Technology Assessment and Roadmapping

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Executive summary

To meet the 2050 European climate and energy targets, the iron and steel industry's CO_2 footprint needs to reduce by 80-95%, compared to 1990 levels, by 2050. This can only be done if adequate and innovative solutions are established to shift current processes towards carbon-lean production. The Green Steel for Europe (GREENSTEEL) project aims, *inter alia*, to provide transparency about the **technologies needed and their impact,** and the **barriers to be overcome** and the **remedies needed to initiate the crucial next steps**.

This report, which is Deliverable D1.2 of the GREENSTEEL project, provides the **technological foundation for the evaluation of CO_2 mitigation strategies** with specific low-carbon technologies, and for implementing complete technology routes in the European steel industry. It summarises iron and steelmaking technologies, supporting technologies and technology routes, describing their technological approaches, their current maturity (in terms of readiness level) and their expected development, as well as the influencing framework conditions. The technological foundation provided by this report is used for the development of scenarios as reported in the report Decarbonisation Pathways 2030 and 2050 (Deliverable D1.7 of the GREENSTEEL project).

The **CO_2 mitigation pathways**, which are currently being addressed in the European steel industry, are **carbon direct avoidance** (CDA), **process integration** (PI) and **carbon capture and usage** (CCU). The parallel circular economy strategy targets a 'zero waste' concept and complements the above-mentioned pathways as an overarching approach.

- The **CDA pathway** primarily focuses on the development of new steelmaking processes using fossil-free reductants and (renewable or clean) energy sources to produce steel from virgin iron ore, thereby avoiding the generation of carbon oxides and its emissions.
- The **PI pathway** concerns possible modifications or adaptations to existing steel plants in order to reduce greenhouse emissions and can be complemented by CCU and/or carbon capture and storage (CCS).
- The **CCU pathway** consists of the capture of CO_2 or CO from steel production process gases and the production of further valuable carbon-based products from captured fossil carbon, thus mitigating emissions caused by fossil resources in their conventional production chains.

The following **nine iron and steelmaking technologies** were identified as the most relevant within these pathways:

- hydrogen-based direct reduction (H_2-DR)
- hydrogen plasma smelting reduction (HPSR)
- alkaline iron electrolysis (AIE)
- molten oxide electrolysis (MOE)
- carbon oxide conversion
- iron bath reactor smelting reduction (IBRSR)
- gas injection into the blast furnace
- substitution of fossil energy carriers by biomass
- high-quality steelmaking with increased scrap usage

The **selection of iron and steelmaking technologies** is based on desktop research of various global publications, a comprehensive stakeholder survey and the outcomes from the previous RFCS Project LowCarbonFuture - Exploitation of projects for Low-Carbon Future Steel Industry (Grant Agreement No. 800643). Table 1 provides an overview of the technologies and their main data.

Table 1: Overview of low-carbon iron and steelmaking technologies

Technology	TRL development			Economic assessment	Reference projects[1]
	2020	2030	2050		
Hydrogen-based direct reduction (utilisation of 100% H_2)	TRL 6-8	TRL 7-9	TRL 9 (ind. deployed)	20-80% cost increase; production costs: ~€532-640/t CS	HYBRIT, SALCOS, tkH_2Steel, Hydrogen Hamburg
Hydrogen plasma smelting reduction	TRL 5	TRL 6	TRL 9 (ind. deployed)	No information on CAPEX or OPEX	SuSteel
Alkaline iron electrolysis	TRL 5-6	TRL 6-8	TRL 9	CAPEX + OPEX: ~€645-828/t CS	ULCOS (SP5-13-14), IERO, VALORCO, SIDERWIN
Molten oxide electrolysis	TRL 2	TRL 3-4	TRL 9	CAPEX: ~€1 K/t CS annual capacity; OPEX: increase of 50-80% compared to conventional route	ULCOS, IERO, VALORCO
Carbon oxide conversion	TRL 8 (conversion) TRL 4-5 (impl.)	TRL 9	Ind. deployed	CAPEX increase of ~€13/t CS OPEX increase of €408-629/t CS	Carbon2Chem, Carbon4PUR, STEELANOL
Iron bath reactor smelting reduction	TRL 6	TRL 8	Ind. deployed	CAPEX: €500 M (for a 1.15 Mt/year plant excl. O_2 plant) Neg. OPEX (-25 to -€30/t CS), due to efficiency gains	HIsarna
Gas injection into the blast furnace	TRL 5-8 (preparation / gas reforming) TRL 9 (H_2 rich)	TRL 8-9	Ind. deployed (in 2040)	CAPEX: €80-110 / €110-150/t CS (without / with CCUS) OPEX: €0-10 / €40-50/t CS (without / with CCUS).	ULCOS
Substitution of fossil energy carriers by biomass	TRL 2-7	TRL 8	TRL9 (ind. depl. in 2035)	CAPEX relatively low and OPEX depends mainly on the raw materials	SHOCOM, GREENEAF2, ACASOS
High-quality steelmaking with increased scrap usage	TRL 4-8	TRL 7-9	Ind. deployed	OPEX: significant depending on the scrap price	FLEXCHARGE, ADAPTEAF, SSIA, LCS

