots of each technology might demonstrate the technical feasibility in principle, the technology subsequently needs to be tested at full industrial scale, ideally within a real industrial environment and with actual process conditions. In the case of CCU, for example, this would mean treating actual flue gas in an installation.

Problems often occur during long-term industrial operation under real industrial conditions and with real materials, when several non-ideal conditions appear at the same time. These create new challenges which are often difficult to tackle, including losses of efficiency (thus raising OPEX), process instabilities (raising the measurement, control and installation effort) or additional maintenance needs (e.g. because of premature wear or fouling, thus raising maintenance costs and downtimes, as well as OPEX).

This risk of unsuccessful development must be evaluated considering the low (if not non-existent) profit margins in the steel industry. Since high quantities of goods need to be produced in order to gain significant revenues, any negative influence on the production of these goods can have a considerable impact on revenues. Consequently, even problems during the deployment of a technology might lead to high risks for the economic operation of steel production.

2.2 Organisational barriers

An organisational barrier is defined as any obstacle to the development or deployment of a specific decarbonisation technology caused by the management, administration or personnel of an implementing organisation. Four specific organisational barriers were identified and are presented below.

2.2.1 Limited availability of qualified staff

The availability of qualified staff is a precondition to push forward the development of the decarbonisation technologies, including the needed scale-up steps from TRL 7 (which most technologies currently have) to the first industrial deployment (Stubbe et al., 2020). Due to the huge size of steel production plants, the pilot and demonstration plants in the steel industry have a capacity similar to the full industrial production of many other process industries: steel pilot plants in larger lab scale typically have a production of about 10-100 kg/day and demonstration plants typically have a production of about 10-100 t/day. Thus, the planning and operation of those plants need significant human resources. This applies even more to the first small industrial scale installations with a production of typically more than 1000 t/day.

When assessing this barrier, it should be considered that the development and operation of new technologies need more manpower compared to usual commercial processes, which are more automated and optimised with respect to maintenance. Besides manpower, the technical efforts for accompanying analyses and continuous monitoring are also much higher. The gained insights then feed back into the increased efforts for research and development, which also require a significant number of qualified staff. Due to the ongoing process of digitisation of iron and steel production, the skills required of the staff overlap with other sectors. Thus, the iron and steel industry must compete for a limited pool talent available.

The availability of experienced staff with specific expertise is key to the successful operation of an industrial steel production plant. However, when it come to the new technologies, the experience and expertise are still missing. This barrier will be relevant not only during the development phase, but also during at least the first 5-10 years of full industrial deployment. This barrier is relevant to different technologies to a different degree, depending on the effort needed for development as well as on the difference between current and future processes and plants.

2.2.2 Administrative requirements

Administrative requirements and procedures may hinder the deployment of low-CO_2 technologies. The increasing environmental protection and occupational health requirements for new plants and processes are expected to represent an additional burden in this respect since new plants always require more planning and authorisations. Generally speaking, providing the proof of compliance demanded by national and/or local authorities according to relevant standards may be challenging at the time of first implementation. Besides, technical implementation requires a time-consuming authorisation process, which additionally decelerates the deployment of new technologies.

As for research and development activities, especially within collaborative research and funded projects, internal and external bureaucracy will impose an additional burden.

2.2.3 Issues related to the management of industrial transformation

The decarbonisation of industrial production can be referred to as the 5th industrial revolution, considering the overarching and fundamental changes it implies to all process chains, including energy and raw material supply chains. This barrier covers all issues related to this revolutionary transformation process. Thus, it is connected to many other barriers and covers different steps of research and development, planning and implementation, in particular:

- effort and issues related to research on and demonstration of the new technologies (see Sections 2.1.4 Risk of unsuccessful development, 2.2.1 Limited availability of qualified staff, 2.2.4 Issues related to intellectual property management (intra- & inter-firm) and 2.4.2 Additional capital expenditure for demonstration plants).

- issues related to planning future investments with unclear framework conditions (see Sections 2.1.4 Risk of unsuccessful development, 2.3.5 Uncertainty related to carbon contracts for difference, 2.4.3 Additional capital expenditure for industrial deployment and 2.4.5 Unknown market conditions for clean steel).
- practical issues during industrial deployment (see Sections 2.1.1 Limited availability of raw materials, 2.1.2 Limited availability of renewable energy, 2.1.3 Limited technical integration potential into existing plants, 2.2.1 Limited availability of qualified staff and 2.4.1 Increased operational expenditure).

The industrial transformation poses a logistical challenge for each plant, affecting material, energy and work flows. Since the barrier covers several different aspects, its impact should be assessed specifically for each technology and plant. However, most barriers will be more severe if the technology leap compared to the current status at the plant is large.

2.2.4 Issues related to intellectual property management (intra- & inter-firm)

Intellectual property management refers to the management of intellectual property (IP) rights, among which patents are most relevant to industrial applications (Nappo, 2011). Patents are technical in substance and legal in structure and grant exclusive rights over the commercial use of an invention in exchange for its public disclosure (Junghans et al., 2020). Exclusionary rights can be utilised in four different ways (Junghans et al., 2020):

- to exclude competitors from the use of the invention, improving the relative market position of the patent owner by direct implementation of the invention (‘in-house use’). In terms of industrial iron and steel production, this might lead to an upgraded production chain of the patent owner, while competitors cannot implement this invented upgrade;
- to generate a continuous revenue from licence payments paid by a third party operating under the cover of the patent (‘licensing’);
- to generate a single revenue by direct sale of the patent (‘sale’); and
- to block competitors from utilising or implementing patented technologies (‘blocking’ or ‘fencing-in’).

The use of exclusionary rights generates burdens and limitations for the competitors. In case of exclusive ‘in-house use’ or ‘blocking’, competitors are excluded from the implementation of the patented technology. In that context, it should be borne in mind that most decarbonisation technology routes comprise different components with specific technologies. Patenting and exclusive use of one specific partial technology could hinder competitors’ implementation of complete technology routes or result in additional costs and efforts for licensing.

Additionally, further research on the patented technology can be fully controlled by the patentee, and larger demonstration units may require licensing or purchase of exclusionary rights. So, the exclusion of a competitor might lead to a delayed or altered implementation of decarbonisation technologies, possibly resulting in less CO_2 mitigation achieved or higher costs.

