What is green steel?

Towards a strategic decision tool for decarbonising EU steel

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What is green steel? - Towards a strategic decision tool for decarbonising EU steel

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Summary
The climate debate has sparked an interest for alternative steelmaking processes within the European steel industry. For the steel industry the Paris Agreement means it must undergo large-scale technological change. Public funding for research and demonstration projects has been successful in nurturing a variety of technology innovation projects, such as projects aiming to use renewable hydrogen in the direct reduction process, or to produce chemicals from steel off-gases via carbon capture and utilisation. If these technologies can be demonstrated successfully, their commercialisation will require further public support in the form of demand pull policy to create a market for these technologies in which they can mature and reach competitiveness.
In respect of the large sums of public support required for the push and pull of climate-friendly steelmaking technologies, support decisions must be based on a project's compatibility with climate goals and avoid carbon lock-in. The aim of this paper is thus to analyse the implications the Paris Agreement has for future investments in the EU steel industry. We do this by reviewing technological pathways and suggest a methodology to determine if investments are in line with climate goals. The methodology is based on the carbon footprint of steel and we review the main choices that have to be made in a life cycle analysis for alternative steelmaking processes. We conclude that the technological options to reach zero emissions by mid-century are limited. The early articulation of support for high-ambition investments has the potential to create stable long-term market expectations and form the basis of a demand pull for green steel. Our insights can inform policy makers to bring innovation policy in line with long-term climate goals.

Key Words
Climate policy, innovation, steel, Paris Agreement, deep decarbonisation, LCA

Introduction
The Paris Agreement on climate change in 2015 requires us to reduce global greenhouse gas emissions to zero by 2050 to 2070 [1]. Based on the common but differentiated responsibilities principle (CBDR) enshrined in the climate convention (UNFCCC) developed countries should pioneer this process and reduce emissions faster than the global average. The production of steel is one of the large emitters globally and responsible for 5% of global greenhouse gas emissions [2]. It is also one of the economic sectors that are the hardest to decarbonise, due to tough global competition, the dependence of the production process on carbon, and the need for new "breakthrough" technologies with high abatement cost and long investment cycles. In Europe a set of technologies have been identified and a variety of research projects aims to develop these breakthrough technologies. Most of these projects follow one of two distinct strategies – either using renewable fuels (hydrogen, electricity, biomass) or end-of-pipe capturing of CO_2. The successful commercialisation and diffusion of these "low-carbon[1]" technologies for steel will require significant public support, especially with regards to the short time horizon the threat of climate change mandates.

The prescribed climate policy solution for reducing emissions has been the pricing of carbon on a "free" carbon market. However, both the actual experiences from the development of renewable energy [3-5] and innovation theory [6, 7] strongly suggest that a carbon price must be complemented with directed, technology-specific support for creating an early niche market for new innovative technologies. This is especially true for steel companies, which stand under strict global competition but are subject to different climate regulations in the various countries they operate in. Innovative and climate-neutral steel

[1] Carbon is an essential component of steel. With low-carbon we mean low in emissions. Decarbonisation refers to reducing emissions, not the carbon content in steel.

comes with higher production cost compared to business as usual and faces several other systemic barriers such as a lack of infrastructure, weak trust in long-term climate policy, technical uncertainties, and immature market knowledge. Carbon pricing alone cannot alleviate all of these disadvantages. An effective technology policy thus contains both a supply push and a demand pull [6, 8, 9].

In the EU, the emissions of CO_2 in the steel sector is primarily governed by the emission trading system (EU ETS) that covers 45% of EU emissions and includes both the power sector and all large industrial installations. The EU ETS sets an emission cap that declines down to -40 % by 2030 with an indicative target of minus 80 – 95% by 2050. It is complemented with several other policy instruments in order to avoid the negative societal consequences of a carbon price and to align with industrial policy objectives. The most salient are the free allocation of emission allowances to protect energy-intensive industry from carbon leakage and various supply push technology policies such assuch as the R&D programme Horizon 2020 and ULCOS[2]. .

