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The potential of hydrogen for decarbonising steel production

The iron and steel industry is a major contributor to the overall anthropogenic CO2 emissions worldwide, and therefore a significant driver of climate change.

This paper explores the possible options for decarbonising iron and steel production processes, focusing on the use of renewable hydrogen as an alternative to fossil coal. It explains the basic physical and chemical differences between the two alternative processes, their cost structures and potential for further cost reductions, as well as the larger implications and longer-term consequences of switching to hydrogen in this key industrial sector.

1. Key findings:

- The iron and steel industry is responsible for about 4 % of anthropogenic CO_2 emissions in Europe, and 9 % worldwide, due to the massive use of coal.
- Replacing coal by hydrogen generated with renewable energy would make it possible to largely decarbonise the industry. The way in which hydrogen can replace coal is well understood in principle, and the first pilot plants currently being set up will make it possible to further refine the processes.
- At current price levels, replacing coal with hydrogen would drive up the price of a ton of steel by about one third. This gap will likely narrow in the coming years, and could disappear by 2030, as carbon and carbon-emission pricing could drive up the cost associated with the use of coal on one side, while, on the other side, the decreasing costs of renewable electricity, efficiency gains resulting from larger-scale production of hydrogen, and optimisation of the hydrogen-based steel-making processes will drive down the costs of this alternative.
- Producing the necessary amounts of hydrogen for a full decarbonisation of the steel industry would require an increase in electricity production of the order of 20 %, thus requiring an even more ambitious expansion of renewable production, going beyond the replacement of current fossil electricity generation.
- Large facilities for producing hydrogen, which could be switched on or off on demand as supply of electricity fluctuates, could be key for helping to maintain power grid stability. By producing hydrogen whenever electricity supply exceeds demand, these facilities could, at the same time, help boost the profitability of renewable energy production from fluctuating sources such as wind and solar.
- Within the wider context of a transition towards a hydrogen economy, efforts undertaken in the steel sector can lead to synergies with decarbonisation efforts in other sectors such as transport (hydrogen-powered trains, trucks, cars, ships, airplanes), heating (e.g. replacing natural gas), and industrial processes such as ammonia production.
- Higher steel prices would dampen the demand for steel in many other sectors of the industry, which might partially switch over to alternative materials. Partially replacing steel and cement in the building industry with wood as a construction material, or partially

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replacing steel with aluminium or composite materials in the automobile industry, would lead to further carbon savings and drive innovation in these sectors.

- A number of pilot projects recently launched in Europe underline its ambition to become a technological leader in this area.
- The switchover from coal to green hydrogen on a worldwide scale would also have implications for the geospatial distribution of the global steel industry. Access to domestic coal or easy shipping facilities for imported coal were key aspects in the past for the implantation of new steel mills. With the transition to green hydrogen, the local availability of cheap renewable electricity, or the existence of transport facilities for hydrogen (pipelines, port facilities) will become important aspects of steel industry competitiveness. Investments into renewable energies and an accelerated push towards the hydrogen economy in Europe could therefore translate into longer-term competitive advantages for the European steel industry.

2. The overall challenge: iron and steel industry and climate change

Anthropogenic CO_2 emissions have driven CO_2 concentrations in the atmosphere to unprecedented levels, and this will potentially have catastrophic effects on the climate. Today's CO_2 concentration levels in the atmosphere are about 50 % higher than the 280 ppm of pre-industrial times. While the atmospheric concentration of CO_2 reached 350 ppm in the 1990s (a level that is still considered 'safe' in terms of its effect on climate), the current value of 420 ppm means that we have added as much CO_2 to the atmosphere in the last 30 years (i.e. this generation), as mankind had in its entire existence before 1990.

If we want to limit global warming to between 1.5 and 2 degrees, we will have to make ambitious steps towards net-zero carbon emissions within the next 10 to 20 years. Meeting this challenge will require re-inventing almost all sectors of our modern life.