In case of ‘licensing’ or ‘sale’ of intellectual property rights, competitors may incur additional capital or operational expenditure linked to a certain technology, if this technology or parts thereof were patented. On the other hand, filing a patent requires both human and financial resources for the inventor, causing further costs.

This barrier is very topical since extraordinarily intensive R&D activities will be needed in the next decades to develop all necessary decarbonisation technologies and to solve all related issues.

R&D will go along with numerous new patents, which, on the one hand, can be an advantage for the European industry in the long term (in particular for technology and plant suppliers), but on the other hand may cause distortions within the European steel industry. IP protection of technologies represents a higher risk for smaller companies which have no resources for large-scale R&D activities. Thus, there small companies may lose their competitiveness against large ones along the industrial decarbonisation process. They may be unable or slower to deploy innovative and IP-protected technologies.

<u>Collaborative research: information exchange with other parties</u>

Besides the limitations directly related to intellectual property rights, they may also an effect on communication and information exchange between different companies taking part in collaborative research projects. To ensure intellectual property management, collaborative research requires an agreement over ownership and exploitation rights of the resulting intellectual property (Bader, 2006). In the EU, patents are based on the date of registration: the earlier an invention has been registered (‘priority date’), the higher ‘priority’ it obtains. In case of multiple entities claiming the same invention or overlapping contents, priority is given to the earlier patent registration. This may decrease the information exchanged between competitors outside of regulated environments, out of fear that a competitor may use the information for patent filing.

Besides, the overall dissemination quality and quantity is influenced by intellectual property management. In the patent filing process, it is highly relevant which information was publicly available at the date of patent registration. If the details of the invention were included in any publication or if units or technologies were sold before the ‘priority date’, these are no longer patentable. Due to this rule, dissemination activities of common research projects may be limited at least in their contents, as the involved partners aim to avoid those problems.

2.3 Regulatory/societal barriers

Regulatory or socio-ecological barriers refer to obstacles to the development or deployment of a specific decarbonisation technology due to external framework conditions, regulations, policies or social acceptability. Five specific barriers were identified in this category and are presented below.

2.3.1 Limited availability of permanent CO_2 storage

Carbon capture and storage (CCS) is the process of separating CO_2 from a gas stream and storing it underground. CCS can be applied to power generation and industrial facilities, and includes three main steps which are: i) separating of CO_2 from the gas stream; ii) compressing and transporting it (via pipelines or shipping); and iii) storing it in a suitable geological site (e.g. saline aquifers, depleted oil and gas reservoirs). In Europe, CO_2 storage will mostly be offshore (e.g. North Sea), due to less concern over public perception compared to onshore (Budinis et al., 2018).

CO_2 storage has three main elements (Harding et al., 2018), all of which must be present to fulfil its climate protection objectives:

i) capacity to identify a large subsurface storage site capable of holding the CO_2;

ii) injectivity (inject the CO_2 into the underground geological formation at the site); and

iii) containment (securely retain the CO_2 in the formation at the site indefinitely).

The cost of CCS has been previously identified as a major barrier to its adoption. However, there are also other potential barriers which are preventing its wider implementation. From a legal point of view, the restrictions on CO_2 storage in Europe are mainly due to public concern and/or geological issues (seismic zones) (European Gas Regulatory Forum, 2019). An overview is given in Table 3.

In principle, no explicit technological barriers exist to the capture, transportation and storage of CO_2. Currently, CO_2 is being stored for instance in depleted oil and gas fields. Table 4 shows an example of storage costs for different storage sites (depleted oil and gas fields or saline formations), different locations (onshore or offshore) and depending on whether existing oil and gas wells can be reused or not (Budinis et al., 2018).

Regarding the location and the capacity of the storage sites, the relevant parameters are the cumulative capacity of CO_2 storage, the rates of release and uptake, the connection from source to store and the climate impact of the storage timescale. Cumulative storage resources are in the range of 10,000 to 30,000 Gt CO_2, including 1000 Gt in depleted oil and gas reservoirs (Nappo, 2011). Thus, the importance of this barrier will vary depending on the local CCS-related framework conditions.

It should also be noted that CO_2-storing technologies are cross-sectoral, and are not strictly related to steel production. As storage sites and their capacity are naturally limited, the iron and steel industry is competing with other sectors, possibly leading to some kind of regulation or prioritisation issues. Storage sites are mostly located in similar areas, depending on geographic/geological conditions. Large source emission clusters can help also through economies of scale.

Table 3: Overview of info on CO_2 storage policies in Europe

Country	Government attitude	Current legislative restrictions
Austria	Unfavourable	No storage
Belgium	Favourable	Not in Brussels-Capital region
Bulgaria	Favourable	Max. storage of 160 Mt CO_2 until 2030
Croatia	Neutral	No storage
Cyprus	Neutral	-
Czech Republic	Neutral	No storage until 2020
Denmark	Neutral	No onshore storage until 2020
Estonia	Neutral	No storage
Finland	Favourable	Only for demonstration purposes until 2024
France	Favourable	-
Germany	Neutral	Max. storage of 4 Mt/y CO_2. No storage allowed in five federal states
Greece	Favourable	-
Hungary	Favourable	-
Ireland	Favourable	-
Italy	Neutral	No storage in seismic areas or unconfined aquifers. No negative impact on maritime traffic and oil and gas exploration
Latvia	Neutral	No storage
Lithuania	Favourable	-
Luxembourg	-	-
Malta	-	-
Netherlands	Favourable	No onshore storage
Poland	Neutral	Only for demonstration purposes until 2024
Portugal	Favourable	-
Romania	Favourable	-
Slovakia	Neutral	-
Slovenia	Neutral	No storage
Spain	Favourable	-
Sweden	Favourable	No onshore storage

Source: adapted from Terlouw et al., 2019 (ANNEX E. Carbon capture, storage and utilisation); and European Gas Regulatory Forum, 2019.

Table 4: Example of CO_2 storage costs for different storage sites

Properties	Storage cost ($2015/t$CO_2$)	
	Min	Max
Depleted oil and gas field – reusing wells onshore	1.6	11
Depleted oil and gas field – no reusing wells onshore	1.6	15.7
Saline formations onshore	3.1	18.8
Depleted oil and gas field – reusing wells offshore	3.1	14.1
Depleted oil and gas field – no reusing wells offshore	4.7	22
Saline formations offshore	9.4	31.4

Source: Budinis et al., 2018.