CS - crude steel; ind. deployed - industrially deployed; CAPEX - capital expenditure; OPEX - operational expenditure; impl. - implementation; neg. – negative
Source: author's own composition.

[1] The list comprises national and international projects (not exhaustive).

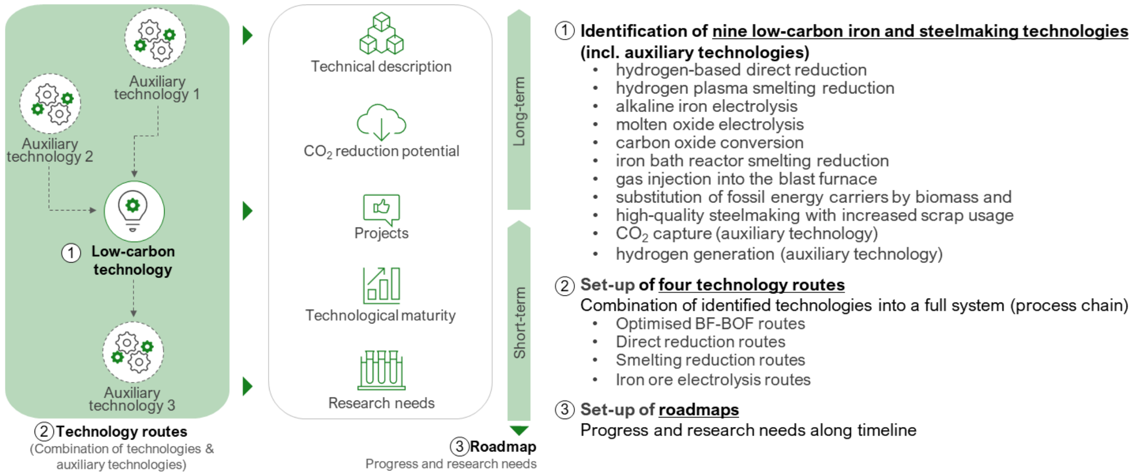
The **majority of the identified technologies have a moderate maturity level**, with technology readiness levels (TRL) between 5 and 7. Certain technologies, such as hydrogen plasma smelting reduction or molten oxide electrolysis, have high CO_2 mitigation potential but are currently at low maturity. Correspondingly, a high number of research and development (R&D) projects are needed, in particular regarding the processes and their upscaling, as well as the related plant technologies, auxiliary processes, material processing and a large number of measurement and control aspects. Several technologies can be combined in order to raise the overall CO_2 mitigation potential above their individual limits. CO_2 capture and H_2 generation are the main auxiliary processes connected to several of the technologies. As H_2 can be extracted from fossil fuels and biomass, water, or a mix of both, there are multiple production processes available such as reforming of gas, gasification (biomass, waste etc.) or water electrolysis.

The analyses showed that for most technologies, a **huge amount of additional clean energy** is needed and that the material cycles in the plants will be fundamentally influenced. Moreover, many technologies imply a **significant increase** in terms of **CAPEX** (due to the need to replace main parts of the upstream process chain) and **OPEX** (mostly due to expensive renewable energy supply). The exchange of fossil energy sources by biomass usually needs less changes within the process chain; however, its use is strongly limited by the (local) **availability of biomass resources**.