Up to 2010, the EU climate governance for steel was focussed on short-term marginal reductions via energy efficiency and protecting against carbon leakage. This policy response was conserving existing industrial structures rather than supporting innovation and change [10]. However, since the adoption of an indicative reduction target for 2050 [11] the focus of EU climate governance for the steel industry has changed towards innovation and technology support instead. The EU 2050 ambition introduces a strict timeline of when steel production has to be decarbonised in the EU. Recently, the Commission has even adopted a more ambitious target, which is more in line with the Paris Agreement and aims at net-zero emissions by 2050 [12]. However, even if the basic policy framework is in place including carbon pricing and ample funding for both R&D and demonstration projects, what is still missing is a demand pull policy for creating an early niche market for climate-neutral steel. A stable demand for green steel is crucial for lowering the risks of the first large investments into breakthrough technologies [8, 9].

The new 2050 ambition reduces the long-term uncertainty and narrows down the technological options to only a few capable of reaching net-zero emissions. Effective business investment decisions and public support for the steel industry needs to support projects that are aligned with this target and must avoid inducing carbon lock-in [13]. The aim of this study is thus to analyse the implications of a net-zero 2050 target for future investments in the EU steel industry. The methodology presented can be used as a decision tool for strategic investment by industry but also for defining what “green steel” is and what should be supported by policy in order to be compliant with climate targets. The methodology is built on a life cycle perspective and connects the 2050 targets and the possible technical pathways for the steel industry.

We start our article by summarising different pathways the steel sector can take towards 2050. In section 3, we outline a life cycle perspective that also serves a long-term climate purpose. In section 4, we design a robust and workable methodology and decision tool that can be used to support climate-compatible investments. Finally, we discuss the potential contribution of the tool for both industry and policy for creating a demand pull for green steel.

2. The steel transition in the EU

The European steel sector produced 168 million tonnes of steel in 2017 and emitted 128 million tonnes of CO_2 [14, 15]. The blast furnace – basic oxygen furnace route accounts for 60% of steel and the rest from recycling of scrap (67 million tonnes). On top, there is one direct reduction plant in the EU. Due to the saturation of demand the EU steel demand is projected to be similar or slightly below current levels in 2050 [16, 17]. However, scrap[3] availability will increase and may reach 136 Mt by 2050 [18]. Consequently, production volumes from primary and secondary steelmaking might more than reverse and secondary steelmaking might become the new dominant production route by 2050. This shift towards more secondary steel is not only due to increased scrap availability but will also be driven by EU circular economy policy. Following the trend of a declining share of primary production in the EU, several of European primary steelmaking sites would be converted to secondary steelmaking, or that new mini-mills open up and some integrated plants close. However, primary steelmaking would still be responsible for about 60 million tonnes CO_2 in 2050 assuming with today’s production technologies and the direct emissions from secondary steel would amount to 7 million tonnes with current practice.

[2] The EU recently also launched the Innovation Fund for financing commercial-scale demonstration projects for industry

[3] This includes also scrap from production and manufacturing.

2.1 Anticipated pathways for steelmaking

The deep decarbonisation of steelmaking requires the roll-out of several different strategies including material efficiency, dematerialisation and maximised recycling. Large potentials are yet untapped when it comes to the materially efficient production and use of steel [19, 20]. However, as long as global demand for steel keeps increasing primary production will be needed to supply additional primary steel to the societal stock. The blast furnace is the largest emission source in the steel value chain and further efficiency potentials are small [21]. Net-zero emissions means the steel industry must replace current primary production processes, namely the blast furnace route, with low-, or preferably zero-emission production processes.

Production route	Emission intensity	Relative emissions vs. BF
BF[22]	1682	100%
NG-DR[23]	1020	61%
scrap EAF without fossil fuels [22, 23]	<100	<6%
H-DR[24]	<100	<6%
Electrowinning	<100	<6%
BF CCS[25, 26]	673	40%
BF CCU	673 -1682	40-100%
BF Bio[27]	1009	60%
BF BioCCS[28]	<100	<6%

Table 1: The emission intensity of different steelmaking technologies. Indirect emissions are excluded and the emission backpack of scrap is considered zero, as explained in section 3 (unit [kgCO2eq / t steel]).