2.3.2 Limitations stemming from emission-related legislation

Set up in 2005, the EU emissions trading system (EU ETS) is a carbon market based on the 'cap and trade' principle. The system sets a cap to the total amount of certain greenhouse gases that can be emitted by installations. Within the cap, each company is allocated emission allowances (the so-called 'EUAs' or 'EU allowances'), which can be used or traded with other companies. The main objective of the EU ETS is to reduce greenhouse gas emissions cost-effectively, contributing to climate change objectives[1]. For the steel sector in particular, the EU ETS covers emissions of carbon dioxide (CO_2) produced by steelworks. Despite the original aim of the EU ETS, as further discussed in what follows, the system has some limitations and does not properly foster the decarbonisation of the EU steel industry.[2]

<u>Low price of emission allowances</u>

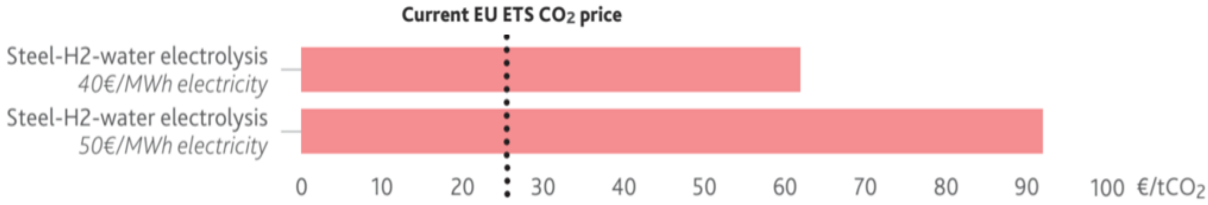
The current low carbon price under the EU ETS does not make breakthrough technologies economically viable and competitive.[3] Stakeholders from the EU steel industry participating in a consultation carried out by Sandbag (2018) argue that the carbon price is too low to motivate investments in low-carbon technologies (Lytton, 2018). While the carbon price is currently ranging around €25-30/t CO_2, it would need to be above €60/t CO_2 to make lean-CO_2 steelmaking technologies attractive to investors (see Figure 1), i.e. resulting in lower production costs for green steel compared to current steelmaking routes, assuming that electricity is available at about €40/MWh (Sartor et al., 2019). Other studies estimate that an even higher carbon price (in the area of €68-80/t CO_2) would be necessary to foster investments in low-emission steelmaking (Mandova et al., 2019; Vogl et al., 2018). Low carbon prices, coupled with high price volatility, increase investment risks especially for first-of-a-kind investments in low-carbon technologies (Vogl et al., 2020).

[1] European Commission, EU Emissions Trading System (EU ETS) (ec.europa.eu/clima/policies/ets_en).

[2] It is worth mentioning that over the period 2008-2015, the EU ETS also generated extra profits in the area of €7.5 billion due to the free allocation of emission allowances for the whole European industry (De Bruyn et al., 2016).

[3] For similar reasons, the current EU ETS framework does not properly support the development of hydrogen, CCS and low-carbon power infrastructure needed for the decarbonisation of steelmaking (Lytton, 2018).

Figure 1: Breakeven cost estimates of very low-carbon primary steel technologies



Source: Sartor et al., 2019.

Setting a price floor for carbon might represent a solution to foster decarbonisation. However, an increasing carbon price is expected to have a counterproductive effect on the risk of carbon leakage, if not accompanied by comparable measures in third countries.

<u>Carbon leakage risk</u>

While fostering decarbonisation, CO_2 pricing and the EU ETS are expected to affect the global competitiveness of the EU steel industry by increasing costs to produce steel in Europe, possibly resulting in carbon leakage, i.e. shifting steel production from the EU to third countries where carbon emissions legislation is less strict so that overall greenhouse gas emissions rise. So far, there is little empirical evidence of carbon leakage (Verde, 2020; Joltreau et al., 2018; Naegele et al., 2017), especially due to the low carbon prices registered so far in the EU and mitigation measures such as free allocation of EUAs[4] or compensation for indirect EU ETS costs passed on in electricity prices[5]. As the free allocation of EUAs is assigned to specific production plants, their replacement with the implementation of decarbonisation technologies might lead to a reduction of allocated free EUAs, thus hindering the deployment of such technologies. This issue will be assessed in more detail in work package 3 of this research project.

Substantial increases in carbon price and/or changes in mitigation measures could, however, ultimately result in carbon leakage. This is especially true if one considers that production costs for green steel are expected to be substantially higher than costs for conventional steel. Steel imported from third countries with less stringent climate rules than the EU could be sold at lower price, while generating comparable or often higher carbon emissions than those linked to EU steelmaking (ArcelorMittal, 2020). Today, the EU imports 30 m t of steel that are not subject to comparable emission legislation and do not face CO_2 costs, while exporting about 20 m t bearing the costs generated by the EU ETS (EUROFER, 2019b). The magnitude of the carbon leakage challenge is increased by the global overcapacity and heavy competitive pressure from the global steel markets. In 2019, the global steel overcapacity was around 440 m t (equivalent to nearly 25% of the global steel production capacity); China's capacity alone can meet 62% of world steel demand in 2019 (World Steel Association, 2020; OECD, 2020). The risk of carbon leakage may hamper the financial

[4] To reduce the risk of carbon leakage, the EU has been providing free allocation of emission allowances for the manufacture of steel and products from steel (tubes, pipes, hollow profiles and related fittings). The revised ETS Directive has prolonged this free allocation system for the period 2021-2030. Further information on the EU system of free allowance is available at: https://ec.europa.eu/clima/policies/ets/allowances/industrial_en

[5] The current state aid guidelines were meant to last only five years, a time span that is much shorter than the investment cycle in the steel industry. This limited timeframe may harm the viability of low-CO_2 pathways for energy intensive industries including those in the steel sector (European Commission, 2012).

and economic viability of low-CO_2 steel and potentially lead to GDP and job losses for the EU, and most importantly may have no net impacts or even negative impacts on global carbon emissions (EUROFER, 2020b).

The risk of carbon leakage may alternatively be mitigated by introducing a carbon border adjustment mechanism (CBAM), which would add carbon costs to steel imported from outside the EU. However, different challenges (e.g. consistency with WTO rules, accounting and certification efforts) make the introduction of CBAM rather complex (European Commission, 2018). These issues will be assessed in more detail in work package 3 of this research project.