The technologies described in this report focus on the **predominant trends** within the **EU**, supported by a literature review relating to non-EU countries. In **Japan**, the COURSE50 programme is aiming to mitigate CO_2 emissions in steel production by using several approaches, including hydrogen gas injection into the blast furnace (BF) and carbon capture and storage. The POSCO programme in **South Korea** focuses on the carbon-lean FINEX process, pre-reduction, heat recovery of sinter, carbon capture and storage as well as hydrogen-based reduction of iron ore. In the **US**, steelmaking by molten oxide electrolysis, hydrogen flash smelting and CO_2 capture and separation are being investigated. **Australia** is working on two programmes regarding the utilisation of biomass and heat recovery from molten slags through dry granulation in blast furnaces.

The **iron and steelmaking technologies** within each pathway (CDA, PI, CCU) **can be considered as individual modular components** (mitigation options) within the complete steel production chain. **Technology routes integrate these components into a full system** (process chain), which includes upstream operations (transformation of raw materials into intermediate steel products) and downstream applications (production of final shaped and coated products). When projecting the development and research needs of the technologies as well as technology routes onto a time frame, a corresponding roadmap is created. The compilation of technologies to technology routes including the integration into existing/new production chains needs substantial additional effort (both with respect to R&D activities and to accompanying investments needed) as all material and gas flows including upstream and downstream processes and infrastructures are affected. Combining mitigation technologies in technology routes is by essence not limited to a specific mitigation pathway (CDA, PI, CCU) but may include elements from all of them. This correlation between technologies and technology routes, as well as the approach within the report, is shown in Figure 1

Figure 1: Link between technologies and technology routes



Source: author's own composition.

The CO_2 emission of downstream processes is much lower than from ore-based upstream processes. Therefore, the focus lies on **upstream applications** and **scope 1** (direct emissions) and **scope 2** (indirect emissions from the production of required energy) emissions.

Four promising technology routes (Table 2) were identified within the project work as highly relevant (but non-exclusive) examples. The **first** one is based on conventional BF-BOF plants (blast furnace, basic oxygen furnace), into which a number of add-on CO_2 mitigation technologies are incorporated (PI, CCU). This route can be considered a short-term solution. The **second** is based on the utilisation of direct reduction based on natural gas or hydrogen, in which all ironmaking and steelmaking units are replaced by new production methods. The **third** technology route comprises technologies based on smelting reduction. This includes, on the one hand, the iron bath reactor smelting reduction option, in which the ironmaking part is replaced and, on the other hand, hydrogen plasma smelting reduction, which enables the direct transformation of iron ore into liquid steel. The **fourth** technology route refers to the electricity-based steelmaking by iron ore electrolysis. It can either be carried out at low temperatures (alkaline iron electrolysis; replacement of the iron making part) or at high temperatures (molten oxide electrolysis; direct production of liquid state metal from oxide feedstock).

The **advantages and disadvantages of a technology route** are strongly related to the associated framework conditions and the considered facility since each plant entails different possibilities and hurdles. The adequacy of a technology route must be assessed on an individual basis. The following table (Table 2) summarises necessary framework conditions for each technology route.