Table 1 lists the emission levels of possible steel production processes according to the literature. Keeping the blast furnace means that in order to eliminate greenhouse gas emissions CCS must be installed and a part of the coal injection needs to be done with biogenic carbon with a net-zero carbon footprint (BF CCS/CCU; BF Bio, BF BioCCS). In theory it is possible to reach zero emission with a blast furnace by using both biomass that can replace up to 40% of coal use [27] and complementing this with CCS on the major point sources. Direct reduction with natural gas (NG-DR) complemented with an EAF has a substantially smaller carbon footprint compared to current blast furnaces. A zero emission option for the direct reduction plant is to use renewable hydrogen (H-DR). The only residual emissions arise in the EAF due to the consumption of graphite electrodes, as well as the use of lime and natural gas. The mitigation of these emissions will require some research into new electrode materials and slag foaming, but the innovation challenge can be regarded significantly smaller than the one for primary steelmaking. Producing secondary steel from scrap in an EAF is substantially less carbon intensive if the indirect emission from the electricity is excluded and if natural gas is replaced with a renewable heat source. Another way of making iron is electrowinning, which can be used to produce iron directly in an electrolytic process and must be integrated with an electric arc furnace for producing steel. Electrowinning uses electricity and is thus another option that could also reach zero emissions, but it has yet to be demonstrated on full scale and in an integrated production system. Currently, one pilot plant is operated in Europe and one further project in the US has entered the demonstration phase [29].

In Figure 1, we outline different paths that can lead from the blast furnace route to different steelmaking processes with low emissions. In a first step, the blast furnace can be either complemented with carbon capture or the site can be converted into an EAF mill. A change from current production to fossil-free steelmaking does not need to be a single big step-change, but can be gradual through introducing bridging technologies such as switching to arc furnaces or natural gas direct reduction, or alternatively CCU, top-gas recycling or injections of biomass into the blast furnace. The range of possible low-emission processes becomes narrower once an investment in a bridging technology has been undertaken, as this investment will create some path dependency and make some later options more suitable than others. Thus, it is likely this first investment step will decide if the blast furnace shall stay or go. In the case of scrap steelmaking, operators have a larger flexibility later on as several iron making processes can be combined with electric arc furnaces. On the other hand, if a site invests in a carbon capture facility, a later reorientation away

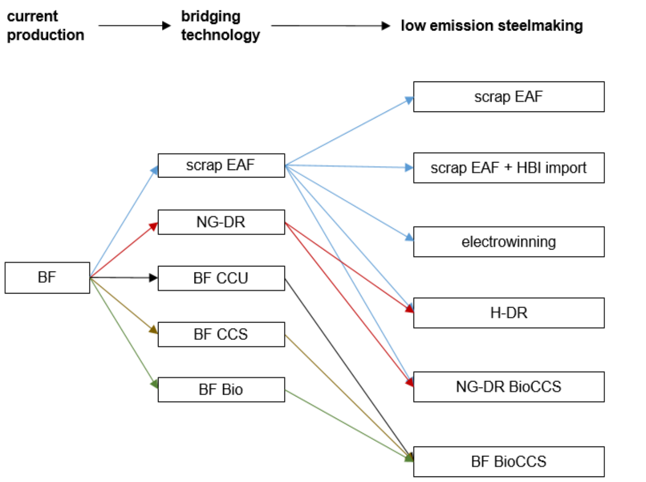

Figure 1: Technical emission reduction pathways for primary steelmaking. Abbreviations: BF: blast furnace; EAF: electric arc furnace; NG-DR: natural gas direct reduction; CCU: carbon capture and utilisation; CCS: carbon capture and storage; Bio: use of biomass; HBI: hot-briquetted iron; H-DR: hydrogen direct reduction.

from the blast furnace becomes more difficult due to sunk costs, infrastructure and the gained experience with the process. Such a site will thus more probably go on with CCS and use biomass.

3. Steel from a life cycle perspective

Different life cycle assessment (LCA) tools can be used to assess the carbon footprint of steel production. The Life Cycle Inventory (LCI) describes the collection of data on emissions regarding their source and forms the basis of a LCA. An LCI database for several steel products has been compiled by the World Steel Association [30]. LCA is the interpretation of LCI data at a systemic level and involves a number of choices on system boundaries and the allocation of emissions to various parts of the system. Thus, interpretations of the same LCI data can result in very different LCAs.