2.3.3 Limitations by social acceptability and environmental protection

Besides the technical and economic feasibility, the implementation of a specific technology also requires social acceptability. The deployment of CCS and renewable energy installations (specifically wind turbines or power supply lines) has already faced social acceptability issues and other technologies might also encounter these challenges in the coming years (e.g. hydrogen or CO_2 pipelines). Public opposition might delay the implementation of decarbonisation technologies or completely rule out specific technologies and measures.

According to the POLIMP policy brief (Hofman et al., 2014), the elements affecting the public attitude can be categorised as follows:

- awareness of climate change and knowledge of the technology;
- fairness of the decision-making process;
- overall evaluation of costs, risks and benefits of a technology;
- local context; and
- trust in decision-makers and other relevant stakeholders.

Public acceptance is therefore a highly significant subject to local regulators and project developers as well as EU and member states' policymakers. Policies, including (partial) financial support to low-carbon technologies, need to reflect the public willingness to invest in them and should be based on awareness and fairness.

Besides the direct consequences for the people affected, environmental protection concerns may hinder social acceptability. For instance, the required transport and storage infrastructure might impact the environment or biodiversity, resulting in a lack of social acceptability. Social acceptability can be scarce not only where the new technologies are supposed to be implemented, but also in the regions from which the necessary materials come. As a matter of fact, the provision of critical materials (such as those required for electrolysers) can affect regions that are very different from the place of technological deployment.

Overall, public acceptance, social acceptability and environmental protection concerns affect the predictability of clean technology investments from an industrial point of view.

2.3.4 Burden by local taxes and fees

Decarbonisation actions can be subject to additional or changing local taxes and fees, which can even equal the costs for revamping/adapting the plants to the new technologies. This represents a barrier for producers, which can encourage them to adopt the most conservative solutions and prevent them from reaping the full benefits of the technologies in terms of CO_2 emission reduction.

The European climate policies related to carbon pricing and tradable emission standards affect European stakeholders equally, but local differences can appear regarding, for instance, partial compensation (see Section 2.3.5 for more details).

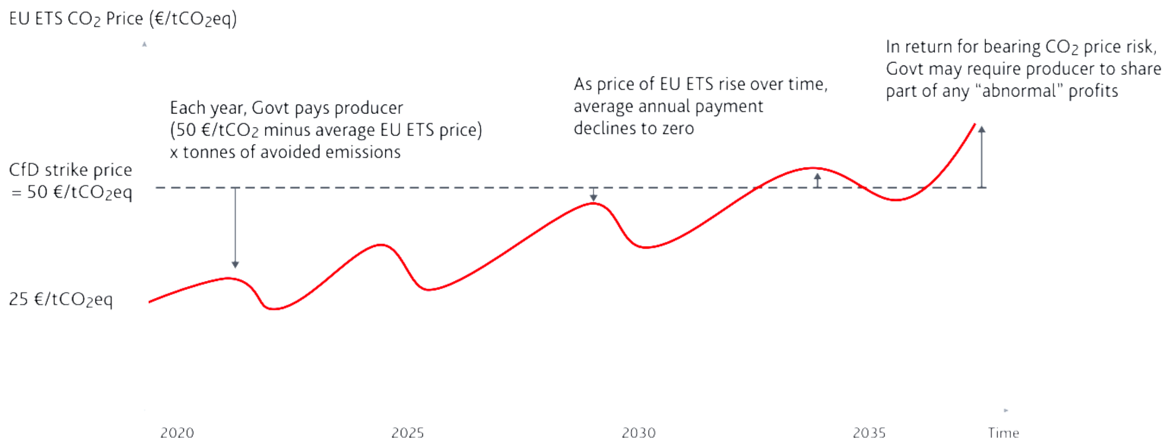
When it comes to this barrier, special examples are feed-in tariff schemes which several member states have unilaterally changed to support renewable energy. Although they were intended as a support measure, these schemes might generate legal uncertainty, lack of trust and litigation costs, and might therefore increase investment risks (Eufores et al., 2015). Specifically, the German EEG plays a significant role for the local electricity costs in Germany. Steelmakers may incur additional taxes and fees for the transportation of electricity via the grid if they acquire renewable electricity externally instead of producing it internally. This could become a significant barrier, in particular for the BF-BOF producers, which today self-produce most of their electricity and heat tanks for the internal reuse of waste gases.

2.3.5 Uncertainty related to carbon contracts for difference

Carbon contracts for difference (CCfD) were proposed as one measure to guarantee producers of low-carbon steel a fixed carbon price (the so-called ‘strike price’) for a period of 20-30 years, making their decarbonisation projects investible (Elkerbout et al., 2018). However, uncertainty on the relevant rules at national level can become a barrier to decarbonisation. Figure 2 illustrates how a CCfD could support commercial-scale investments in lean-carbon technologies. Steelmakers decarbonising their production can sell their surplus of emission allowances (EUAs) on the market through the EU ETS. However, the current low carbon price (of around €25/t CO_2 in 2020) does not guarantee enough revenues to invest in decarbonisation projects. These investments could potentially have to wait until the 2030s or 2040s when a sufficiently high carbon price could materialise. To accelerate the decarbonisation process, national or regional authorities can intervene through a compensation mechanism based on a guaranteed price for EUAs – the ‘strike price’. At the end of each year, the public authority pays the investors the positive difference, if any, between the strike price and the market price of the EUAs. For instance, if the strike price is set at €50/t CO_2 and the EUA price is at €30/t CO_2 that year, the public authority would pay steelmakers a compensation of €20/t CO_2 (Sartor et al., 2019).

CCfD are principally implemented at national level (Neuhoff, 2018). They guarantee investors in climate-friendly measures, including those aiming to decarbonise the steel industry, a fixed price for emission reductions below today’s emission benchmark. It is an effective instrument to derisk investments in decarbonisation technologies, addressing particularly risks linked to fluctuations of the carbon price (EUROFER, 2020a). CCfD are especially used to support first-of-a-kind, proven and pilot-tested technologies. Using a competitive tendering process, governments could enter CCfD for projects that lead to innovative low-carbon basic materials (Sartor et al., 2019).

Figure 2: Example of the CCfD mechanism



Source: Sartor et al., 2019.

