Sustainable transition of the primary steel production: Carbon footprint studies of hot-rolled coil according to ISO 14067

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Abstract. A shift away from traditional carbon-based towards a hydrogen-based steel production has to be stepwise so that technological challenges can be solved simultaneously to various other challenges like the evolution of green markets, political framework as well as the creation of hydrogen supply.
First bridge technologies towards hydrogen-based steelmaking are crucial to generate a stable demand for hydrogen so that hydrogen supply can follow. Injection of hydrogen into existing blast furnaces is a prominent example to reduce greenhouse-gas emissions without the ambition to reach complete carbon neutrality.
A subsequent next step on the way towards climate neutrality are modern Direct reduction units. This technology is able to reduce Iron oxides by natural gas and hydrogen, respectively. Within the existing plants Direct reduction units can be incorporated in various ways over time, thus offering a gradual and in the end complete transition to hydrogen and electricity based production.
Since LCA studies provide crucial input for political and market-economy decision-making, the LCA community is of great importance for giving direction of transformation processes. Like other industries, the steel industry needs an allocation approach for greenhouse gas emission savings to evolve green markets, of which the methodology shall be discussed within the life cycle community.
The current study presents carbon footprint assessments (ISO 14067) of hot-rolled coil for different future production scenarios. The following production routes are investigated:

- Conventional blast furnace – basic oxygen furnace route
- Injection of H_2 into a blast furnace
- Input of H_2-based direct reduced iron (DRI) into a blast furnace
- H_2-based direct reduction combined with electrically melting from renewable energy.

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1 State of the art of primary steel production

The current primary steel production is based on coal, see **figure 1**. Iron ores are reduced and melted by coal and coke in a blast furnace to hot metal. The hot metal is refined in a basic oxygen furnace to crude steel and further processed to steel within the secondary metallurgy. The blast furnace process is the most energy-intensive and emission-intensive process of an integrated steel site. About 420 kg carbon in the form of coal and coke are inserted per ton of hot metal leading to emissions of about 1.5 kg CO_2/kg hot metal [1].

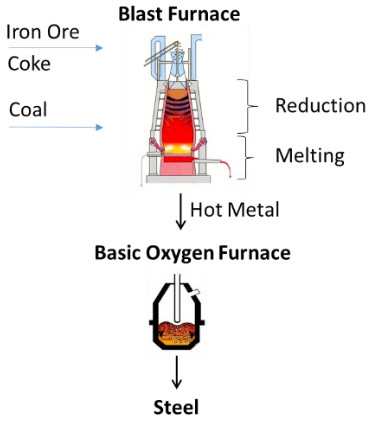

Fig. 1: Coal-based metallurgy of steel production via a blast furnace route.

In sum, the carbon footprint of primarily produced hot-rolled coil is 2.1 kg CO_2eq/kg [2]. This carbon footprint is the result of a cradle-to-gate approach. It includes upstream impacts for imported raw materials and energy feedstock, direct impacts of a typical integrated site, and credits for co-products. Co-products substitute emissions within other industries. E.g. the blast furnace slag serves as cement substitute and replaces primarily produced cement.
From a global perspective, about 7% of the worldwide GHG emissions are caused by the steel production [3]. Thus, the decarbonisation of the steel industry is a necessary goal in order to reach the goals of the Paris climate agreement. In the following it shall be discussed how a fossil-free steel production can be implemented.

2 The goal: A fossil-free steel production

In order to reach a fossil-free steel production, the reduction and melting of the iron ores must be shifted from coal towards a renewable energy source. Via Direct reduction (DR) plants iron ores can be reduced by hydrogen, see **figure 2**. On an interim basis, the reduction with natural gas is possible, as well [4]. If hydrogen is made from water electrolysis driven by electricity from renewable sources, the iron ore reduction can be completely fossil-free. In order to improve the carbon footprint of steel, the way of producing hydrogen is very important as highlighted in previous work [5]. If hydrogen is based on fossil fuels, the use of hydrogen can even be disadvantageous from a carbon footprint perspective in comparison to the status quo.

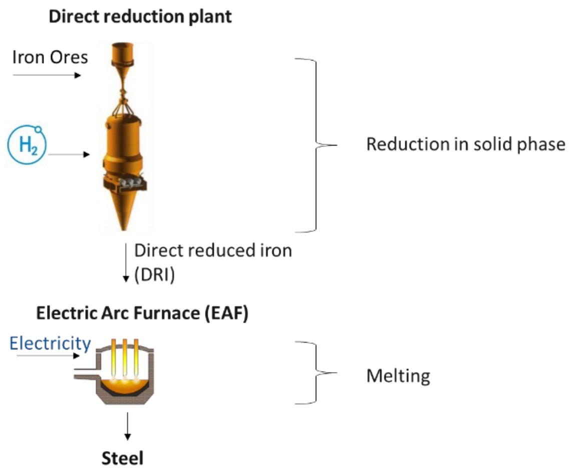

Fig. 2: Fossil-free steel production via direct reduction (DR) plants with subsequently electrically melting.