Two principle streams of thought in LCA have emerged the last 20 years: *attributional* or *consequential* LCA [31]. Attributional LCA can be seen as a book-keeping instrument where the actual emission from a specific value chain is allocated to end-user products. Consequential LCA, on the other hand, interprets the consequences from a change in a value chain or the emergence of a new value chain. Consequential LCA is a forward-looking instrument that is better used for strategic decision making (e.g. comparing future investments). Below we discuss three methodological issues that arise in determining the carbon footprint of the alternative steelmaking routes reviewed in section 2: indirect emissions from electricity use, the emissions backpack of end-of-life scrap, and how to calculate embodied emissions of the CO_2 used as a feedstock for the chemical industry via CCU. Furthermore, we analyse how suitable these approaches with regards to incentivising a decarbonised and more circular steel system.

3.1 Indirect emissions from electricity use

Attributional LCA considers the CO_2 emissions from electricity based upon actual emissions at the time of analysis. In the methodology practiced by the World Steel Association this is done by calculating emissions from electricity use drawing on the grid emission factor within the relevant region or country [32]. Consequently, the location of a plant matters. For the whole of EU, the grid factor was 296 grams CO_2 per kWh but with great variation across the Member States. The current Polish grid factor is more twice the EU average, whereas Sweden’s is close to zero [33]. However, when the aim is to analyse change, using attributional LCA will only provide a static view.

A consequential LCA offers two main approaches to analysing the changing electricity system: using the short-term marginal production or the long-term marginal production. The difference between these two methods is vast. The short-term marginal effect represents the immediate change in the system where the response to an increasing load is based on the margin with dispatchable electricity supply of high OPEX/medium CAPEX power facilities. The way the electricity market regime is designed and the way the grid operates today, short-term marginal electricity production is almost exclusively based on either coal or natural gas with relatively high emission factors. The short-term marginal view assumes that the electricity system does not change (e.g. no new investments), but that the increasing electricity is merely an operational adaptation for keeping the system in balance.

The short-term marginal electricity production is not useful when analysing long-term trends where we can assume that (i) the increase in electricity demand will influence the system calling for more investments and (ii) that the electricity system in itself changes due to other factor such as the EU ETS and the EUs climate and energy policies. Currently, the new investments made in electricity production in the EU are dominated by renewables such as wind and solar PV. Taking a look at the added capacity during the last years, one can get a glimpse on what the dynamic effects of increasing electricity demand will be. On top of this, taking into account climate policy targets and the rapidly decreasing cost of renewables vis-a-vis large-scale thermal power plants (with or without CCS), the electricity system will become ever more renewable and eventually be decarbonised by 2050, at latest. This suggests that a long-term dynamic marginal production approach is more suitable for analysing emissions from electricity production in steelmaking. This approach then assumes that all new investments in electricity will be renewable.

3.2 Emissions from recycled steel and the benefits of CCU

For end-of-life (EoL) scrap, the main question is if it should carry an “emission backpack” from previous life cycles or not. In an attributional LCA, the calculation of embodied emissions in recycled steel follows either the “recycled content approach” (or cut-off, 100-0) or the “avoided burden approach” (or EoL, 0-100). The recycled content approach allocates all emissions to the primary steelmaking process (hence “100-0”) whereas in the avoided burden approach, the recycled scrap carries a part or the full burden from earlier life cycles. The exact share and how to calculate the footprint for a product system depends on the method used [30]. The World Steel

Association's "net-scrap" method builds on the avoided burden approach. In the net-scrap method the size of the burden depends if products increase or deplete society's scrap pool [30]. Taking a consequential perspective on the net scrap approach shows that if external parameters are held constant the method incentivises products that "produce" (i.e. make available) more scrap than is used in their production. The net-scrap approach is thus not suitable for incentivising increased *use* of recycled content in products, or at least only up to a certain limit. The recycled content approach gives incentives to increased *use* of recycled content in steel products, which fits better with circular economy objectives and the barriers facing the increase of secondary steel use. However, there is no optimal allocation here and the recycled content approach hinges on supplementary policies for better scrap availability e.g. through ensuring the quality and economy of good scrap.

The large amount of CO_2 represents a major waste stream in steelmaking. Instead of avoiding emitting CO_2 to the air altogether, CO_2 can be captured and used as a feedstock for further processing into chemicals thus replacing fossil feedstock. The steel and chemicals industries are collaborating in several respective innovation projects in the EU (e.g. Carbon2Chem, Steelanol, FresMe, Carbon4PUR etc.). In a consequential LCA with a long-term focus, understanding changes in the surrounding systems is key and has several implications on how to best allocate emissions for by-products and end-of-life waste. In a transition to a low carbon economy, steel will have several relevant by-products that need to be accounted for but whose usefulness/value will change due to climate policy over the years. Following this logic the value of using waste CO_2 from blast furnaces for replacing fossil feedstock will decrease for the chemicals industry, as this industry will face increasing pressure to use non-fossil feedstock in the future. The same goes for e.g. waste heat if the origin is a process operated with fossil or non-CCS fuels.