Despite their potential to derisk decarbonisation technologies, CCfD still have some shortcomings that prevent them from being applied widely in the EU:

- **Limited transparency of the compensation mechanism**. As mentioned, the public authority would pay steelmakers a difference between the actual EUA price and the strike price if the former is lower. However, if the average annual EUA price goes above the strike price (as illustrated at the right end of Figure 2), the public authority would have two options to allocate such 'abnormal' profits. One option would be not to require the investors to pay back to the public authority the positive difference between the EUA price and the strike price. The other possible option would require steelmakers to share a portion of the 'abnormal' profits with the public authority. With no clear agreement in the contract, CCfD might lead to investors' uncertainty over the obligation to pay back profits to public authorities.
- **Legal uncertainty and investors' concerns about government's changing contracts unilaterally**. Profit sharing rules in case of 'abnormal profits' can be negotiated and spelled out in contracts. In addition, both public authorities and investors may agree not to change contractual obligations over time, or to make periodical revisions with fixed terms and mechanisms. For instance, the revision period can be set at five years, with a maximum percentage of change in the strike price. Nevertheless, for the time being, companies are quite concerned about some member states' track record of changing contracts unilaterally. By way of example, in the case of renewable energy, several member states have unilaterally changed the feed-in tariff schemes with retroactive effects, generating legal uncertainty, lack of trust and litigation costs, thus ultimately increasing investment risks (Eufores et al., 2015).
- Finally, there are **concerns that CCfD implemented at member state level** might lead to a potential conflict with EU state aid rules and hamper inter-firm competition (Richstein, 2017; Sartor et al., 2019). For these reasons, competitive tenders at EU level might help increase the efficiency of CCfD and address competition concerns (Vogl et al., 2020).

2.4 Financial barriers

Financial barriers are defined as obstacles to the implementation of a specific decarbonisation technology due to limitations to the economic operation of iron and steel production. Five specific financial barriers were identified and are presented below.

2.4.1 Increased operational expenditure

The implementation of a technology is highly dependent on its competitiveness. In that context, the required capital investments (CAPEX) and operational expenditure (OPEX) are of specific relevance. The OPEX includes energy and input material, as well as operating and maintenance costs, with varying significance of these single parameters for specific sites and technologies. The OPEX related to energy and material inputs generally makes up over 50% of the total steel production cost (Wörtler et al., 2013). Those costs tend to be very volatile over time because of the evolution of the prices of key input factors for steel products. Considering the very low profit margins of less than 4% net profit in world-wide average (in 2018) (OECD, 2019) within the steel markets (see also Section 2.3.2), the decarbonisation of the steel production is an economic challenge under current framework conditions. Thus, the efforts undertaken in regard to decarbonisation might result in the possibility of shifting the iron and steel production outside of EU borders (i.e. carbon leakage).

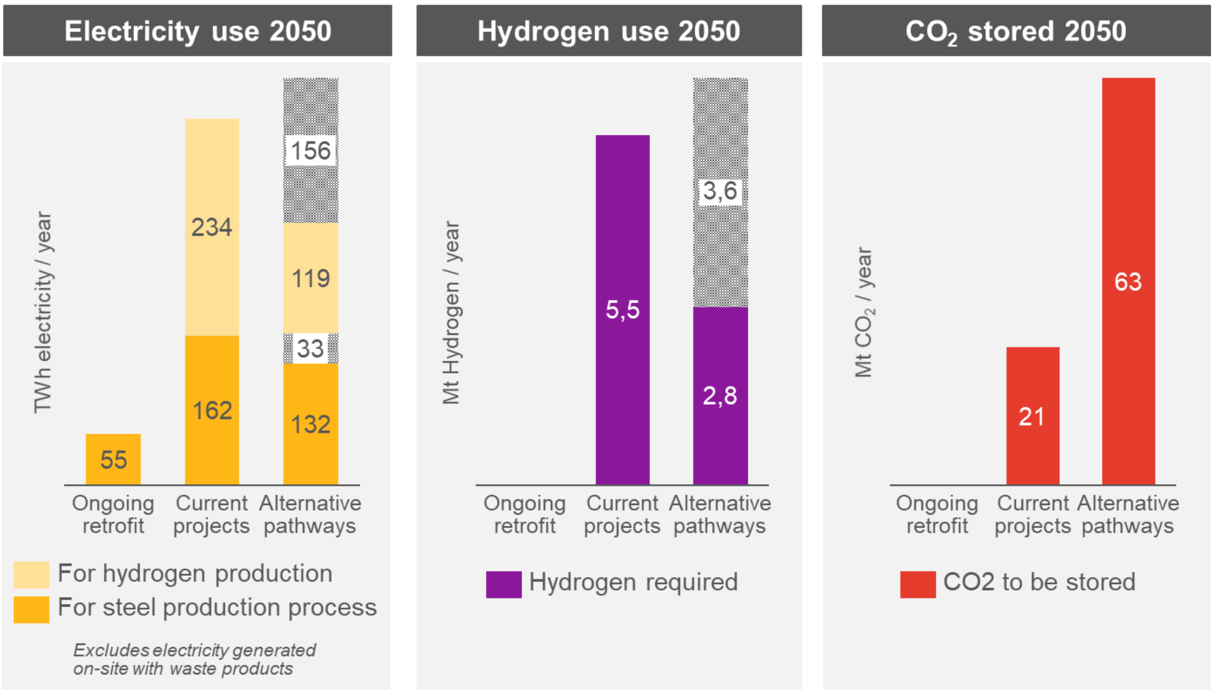
Electricity

Most decarbonisation measures, in particular technologies belonging to the carbon direct avoidance pathway result in the increased substitution of fossil fuels by electricity (electrification), either by direct use of electricity or by use of electricity to produce other energy sources like hydrogen. The price for electrical energy is significantly higher than for thermal energy provided by fossil fuels. The average price of electricity in final demand sectors within the EU is ca. €81-87/MWh_{el} (National Technical University of Athens, 2016), whereas the average price for coal (neglecting associated environmental costs as well as transport costs) is ca. €12/MWh_{th} (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2020). Thus, the replacement of fossil fuels by electricity results in an increased cost of energy supply and a significantly increased operational expenditure, since the cost of energy is a significant part of the overall OPEX.

Furthermore, integrated steelworks using the conventional BF-BOF route are almost self-sufficient with regard to their electricity needs thanks to the use of their process gases (Wirtschaftsvereinigung Stahl, 2019). The BF gas is also used within carefully optimised energy supply systems all over the plants to heat different furnaces. Consequently, shutting down BFs and ‘losing’ the main energy carrier would significantly raise the operational expenditure for these works.