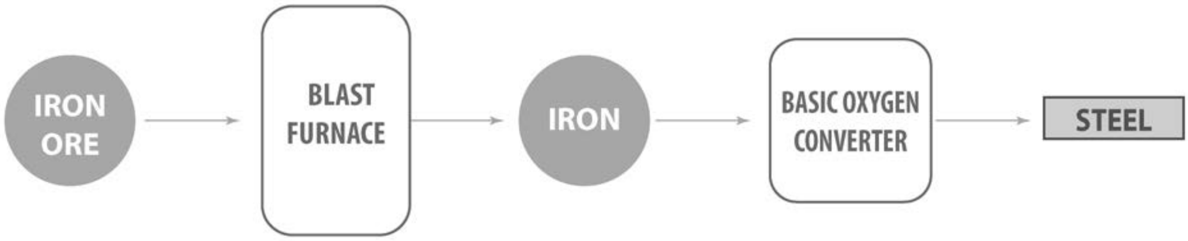
The worldwide use of fossil fuels for electricity generation, transport, heating and industry leads to the release of about 37 gigatonnes (Gt) of CO_2 annually. A significant part of these emissions, about 3.3 Gt CO_2, or 9 % of all CO_2 emissions, can be attributed to the iron and steel production industry. Decarbonisation of this industry will therefore be a key part of the overall effort towards reaching net-zero emissions in the near future.

The annual production of steel worldwide amounted to about 1.8 Gt in 2018. About half of that is produced in China, while the EU-28 accounted for 9 % of world steel production. Within the EU, about a quarter of the steel was produced in Germany, another quarter in Italy and France, a further quarter in Belgium, Poland, Spain and the UK, and the remaining quarter mainly distributed over nine countries (Austria, Czech Republic, Finland, Hungary, Luxembourg, the Netherlands, Romania, Slovakia and Sweden).

3. The role of carbon in the iron and steel industry

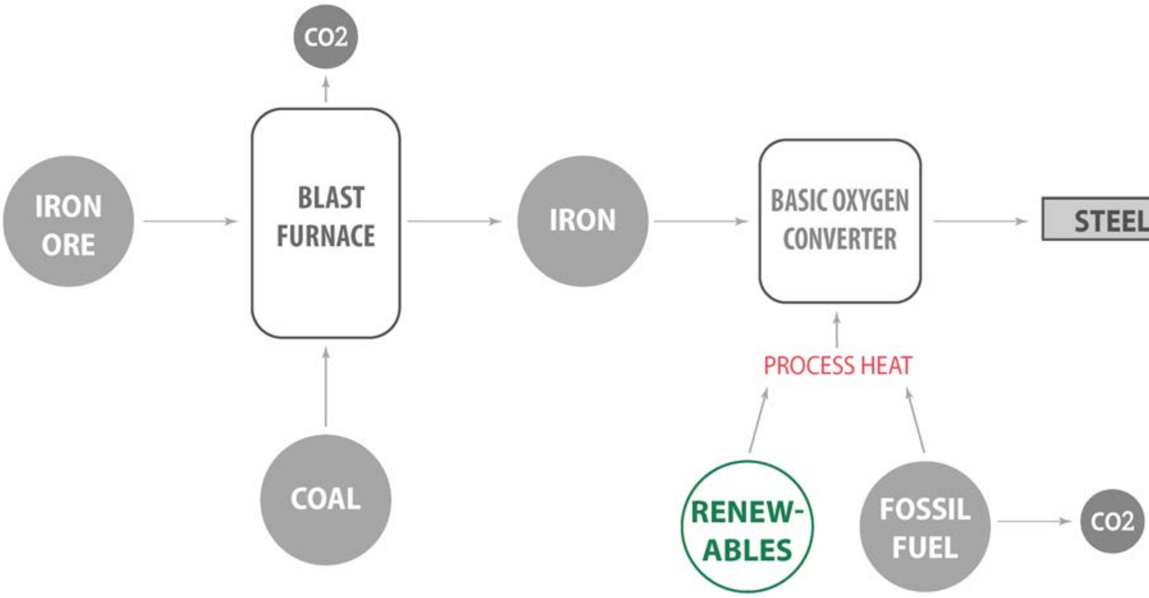
The production of iron and steel with current technologies requires large amounts of coal. Producing 1 ton of steel releases about 1.85 tons of CO_2 on average, as emissions into the atmosphere.

Steel production typically happens in two steps: First, iron ore is turned into iron, e.g. in blast furnaces, and then, in a second step, the iron is turned into steel, e.g. through the basic oxygen converter process:

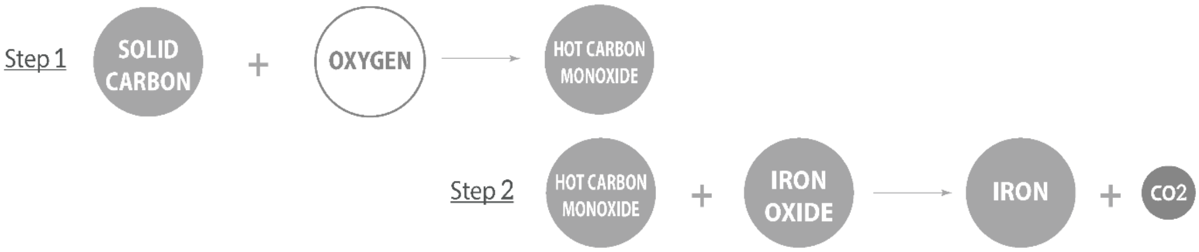


Both steps are very energy intensive, and are responsible for CO_2 emissions in quite different ways. They both require huge amounts of energy to process the materials at high temperature. If this energy is derived from fossil fuels, these furnaces are thus responsible for large CO_2 emissions.