4. A strategic decision making tool for decarbonising steel

In this section, we outline a methodology to identify steel production pathways that are in line with long-term climate targets. The methodology is simple and builds on the carbon intensities of various steel production routes and an emission trajectory in line with the goal of net-zero emissions by 2050. Special consideration needs to be taken to the long investment cycles in the steel industry of around 15 to 20 years between major rebuilding opportunities that limit the flexibility of steel producers. Timing of large investments is thus of great significance for the decarbonisation of the steel industry. Endorsing the wrong options will lock in carbon-intensive investments for 15 to 20 years with the risk of sites being prematurely closed as they cannot meet future climate requirements and face high carbon costs or might lose their social license to operate.
As we showed in the previous section, calculating the carbon footprint from electricity, the scrap use and the use of CO_2 as a feedstock can be done in several ways from a life cycle perspective. For the purpose in this paper, we adopt a consequential LCA perspective where we assume that the surrounding systems will both (i) decarbonise and (ii) substantially increase recycling and material efficiency. Hereby, we treat electricity as renewable, scrap as carrying no backpack from previous cycles, and the benefits from using fossil CO_2 as feedstock as declining over time.

In Figure 2, we illustrate the emission trajectory for the carbon footprint of steel production that is in line with the net-zero goal as proposed by the European Commission. The starting point in 2020 is the current EU ETS benchmark level, which reflects the LCI-data for best performing installations for primary steelmaking in the EU. Proceeding from this level the threshold decreases linearly until it reaches zero in 2050. Steel production with a carbon footprint below the limit in a certain year is in line with climate targets (within the grey area). Natural gas direct reduction thus represents a sufficient improvement from current emission levels up to 2032, and a blast furnace with

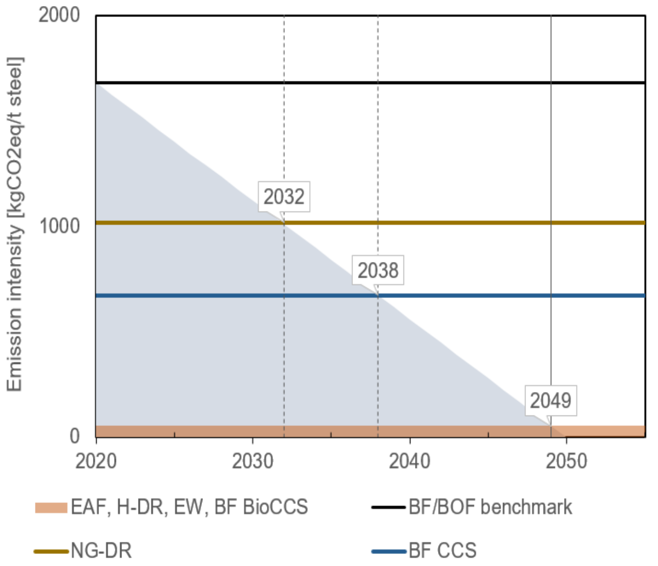

Figure 2: Linear emissions trajectory for primary steelmaking in the EU28. Horizontal lines are the emission intensities of different production routes (see Table 1).

CCS and savings of 60% is sufficient up to 2038. Following our logic, steel from these production routes should thus not be eligible for public support after 2032 and 2038, respectively. Considering the previous example of a BF CCS investment, the technical operating space is strongly restricted by taking the long investment cycles into account. For example, assuming a 15-year lifetime for BF/CCS, the last year to invest in this option is 2023.