Energy is a decisive component of the OPEX. A transformed, future EU steel sector will have substantial demand for energy (EUROFER, 2019c). The sector will need annually about 5.5 m t of hydrogen in 2050. The future demand for CO_2-free electricity is estimated to be around 400 TWh/y, consisting both of electricity purchased from the grid for steel production processes (about 162 TWh/y) and for the production of the above reported amount of hydrogen (see Figure 3). The aforementioned 400 TWh/y are 700% of EU steel industry’s current demand for electricity from the grid (EUROFER, 2019c). Thus, the future energy prices will be essential to ensure the competitiveness of low-carbon technologies.

Figure 3: Projected demands for electricity from the grid, for hydrogen and for CO_2 storage capacity in 2050



Source: EUROFER, 2019c.

Currently, the energy market trends seem to increase the relevance of this barrier. The electricity prices show a dynamic pattern: in the EU reference scenario 2016, it is expected that the electricity prices will be significantly higher in 2030 and 2050 compared to 2010 in almost every EU member state. This would result in a further increase of the impact of this barrier on most decarbonisation technologies, including the EAF-based route of secondary ironmaking and the energy-intensive CCS technologies, whereas biomass-based technologies or CCU-technologies are influenced to a lesser extent.

The cost levels of renewable energies are particularly important for the industrial deployment of the technologies and the degree of industrial decarbonisation of the industry will strongly depend on the future conditions of the energy markets.

Raw materials

The raw material costs depend on internal and external conditions. Internal conditions are under direct influence of the steel industry and are related to the strategic and operational orientation of the steel companies. As a matter of fact, the low-carbon strategies of the iron and steel industry include the increase of resource efficiency which helps to improve environmental performance and to reduce production costs.

However, external conditions and uncertainties are largely beyond the influence of any individual steel company, although they require company-level attention and adaptation (Florén et al, 2019). The first external uncertainty is related to policies and regulations (such as environmental regulations and trade barriers) that often have direct effects on the availability and price of raw materials. The second uncertainty is related to the bargaining power of the suppliers of raw materials. The third external uncertainty is related to the potential dramatic changes in the supply and quality of important raw materials over time. If ores are replaced with (high quality) scrap or with pellets, significantly higher raw material prices will probably need to be accounted for.

Higher prices for raw materials reduce/tend to offset the positive outcome from increased material efficiency. As some of the decarbonisation technologies have low flexibility and require high quality raw materials, the increase in OPEX linked to raw materials can be an important barrier for investment decisions.

Carbon capture and utilisation/storage (CCUS)

Carbon capture and storage (CCS) could play an important role, but its potential is not distributed equally throughout the EU. In some EU member states, there are significant hurdles or even prohibitions on the deployment of CCS. It is estimated that about 21 m t/y would be captured and made ready for transport and storage by the steel industry in 2050 (see Figure 3) (European Commission, 2018). The EU steel sector is not the only sector considering CO_2 capture and storage; hence, further cross-sectoral alignment on a Europe-wide CO_2 transport and storage infrastructure would be required. The costs for CO_2 transport and storage will also impact the OPEX of the steel sector.

Carbon capture (usually done via absorption) needs thermal energy supply. The thermal energy shall either be provided externally (causing further operational expenditure) or internally, possibly lowering the overall process efficiency and resulting in an increase of specific operational expenditures. After capture, the CO_2 is further processed and either stored indefinitely (CCS) or converted into valuable products (CCU). In case of CCS, the further processing is dependent on the transport to the storage location. In case of a transport by truck (as it is the case in current demonstration plants), the captured CO_2 has to be compressed until liquefaction, resulting in a higher electrical energy demand, which increases the operational expenditure. The indefinite storage of CO_2 reduces the amount of CO_2 emissions, resulting in savings on CO_2 certificates. At current certificate pricing of €25-30/t CO_2, these savings are not expected to compensate the increased operational expenditure to a significant extent.

In case of CCU, the carbon oxide stream typically has to be enriched with other substances, depending on the intended specific product. Most intended CCU products, e.g. ethanol, methanol or other hydrocarbons, require hydrogen for their formation and that results in a significant hydrogen requirement for the conversion process. The hydrogen production or provision causes further significant operational expenditure. Since the targeted CCU product is supposed to be capitalised, the additional costs stand against both, the savings due to less required CO_2 certificates and the additional revenues by selling or utilising the CCU product. At the current state of technological development and CO_2 pricing, the additional expenditures typically exceed the savings and the additional revenues (in case of CCU).

Process efficiency

Finally, process efficiency, reliability and safety are important for a successful industrial deployment of technologies. The implementation of first-of-a-kind technologies under real industrial conditions generates problems due to non-ideal operating conditions before optimisation. This often results in the loss of efficiency of the industrial processes, e.g. higher energy and material consumption, increased downtime and maintenance effort (see Section 2.1.4), as well as increased OPEX (Wyns et al., 2019), since the new technologies have to compete with the conventional steel production which can rely on a long-standing experience. Further R&D on the new technologies will be essential to handle any unforeseen issue.

2.4.2 Additional capital expenditure for demonstration plants

Most breakthrough decarbonisation technologies currently have TRLs in the range of 7 (Wyns et al., 2019; Stubbe et al., 2020), meaning that the important step of the demonstration in an operational environment still has to happen and that their completion is still pending. These development steps usually go along with much higher costs than any earlier development on lab scale. CAPEX increases significantly since the scale of steel demonstration plants is already comparable to real industrial plants in many other process industries, with a capacity usually ranging from 10 to 100 t per day.

Based on the results from the questionnaire carried out under the Green Steel for Europe project (see deliverable D1.3), the investment needs for demonstration plants (TRL 8) up to 2050 amount to several billion euros. The research projects, including industrial scale demonstration plants of a chemical CCU technology ('Carbon2Chem') and a hydrogen-based carbon direct avoidance (CDA) implementation ('HYBRIT'), have budgets of €120-140 million (Stubbe et al., 2020).

In these rather early stages of technology maturity, any decision to invest in demonstration plants is coupled with additional risks, compared to usual (production) investment decisions. Firstly, there is a 'technical risk of development' (see Section 2.1.4), and secondly, several other risks are caused by unknown future framework conditions (e.g. market conditions, energy/material/product prices, energy/material availability, taxes and other regulatory frameworks, etc.). All those conditions could hamper the exploitation of an industrial production technology at a later stage, even if its development was successful from a technical point of view.