Blast furnaces, additionally, use carbon as an ingredient in a chemical reaction that turns iron oxide and carbon into iron and carbon dioxide. In this chemical reaction, CO_2 is thus a by-product of iron production:



Inside the blast furnace, carbon particles initially react with a limited amount of oxygen to produce carbon-monoxide. This carbon monoxide gas will then chemically react with the iron oxide particles, producing iron and CO_2.



Source: EPRS

Decarbonisation of the iron-making process therefore requires replacing carbon/carbon monoxide in this reaction with another gas that would lead to lower or zero carbon emissions, such as methane or hydrogen. The use of methane (CH_4), a chemical compound containing both carbon and hydrogen, would allow a reduction in CO_2 emissions, partially replacing them with water vapour (H_2O). The use of hydrogen (H_2) would make it possible to completely decarbonise the process, since it would only produce water vapour as chemical by-product.

Both alternatives are technically well understood. Methane is the main component of natural gas and is thus available in great quantities. It is already used to a limited degree in steel production, but a more widespread use would allow for a partial decarbonisation of the processes. Hydrogen, on the other hand, would make it possible to completely decarbonise these processes. Hydrogen, however, is so far only being produced in limited quantities, and its use for steel production still needs to be further fine-tuned for industrial-scale production.

Decarbonisation of steel production processes therefore poses two major challenges:

- Optimising and scaling-up the hydrogen-based route of iron and steel production through pilot plants, and
- Scaling up the production of hydrogen, producing greater quantities at lower cost with higher efficiency.

In recent months, Europe has seen bold initiatives getting underway to set up first pilot plants in Austria, Germany and Sweden. These pilots put the hydrogen-based route into practice, and will make it possible to gain initial experience and contribute to further optimising the processes.

Sooner or later, switching over to hydrogen in steel production will require setting up new hydrogen production facilities at unprecedented scale. The success of the efforts towards hydrogen-based steel production will therefore crucially depend on making large amounts of hydrogen available as widely as possible at the lowest possible cost.

4. The challenge of green hydrogen production

Hydrogen gas is currently used in the chemical industry in a rather limited way, e.g. for the production of ammonia or in petroleum refining. Most of this hydrogen is currently produced by steam reforming, a process that uses natural gas and emits CO_2 as a by-product. The cost of producing hydrogen from natural gas ('grey hydrogen') depends mainly on the price of gas, which varies from one region of the world to another. On the basis of gas prices in Europe, typical are of the order of €1.5/kilogram (kg) (rising to €2.0/kg when including the cost of carbon emission avoidance – then becoming 'blue hydrogen').

Hydrogen can also be produced through electrolysis. This process uses electricity to split water into hydrogen and oxygen. If the electricity is produced from carbon-free sources, this allows production of carbon-free hydrogen gas, also called 'green hydrogen'. This process transforms about 70-80 % of the electrical energy into chemical energy of the hydrogen gas. It takes about 50 to 55 kilowatt-hours (kWh) to produce 1 kg of hydrogen. The production cost of green hydrogen has fallen by 60 % over the last decade, and is now typically in the range of €3.6-€5.3/kg. This price is expected to fall further, as investment costs for production facilities go down with mass production, and electricity prices from renewable energy, such as wind and solar, continue to drop. Under conservative assumptions, the price of green hydrogen could fall to €1.8/kg by 2030.

With 50-55 kWh required to produce 1 kg of hydrogen, and 50 kg of hydrogen required to produce 1 ton of steel, in the case of Germany (the EU's largest steel producer), it would require about 100 terawatt-hours (TWh) of renewable energy to fully decarbonise the annual production of 42 megatonnes (Mt) of steel. This 100 TWh of additional electricity demand would correspond to a 20 % increase in the total demand for electricity in Germany.

In terms of production costs, one ton of steel currently costs in the order of €400, which includes about €50 required for the coal used. Replacing this coal with hydrogen would require around €180 worth of hydrogen at current best prices (€3.6/kg), which would increase the total price of a ton of steel by about one third. If the large-scale production of hydrogen drives down the price of hydrogen to €1.80/kg by 2030, the price difference between conventional steel and steel produced by green hydrogen would drop to the order of 10 %.