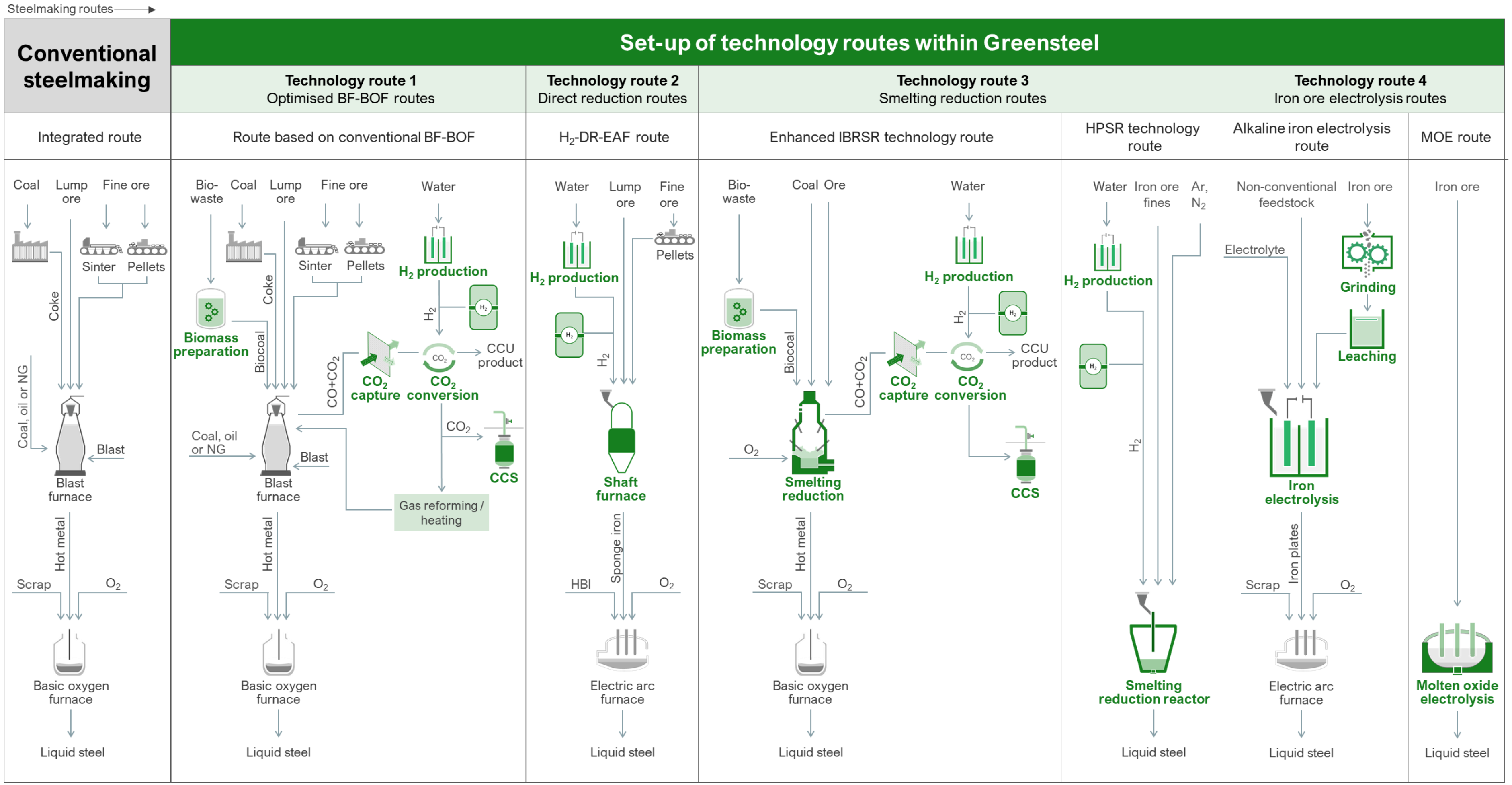
Table 2: Technology routes and their associated framework conditions

Technology route	Framework conditions
Technology route 1 **Technology routes based on optimised BF-BOF**	• Technologies to upgrade alternative carbon sources • Transportation, storage, price and availability of alternative carbon sources • Possibility of integrating upgrading technologies at the steelmaking sites • Energy efficient separation and purification technologies • Availability and price of low-CO_2 hydrogen production • Availability and volatility of renewable energy • CO_2, process gases and hydrogen transport system • Marketability and price of CCU products • Social acceptance
Technology route 2 **Technology routes based on direct reduction**	• Price and availability of natural gas • Process gases transport system • Availability and price of low-CO_2 hydrogen • Energy system without (or with minimum) carbon input • Strengthening of high-voltage grids • Hydrogen transport and storage infrastructure
Technology route 3 **Technology routes based on smelting reduction**	• Carbon capture, usage and storage technologies have to be used in combination with IBRSR to attain sufficient mitigation • Pre-treatment processes for alternative carbon sources (IBRSR) • Price and availability of alternative carbon sources (IBRSR) • O_2 production and CO_2 capture and compression (IBRSR) • Social acceptance (IBRSR) • Availability and price of low-CO_2 hydrogen production (HPSR) • Energy system without (or with minimum) carbon input (HPSR) • Strengthening of high-voltage grids (HPSR) • Hydrogen transport and storage infrastructure must be provided (HPSR)
Technology route 4 **Technology routes based on ore electrolysis**	• Energy system without (or with minimum) carbon input • Strengthening of high-voltage grids

Source: author's own composition.

The illustration below (Figure 2) provides a **comparative view of the technology routes** (green) **and the integrated primary steel production route** (grey). The process chain is visualised from top to bottom of the figure. The objective is to demonstrate to which extent alterations occur.

Figure 2: Overview of the set-up of technology routes in comparison to the integrated steelmaking route



Source: author's own composition.