However, this challenge can be tackled more effectively if a technology is flexible and able to adapt to different framework conditions. One such example is direct reduction, which can be operated using natural gas (NG) with flexible parts of hydrogen. However, since NG is currently more expensive in Europe than, for instance, the frequently used coal, some increase in OPEX will still occur. Obviously, this barrier is also relatively less important, if the CAPEX for industrial demonstration is low, since a technology can rely to a large extent on existing plants (e.g. BF gas injection, usage of secondary biomass, increased scrap usage).

2.4.3 Additional capital expenditure for industrial deployment

The increased costs for investment (CAPEX) in the industrial deployment of decarbonisation technologies constitute a barrier. The impact of this barrier depends on the extent to which the new technology calls for new asset expenditures. This includes not only the investments in the decarbonisation technologies, but also the effort to adapt the existing assets to integrate the new technologies into the brownfield plants (e.g. adaption of material and energy supply chains and warehouse spaces).

The results of the stakeholder consultation conducted under the Green Steel for Europe project foresee a strong CAPEX increase for hydrogen-based technologies and a moderate increase for innovative energy recovery (see Table 5) (Green Steel for Europe, 2020). The end-of-life time of larger units (e.g. BFs) will influence the timing of the shift towards new technologies. However, the CAPEX must be evaluated in relation to the corresponding mitigation potential and will strongly differ for different plants depending on the local conditions (e.g. investment cycles, availability of secondary biomass).

Table 5: CAPEX increase per technology as from indications in scoping questionnaires

Technology	CAPEX increase
H_2-based technologies (H2-DR):	100% compared to existing BF/BOF route
Innovative energy recovery	20%
Biomass technologies	1%
Increased scrap usage	1%
Innovative slag progressing	2%
Multi-fuel combustion system with H_2 > 60%	> 10%

Source: Green Steel for Europe, 2020.

2.4.4 Limited access to funding

Limited access to funding could represent a barrier for different reasons:

- economic reasons because the amount of funding needed may not be compatible with the available funding programmes and/or the funding rates may not be sufficient; and
- bureaucratic reasons because procedures may take too long or be too burdensome for companies, also in view of the changing market or financial scenarios.

Limited access to funding is a concern and would not encourage the desired actions, in particular considering the significant cost of the necessary investments (see also Section 2.4.2 Additional capital expenditure for demonstration plants). As shown in the previous sections, the combination of different barriers such as technical risk of development, high OPEX and CAPEX (see also Section 2.4.5 Unknown market conditions for clean steel) show that the decarbonisation technologies need additional financial investments.

This explains the need for rather sizeable funding. In the steel sector the most incisive technologies to achieve the decarbonisation targets are those involving significant expenditures for assets, specifically appr. €200 to 7500 million[6] for demonstration plants at TRL 8-9 up to 2030. This requires funding programmes that can adequately support such needs.

This barrier particularly impacts technologies with higher TRLs since the corresponding effort is much higher and is not covered by most funding programmes. However, the demonstration stage is the decisive step towards possible industrial deployment and, due to the problems outlined above, this phase is also known as the 'valley of death' between research and deployment of technologies. Thus, the support within the EU framework should be strong and effective, and in line with local funding schemes. A focus on sustainable finance or carbon neutral investments may imply the prioritisation or exclusion of specific technologies.

[6] Preliminary estimation of CAPEX+OPEX, to be validated by stakeholder consultation.

2.4.5 Unknown market conditions for clean steel

At least for the foreseeable future, the production of clean steel will go along with (much) higher costs for several reasons, as discussed in the foregoing chapters. Thus, new markets and business models for clean steel have to be established (Wyns et al., 2019; Stubbe et al., 2020).

However, this strongly depends on currently uncertain public support, e.g. by public procurement. Also, the customer acceptance of higher prices for clean steel-based end-products is unknown. Therefore, the new clean steel market may need legislative support. This high level of uncertainty sets difficult conditions for the long-term investment planning needed to achieve the decarbonisation of the steel production. Consequently, the unknown market conditions for clean steel pose a barrier to the industrial deployment of breakthrough technologies, which enable a strong decrease of carbon emissions but require considerable investments and a long timeframe before they are technically and economically viable. In addition, the current Covid-19 pandemic constitutes an unprecedented socio-economic challenge for the steel business as well.

Generally, the European steel market is facing uncertainties and may have to undergo comprehensive transformations. The European steel market as well as the global market are characterised by severe competition and strongly influenced by dumping and trade policies (EUROFER, 2020c). Although an increase of the European steel demand is expected (EUROFER, 2020c), it is currently unclear if this will be met by European producers. The share of steel imports has been constantly rising in recent years, and this trend might continue as steel imports keep increasing. This would cause carbon leakage (EUROFER, 2020d), as well as social and economic damages to the EU and environmental damages worldwide.

It can be concluded that the future market conditions for clean steel strongly depend on European and worldwide policies. This will be further assessed in work package 3 of the Green Steel for Europe project.

3. Prioritisation of decarbonisation barriers

The aforementioned decarbonisation barriers affect specific technologies and specific iron and steel production sites differently. To gain insight into the significance of the identified barriers and their impacts on the overall decarbonisation process, the barriers were included in the first step of the stakeholder consultations (scoping questionnaire). The stakeholders were asked to share their view on the importance of specific barriers to the operation of their respective company, in a short-term (2030) and long-term (2050) perspective, on a scale from 1 (not important) to 5 (very important). As the scoping questionnaire was developed at an earlier stage of this project, the barriers listed in the questionnaire and their categorisation slightly differ from the list of possible decarbonisation barriers presented above (e.g. Table 2).

The preliminary results displayed in this report reflect the state as of 30th August 2020, and are based on the evaluation of 15 stakeholders' responses. These stakeholders reflect a combined share of 71% of EU steel industry CO_2 emissions (based on 2020 EU ETS allocations).

The evaluation of the importance rating by the stakeholders is based on four different metrics. Basically, the scoping questionnaire assessed the importance of the barriers both in a short-term (2020-2030) and in a long-term (2030-2050) perspective. The provided results were further analysed in two different ways: as a general average rating and as a CO_2-weighted average. The CO_2-weighted average considers the stakeholders' specific share of EU steel industry CO_2 emissions. This ensures that the ratings of significant CO_2 emitters are weighted corresponding to their CO_2 emissions, in such a way that higher emissions equal a higher weight of that stakeholder's response.