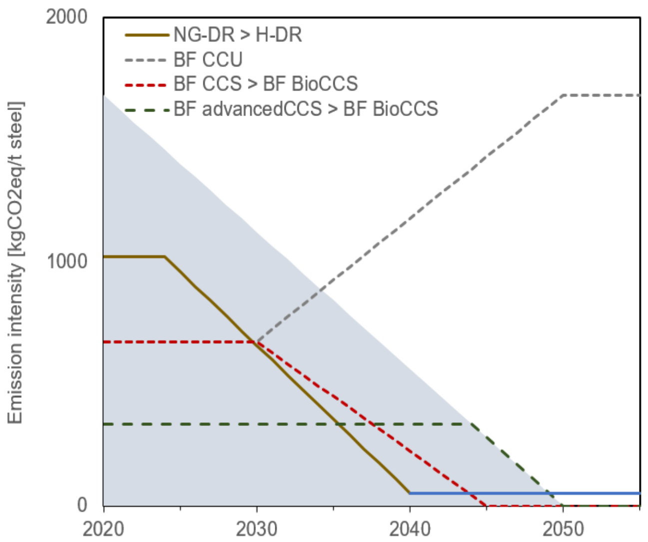

Figure 3: Bending emissions trajectories by injecting hydrogen (direct reduction) or biomass (blast furnace), and declining benefits from CCU over time.

The emission intensity of a new investment is not necessarily constant over its whole lifetime. Existing production routes can be improved gradually in order to stay in line with the declining emission trajectory, as shown in Figure 3. By introducing renewable hydrogen or bio-based fuels the emissions trajectories can be bent downwards. Blending in hydrogen can replace natural gas in the direct reduction process [34], a strategy which for example the SALCOS project is set out to pursue. Alternatively, a higher share of scrap can be used in EAFs, which would also reduce the emissions per tonne of steel (cf. [24]). Alternatively, up to 40% of biomass might be injected into the blast furnace, which could be phased in over time but would depend on the availability of large amounts of sustainably sourced bio-energy [28]. Natural gas could also be incrementally replaced by renewable hydrogen or bio-methane, respectively. For carbon capture and utilisation (CCU) on the blast furnace, our analysis shows a contrary long-term trend, which we schematically indicate in Figure 3. Initially, off-gases will replace virgin fossil feedstock in the chemicals sector and thus have a climate benefit. In the long-run, however, the chemicals sector too faces increasing pressure to meet climate targets and cannot rely on recycled fossil feedstock from steel production but will have to inherently cleaner feedstock such as biomass or hydrogen combined with biogenic CO_2.

Notably, we start our analysis from the emission levels of the EU ETS benchmarks for hot metal, which relate to primary steelmaking. This implies that we regard steel made from scrap in EAFs as green up to 2049. This is justified by the increasing importance of the secondary production route in Europe as pointed out in many scenarios. However, zero-emission recycling in line with the Paris agreement in 2050 would eventually also require technical solutions for emissions arising from both the EAF electrode consumption and the lime calcination with a fuel switch from natural gas to either bio-based fuels or electricity.

4.1 Climate-proof steel investments

Climate targets will be met most effectively if the path to zero emissions is considered already in the planning stage of decarbonisation projects. If this is not the case then investments risk leading to technological dead ends and carbon lock-in. Instead, project developers should engrain the zero-emission into project plans logic up-front. First, investments should make sure to be below the suggested trajectory for their whole lifetime. Second, it must be possible to increase ambition after the end of the life of a decarbonisation project. Public support for such projects could be made contingent on these requirements. This could be done by including a "stress test" into the grant application process to check if projects are aligned with climate targets. The basis for such a test is a transparent communication of the mitigation potential of different projects, which allows for comparisons between contenders.

The outlined logic in this paper is useful to decision makers in industry in the planning and evaluation of investment projects. Most importantly, the emission trajectory in Figure 2 and 3 suggests that when the next investment window arises, business-as-usual as in solely relining the blast furnace puts the investment at risk of being prematurely closed for not meeting climate targets. Instead, steelmakers should factor in the emissions limits sketched out here into their investment projects, which effectively limits their decision space. Decarbonising the sector within 30 years renders unambitious and inflexible projects irrelevant. CCS projects reducing emissions by 50% versus the ETS benchmark are not in line with climate targets without partially substituting coal with biomass. The same goes for natural gas DRI projects, which should contain provisions for blending in increasing shares of renewable hydrogen or scrap. A switch from primary to secondary steelmaking would reduce a plant's climate impact tremendously. While the potential for this switch is limited, the indicated increase in secondary steelmaking in the future suggests that this could be a viable path for some companies.