The route based on conventional BF-BOF and the enhanced iron bath reactor smelting reduction technology route show a horizontal change (i.e. with remaining BOF) as opposed to a widespread vertical alteration within the hydrogen-based direct reduction - electric arc furnace (H_2-DR-EAF) route and the electrolysis-based technology route. The green indications within the flow diagrams show the modifications, whereas the grey-coloured depictions symbolise unchanged procedures. Although the main existing process units are not replaced with new technologies for the proposed CO_2 mitigation route based on conventional BF-BOF, considerable changes must be carried out in conventional plants. To reach significant mitigation through this technology route, considerable investments are required for the add-on technologies (e.g. carbon capture, usage and storage, biomass preparation, gas preparation and blast furnace gas injection systems). For the H_2-DR-EAF route, the technology route based on hydrogen plasma smelting reduction and the technology routes based on iron ore electrolysis, the full ironmaking and steelmaking capacities of existing BF-BOF plants have to be replaced. The effort is almost comparable to greenfield conditions. The data provided in the figure regarding this route refer to the breakthrough technology with (almost) complete usage of hydrogen as reducing gas for direct reduction. The smelting reduction technology route replaces the full ironmaking process in conventional plants; further significant investments are required for add-on technologies (e.g. carbon capture, usage and storage and biomass preparation) to achieve extensive CO_2 mitigation.

Starting from the identification of individual iron and steelmaking technologies, a **roadmap for the proposed breakthrough technologies** has been created (Figure 3). This roadmap indicates the progress and the research needs for each technology involved along the timeline. The needs for integrating the technologies into a complete breakthrough process chain are also visualised. Each line describes one technology. Starting in 2020 (current technology readiness level), the technology readiness level development is shown from left (short-term) to right (long-term) both graphically (grey shaded area) and numerically.

Consistent with all other reports within the project, '**short-term**' refers to the period up to about **2030**, while '**long-term**' refers to a time **after 2040**. As soon as TRL 9 – and thus the maturity for first industrial deployment – is reached, the mitigation potential is presented in a circular diagram. Research needs are grouped and listed in the associated time period.

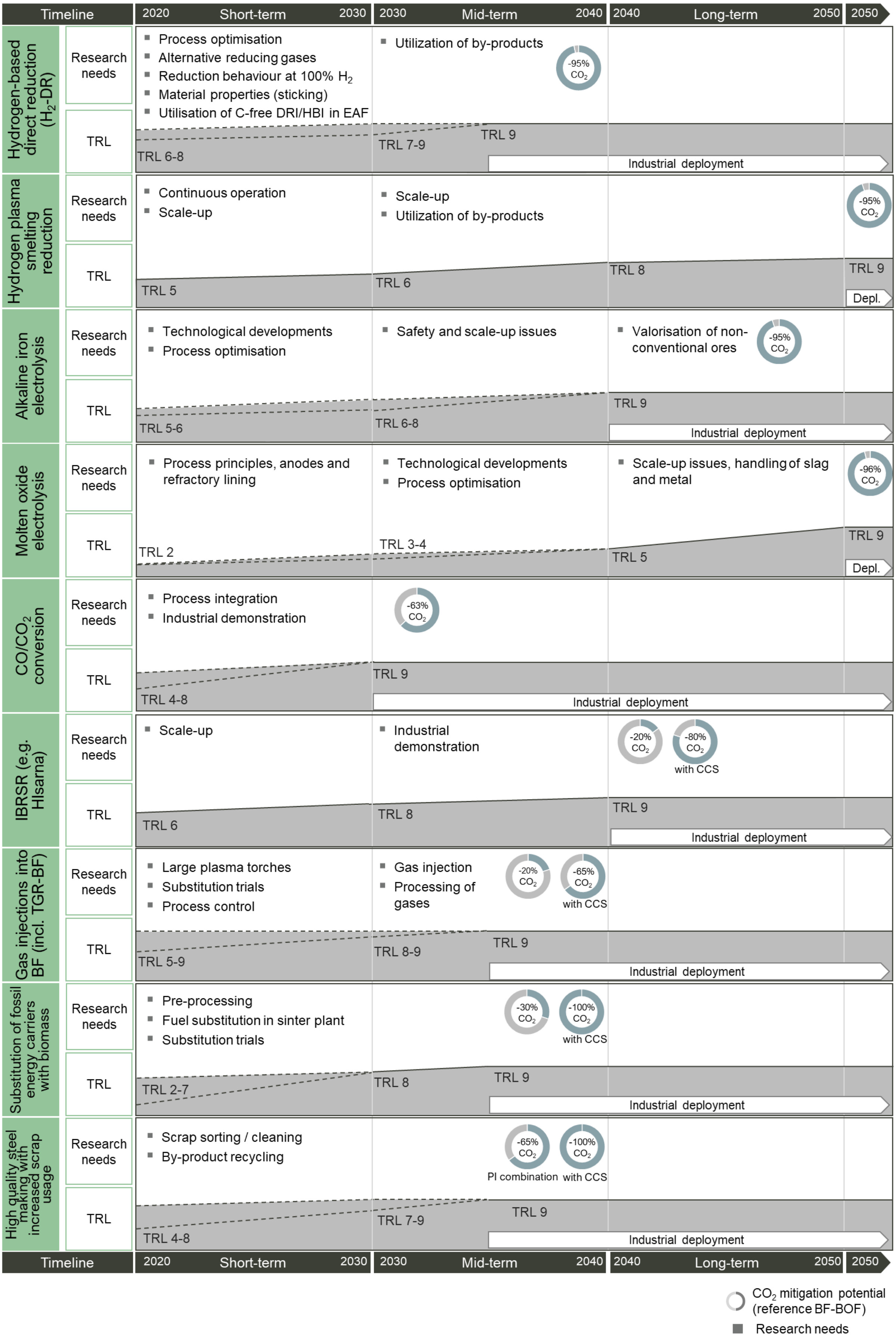
A promising short-term option regarding CO_2 mitigation is to **replace part of the fossil coal used in different plants** (e.g. coking plant, sinter plant and blast furnace) **with biomass**. This can further be combined with recycling the remaining CO and hydrogen from the blast furnace top gas back into the process, effectively decreasing CO_2 emissions. CO and hydrogen can be recovered with a CO_2 separation step, such as recycling fumes in blast furnace hot stoves or some new, in-process, capture technologies. Several gaseous streams in steel plants have rather high concentration of CO_2, therefore offering a great potential for specific/integrated capture processes.