The product of the DR plant, the direct reduced iron (DRI) still contains the gangue. For removing the gangue, the DRI has to be melted. This can be done by electricity for example in an electric arc furnace (EAF). For low grades of steel, the melt can be directly cast into steel. For higher technical requirements, the steel has to be further processed within the secondary metallurgy. If electricity for melting is also from renewable sources, steel production can almost be based completely on renewable sources. Some metallurgical carbon might be required here as well to preserve advantages of a foaming slag within the EAF.
Both, enough renewable electricity and a hydrogen market and infrastructure are not available at the moment. That is why, a pathway to enable the transformation for decarbonisation is required.

3 Intermediate scenarios to enable a pathway towards a fossil-free steel production

In the year 2019, only 0.7 million tonnes of direct reduced iron (DRI) were produced in Europe whereas about 94 million tonnes of crude steel were produced via the BF-BOF route [6]. As a result, the possible demand for hydrogen for the direct reduction based route (H-DR) is presently limited in Europe. Using hydrogen on an interim basis in existing blast furnaces a demand can be generated quickly so that supply can follow, see first step in **figure 3**. The injection of hydrogen can lead to a carbon footprint reduction of about 9%, if hydrogen is from renewable sources [2].
As second step, direct reduction plants can be incorporated into the integrated steel sites. For an interim basis, the DRI can be inserted in the form of hot briquetted iron (HBI) into existing blast furnaces (step 2 in figure 3). The use of hydrogen-based HBI in a blast furnace can lead to a carbon footprint reduction of about 10% [2]. Even if the reduction potential is similar to step 1, this can be achieved with less hydrogen consumption [2]. It is also possible to combine the scenarios and to insert HBI in a blast furnace in combination with hydrogen injection. Thus, the carbon footprint reduction potential could be further increased.

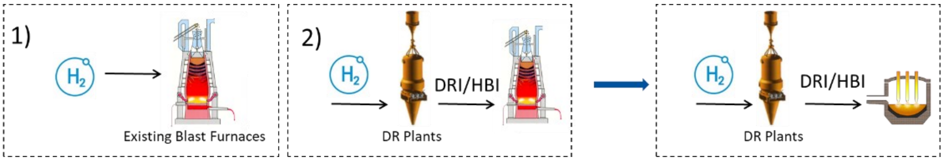

Fig. 3: *Possible pathway towards a fossil-free steel production.*

That followed, the blast furnaces can be replaced by EAFs, which enables the possibility of a fossil-free steel production.

The specific carbon footprint reductions of the intermediate scenarios are moderate. Yet, considering the fact that 94 million tonnes of steel were produced via the blast furnace route in Europe in year 2019 [6], the total CO_2 saving potentials are significant. In addition, most importantly, the scenarios are capable of enabling a transformation towards a climate neutral steel production, see figure 3.

From an economic point of view, the shift from a coal-based towards a hydrogen and electricity, respectively, based steel production is not attractive [7]. This barrier retards the transformation. A price premium for carbon-reduced steel products could overcome this barrier.

4 Allocation approach for carbon-reduced steel products

The necessity of an allocation approach for carbon-reduced steel products is explained with the example of the intermediate scenario injecting hydrogen into a blast furnace. Since an only hydrogen operation is not possible, hydrogen is injected in combination with coke and coal. A physical separation of a hydrogen produced hot metal and a coke and coal produced hot metal is for process related reasons not possible. However, for the total mass balance, it is not important either.

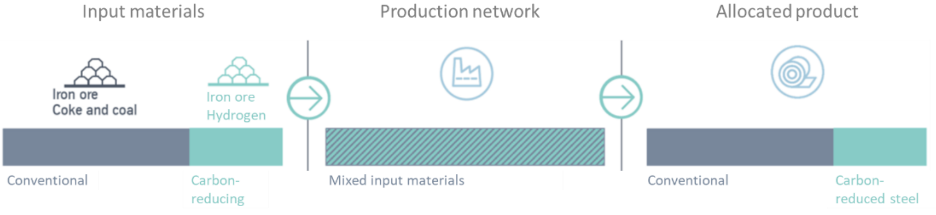

Fig. 4: *Allocating renewable inputs to a specific amount of a carbon-reduced product.*

An allocation of the hydrogen input on a specific amount of a hydrogen-based product results in an allocated carbon-reduced product. If these products are in demand, a market for a carbon-reduced steel can be established and more measures like injecting hydrogen into a blast furnace are supported.

This allocation approach is already implemented in the International standard ISO 22095:2020. A combination of this methodology with integrated LCA approaches would deliver new opportunities for the steel and also e.g. for the chemical industry amongst others to support carbon-reduced production lines. The LCA methodology ensures that the whole production line is considered and environmental impacts are not shifted from one system boundary to another one.

5 Conclusion

A fossil-free steel production is possible and can be based on hydrogen and electricity, respectively. Yet, a hydrogen market and infrastructure has not been established, yet and the supply of renewable electric energy is not sufficient at the moment. Intermediate scenarios can help to push on a transformation towards a climate-neutral steel production. Thereby economic barriers retard the transformation. A market for a carbon-reduced steel can overcome this restriction and serve as a catalyser. Within the steel production, a physical attribution of renewable inputs like hydrogen to a specific amount of product is not possible. However, this fact is not relevant for the total mass balance. Therefore allocation approaches are required to account for carbon-reduced steel. The combination with LCA approaches would ensure that environmental impacts are not shifted from one system boundary to another. Thus, a market for carbon-reduced steel can be established and climate-friendly measures are supported.

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