4.2 Demand-pull for green steel

The required rapid decarbonisation requires public support via both supply-push and demand-pull policy interventions. While significant support is provided in the EU via programmes such as H2020 and the upcoming Innovation Fund, the policy-driven creation of markets for green materials has not yet received significant attention. For renewables, the large cost reductions of wind and solar power were a consequence of strong policy intervention via technology-specific feed-in tariffs and renewable portfolio standards, which have been implemented on top of the carbon price. This apparent success of demand-pull policy in renewables along with ample evidence for the importance of a demand pull from innovation literature calls for the creation of green markets to accelerate the steel transition. However, steel is sold on a complex market with many qualities and variations so comparing with the success of demand pull policies for renewable electricity is difficult. The point of intervention in the steel product value chain needs to be carefully analysed to de-risk investment by creating a first mover steel market.

Taking inspiration from other sectors reveals that several policy instruments for demand pull policy already exist. An early voluntary policy such as voluntary labels or certificates can prepare the ground for more elaborate schemes later on, such as granting feed-in premiums or tendering on a project-basis. Green public procurement targets on the basis of the presented carbon footprint trajectory could increase the use of green steel in infrastructure and buildings. Standards could be employed to regulate the maximum allowed footprint of vehicles or buildings. In order to endorse green products, a distinction between green and non-green has to be made. The method presented in this article can be useful to reach this distinction. Existing footprint accounting schemes such as environmental product declarations (EPD) can be useful and build the basis of a demand pull policy for green steel. Although in theory it would be preferential to have a universal product footprint system, the short time left to act on climate change calls for a pragmatic, simple-to-use scheme.

5. Conclusions

Climate change requires a fast-paced transformation of the global steel industry. In Europe, a recently proposed target of net-zero emissions in 2050 leaves us with 30 years to fully decarbonise the sector. The role of governments and the European Union is not bound to handing out research funding, but must include providing directionality, nurturing early green markets and phasing-out fossil industries. In order to transform heavy industry, thinking needs to move away from comparing breakthrough technologies towards analysing pathways and stepwise changes that take into account industry characteristics.

In this paper we sketch a methodology that can be used to evaluate if a decarbonisation project is in line with the 2050 target. For the steel industry, the timing of new investments need to take into consideration the long investment cycles and the declining emission trajectory. The proposed method is simple and builds on a linear trajectory, pointing from current best performers towards zero emissions by 2050. A life cycle perspective is used for determining whether a steel process is below the threshold or not. We use a consequential LCA approach that builds on existing LCIs with minimal allocation and “gate-to-gate” system boundaries. This makes the calculation simple, understandable and puts the focus on the major emitters in the steel value chain.

Drawing on the available technical options for decarbonising steel, some robust observations can be made. The short time horizon and the long investment cycles of the industry restrict the available technological options. For example, if a project has a lifetime of 15 years, it has to bring about an emission reduction of at least 50% compared to current emission levels. At their respective next investments windows a first step away from conventional blast furnace steelmaking must be made. Due to the ever increasing role of scrap in Europe, not all of today’s primary production will be needed in 2050. Above all, public support should go to projects that are in line with climate targets.

The challenge for industry is large and risks are high, which suggests that large-scale public support will be necessary to decarbonise the sector. Policy makers can draw upon the presented method to determine which projects to support to avoid carbon lock-in and avoid putting climate targets at risk. Furthermore, demand pull policy for the steel sector can draw on the distinction between green and non-green steel made in this paper. The creation of markets where a green premium can be earned can create additional incentive for steel companies to invest in alternative steelmaking technologies.

Abbreviations

RD&D	research, development & demonstration
CBDR	common but differentiated responsibilities
UNFCCC	United Nations Framework Convention on Climate Change
ETS	emissions trading system
BF/BOF	blast furnace/ basic oxygen furnace
EAF	electric arc furnace
NG-DR	natural gas direct reduction
H-DR	hydrogen direct reduction
CCS	carbon capture and storage
CCU	carbon capture and utilisation
LCI	lyfe cycle inventory
LCA	life cycle assessment
IPCC	Intergovernmental Panel on Climate Change
PEF	product environmental footprint
EPD	environmental product declaration
CAPEX	capital expenditures
OPEX	operational expenditures
DRI	direct reduced iron
ETS	emissions trading system
EoL	end of life
EPD	environmental product declaration

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