Besides possible replacement of energy carriers with biomass, the **replacement of primary raw materials with increased scrap utilisation** according to the circular economy strategy (creating a closed loop system) is another measure for CO_2 mitigation. In direct comparison, secondary steel production via the scrap-EAF route makes use of recycled steel scrap and results in about 80% less CO_2 emissions than with the primary BF-BOF-route. Nonetheless, the potential for scrap utilisation is strongly restricted under the requirements for steel product quality. More specifically, the metallurgical requirements for high-quality steel, which is often produced via the primary BF-BOF-route, demand the processing of virgin material and will limit the scrap utilisation significantly for the foreseeable future. A clear R&D demand for improved scrap processing in order to ensure better scrap quality was identified. Indeed, this would alleviate the limitations of scrap utilisation to some extent.

An important intermediate step towards the deployment of the H_2-DR-EAF technology route is the **direct reduction with natural gas** which has been an industrially established technology for a long time. Also, with natural gas the direct reduction technology (NG-DR) provides a significant CO_2 mitigation potential compared to the conventional BF-BOF-route, and thus, a promising short-term option. The share of hydrogen as a partial substitute for natural gas can be increased stepwise towards the possible later target of complete hydrogen-based reduction. This allows a gradual enrichment with hydrogen on industrial scale and enables a flexible increase of hydrogen concentration depending on availability, price, and technical requirements. Regarding the time scale for industrial deployment, this results in the option of direct reduction plants being built as of now (depending on the individual investment cycles of the respective plants) and their shift towards increased hydrogen usage as soon as possible depending on its availability. Natural gas-based direct reduction can be complemented by CCU and/or carbon capture and storage; the realisation relies on the specific situation of the individual steel production site.

To realise the crucial next step of demonstration and completion in operational environment (TRL 7–8) and to enable the European climate and energy targets to be met, the **R&D actions need to be taken immediately**. Since the needed R&D actions are widespread and the effort by far exceeds usual R&D needs, international collaborative research could be useful for effective progress. It can be stated that the four proposed technology routes have a **CO_2 mitigation potential up to 100%,** but not all technologies can be industrially deployed in the short term (by 2030). Some technologies are available, which enable short-term deployment with limited R&D need and investment effort. The technologies need certain framework conditions, the most important one being the **availability of sufficient clean energy at costs that are competitive** with worldwide levels.

Figure 3: Roadmap of selected CO_2 mitigation technologies



Source: author's own composition.