Based on these methods, the decarbonisation barriers were ranked using their specific importance ratings to identify the main ones. Table 6 (on the following page) displays the ranking based on both the average and the CO_2-weighted importance ratings, for 2030 and 2050. In this table, the following abbreviations were used: 'TEC' for technical barriers, 'ORG' for organisational barriers, 'FIN' for financial barriers and 'POSO' for policy or societal barriers.

It can be easily noticed that six out of the seven most important barriers are financial ones. The only exception are the framework conditions created by national or local taxes or fees (ranking 6th). However, despite its being categorised into the group of policy/societal barriers, this barrier also has financial implications. This also indicates that whilst the implementation of decarbonisation technologies appears to be technically feasible for most steel producers, it could be interpreted as an investment decision with currently negative outcome.

The availability of renewable energy was also rated as a severe barrier. It should also be mentioned that the emission-related legislation was considered to be a severe barrier in particular in the long term (ranking among the top 3 for 2050). Most organisational barriers are located at the bottom of the table, which shows to the comparably low ranking by the stakeholders.

The use of the CO_2-weighted metric enabled to recognise the importance of certain barriers specifically for CO_2 intensive stakeholders (i.e. those focused predominantly on primary steel production via the conventional BF-BOF route). Thus, the availability of raw materials is of significantly higher importance to CO_2-intensive stakeholders than to smaller ones. This is plausible since the demand for high quality raw materials is often higher among primary steel producers.

Table 6: Ranking of decarbonisation barriers by average stakeholder rated importance (sorted by 2030 average)

#	Decarbonisation Barrier	Cat.	2020-2030		2030-2050	
			Avg.	CO_2	Avg.	CO_2
1	Investments for industrial deployment	FIN	4.80	3.76	4.50	4.51
2	Increase in OPEX (costs of energy/renewable energy)	FIN	4.50	4.75	4.30	4.25
3	Unknown market conditions for clean steel	FIN	4.50	3.85	4.30	3.85
4	Investments for demonstration plants	FIN	4.40	4.59	4.11	3.11
5	Limited access to funding opportunities	FIN	4.30	4.65	4.20	4.06
6	Local taxes and fees (e.g. German EEG)	POSO	4.22	4.19	4.00	4.13
7	Other increase in OPEX (costs of materials, CCS, CCU, etc.)	FIN	4.20	4.49	4.00	3.98
8	Availability of renewable energy	TEC	4.00	4.24	3.90	4.79
9	Bureaucracy (external) and other administrative burdens	ORG	4.00	2.98	3.50	2.66
10	Emission-related legislation (e.g. EU ETS)	POSO	4.00	4.59	4.10	4.70
11	National implementation of other framework conditions (e.g. contract for difference)	POSO	3.63	3.17	3.50	3.17
12	Risk of unsuccessful deployment	TEC	3.60	2.00	3.40	1.90
13	Social acceptance of certain technologies (CCS, plants, infrastructure for H2/electricity)	POSO	3.60	3.92	3.30	3.86
14	Integration of new technologies in existing plants	TEC	3.40	2.64	3.30	2.74
15	Information exchange with other parties, collaborative research	ORG	3.20	3.26	2.90	3.00
16	Management of industrial transformation	ORG	3.10	2.22	2.90	2.21
17	Intellectual property management	ORG	3.10	2.99	2.90	2.99
18	Availability of qualified staff (for both development and operation)	ORG	2.90	2.60	2.60	2.66
19	Issuing of CO_2 storage permits for CCS	POSO	2.89	3.48	2.67	3.48
20	Availability of (primary or secondary) raw materials	TEC	2.40	3.28	3.10	3.98

Source: authors' own formulation based on stakeholders' consultation.

Vice versa, the risk of unsuccessful deployment and the bureaucracy barriers are of significantly higher importance to less CO_2-intensive stakeholders, which is plausible since their companies are generally smaller (i.e. with predominantly secondary steel production via the scrap-EAF route). Some barriers show a significant increase or decrease in importance for the different timeframes, i.e. 2030 and 2050.

The availability of raw materials appears to clearly increase in importance in the long term (2030-2050). This is plausible since the decarbonisation techniques are assumed to be industrially deployed in the long term (with a corresponding high demand for new raw materials). Furthermore, the availability of renewable energy and the emission-related legislation were rated as severe barriers, in particular in the long term, which is also plausible since they are related to industrial deployment.

Conversely, the investments for demonstration plants strongly decrease in importance in the long term, specifically for CO_2-intensive stakeholders, since the demonstration phase will have already been completed for (almost) all technologies.

Besides these basic interpretations, further evaluations were conducted and are described in deliverable D1.3 of the Green Steel for Europe project, which focuses on the (preliminary) findings from the first step of the stakeholder consultations via the scoping questionnaire.

4. Concluding remarks

This deliverable identifies and analyses possible barriers affecting the decarbonisation of the steel industry. The identified barriers were grouped into four categories: technical barriers, organisational barriers, regulatory/societal barriers and financial barriers. Consequently, this deliverable also provides a preliminary identification of regulatory/policy issues.

Following a general collection and assessment of relevant decarbonisation barriers, these were validated, evaluated and prioritised within a related stakeholder consultation, targetting steel producers covering more than 80% of the CO_2 emissions of the European steel industry.

In this consultation process, it was confirmed that the stakeholders clearly rated the financial barriers as the most severe barriers to decarbonisation. The necessary investments for industrial deployment and demonstration plants, the increase of OPEX; the unknown market conditions for clean steel, the limited access to funding and local taxes and fees are directly hindering the decarbonisation process. As a conclusion, solutions or remedies against these financial barriers need to be addressed on a policy level.

Besides financial aspects, the availability of renewable energy and the emission-related legislation were rated as severe barriers by the consulted stakeholders, particularly in the long term perspective. These barriers are also directly subject to policy decisions, both on member state and European levels.

Concluding the conducted assessments of possible decarbonisation barriers and their prioritisation by stakeholders of the iron and steel industry, there is a strong demand for policy adjustments to minimise these barriers. This gives clear indications for the impact assessment carried out in work package 3 of the Green Steel for Europe project.

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