5. Effect of rising steel prices

The combined effect of rising carbon prices, and decreasing prices for renewable energy and green hydrogen could make hydrogen-based steel production competitive within the next decade. Overall, this would make future steel production more green, but also more expensive.

Higher prices for steel would likely lead to a substitution of steel by other materials in some sectors, which could have additional impact on the overall decarbonisation of our economies.

In the automobile sector, the higher price of steel could lead to a partial substitution of car body parts by lighter materials such as aluminium or composite materials. This could lead to further energy savings for the operation of these vehicles.

In the construction area, the higher prices for steel-reinforced construction could help promote a renewed interest in wood-based construction techniques. If this wood comes from sustainable forestry, this would help store the CO_2 that the trees removed from the atmosphere over longer periods of time.

The success of the overall efforts to reach net-zero carbon could in this way crucially hinge on ensuring that efforts in one area would lead to further gains in interlinked sectors.

6. Options for closing the price gap between traditional and green steel

There are three main drivers that will help tip the balance from coal to hydrogen in the steel industry:

- Increases in the price of carbon emissions;
- Large scale roll-out of hydrogen production driving down the cost of electrolyser facilities;
- Further cost reductions of the price of renewable electricity.

It is estimated that, at a carbon emission price of over €60 per ton of CO_2, hydrogen would become the most economical option. The price of emission certificates within the EU Emissions Trading System depends on the overall number of certificates put up for auction. The price per ton recently jumped from €5 to €20 when the European Commission reduced the offer in late 2018, but it is difficult to predict whether it will further increase to reach €60 per ton anytime soon.

Electrolytic, green hydrogen is currently typically produced in small scale facilities of around 2 megawatt-hours (MW). As the industry moves to larger facilities (up to 90 MW), producing larger quantities, the contribution of investment costs (for electrolysis facilities) in the price of hydrogen could be reduced by as much as 60-80 %. The cost of electricity produced by wind energy could be 50 % lower in 2030, compared to 2017. The combined effect of lower investment costs and lower prices of electricity could drive down the prices of hydrogen by 60 % by 2030.

7. Coordination of efforts

Overall, a timely switchover from carbon to hydrogen in the steel-making industry will require coordinated political action in a wide range of fields, driving up the price of carbon at the same time as driving down the price of hydrogen. In turn, driving down the price of hydrogen will require development of a broad, coordinated set of measures, promoting both the demand for hydrogen and the ramping up of supply capacities as part of a coherent push towards the hydrogen economy. Since hydrogen is currently produced and consumed only in very limited quantities, any overly ambitious strategy, promoting only the supply or only the demand side for hydrogen, would have a limited efficiency.

Fortunately, however, progress in all related areas can, to some degree, be made without having to wait for parallel progress in the other areas at all times. Pilot plants can be set up already without having to wait for sufficient amounts of hydrogen to become available. They can initially be run using natural gas or a mixture of natural gas and hydrogen, while waiting for local hydrogen production capacities to be ramped up. In this way, early investments for pilot plants could have a 'pull' effect on subsequent investments in hydrogen production facilities. Conversely, ramping up the production of hydrogen by electrolysis will not have to wait for the completion of the first steel pilot plants if other uses of hydrogen can be found in the interim, either in the local chemical industry, or in new markets such as the transport and cement industries. Hydrogen can also be mixed into local gas distribution networks. Suggestions have been made to require gas distributors to add a certain percentage of hydrogen into the natural gas distribution networks, in a similar way as gasoline for cars needs to contain a certain amount of bio-fuels.

Progress in all these areas will at least initially require active support from the political side, be it through research and development support for setting up pilot facilities, incentives for ramping up hydrogen production, or incentives for expanding renewable energy production. Fortunately, progress in one of the three areas will also generally facilitate progress in the other two in a synergistic way. Subsidies for setting up pilot plants will create a local demand for hydrogen, and therefore make investments into hydrogen production facilities more attractive. Likewise, public support for local hydrogen production facilities will encourage the setting up of pilot facilities. This will boost the local profitability of investments in renewable energies at the same time; since these electricity producers could then sell their electricity more easily.

The prices of renewable energy, such as wind and solar, are expected to further continue their downward trends well into the next two decades. All measures that promote further capacity build-up in these two areas will help drive down costs of renewable electricity faster, and will thus also help to accelerate the transition towards hydrogen. The large amount of additional electricity required to produce hydrogen for the steel industry (an extra 20 % in the case of Germany), would thus require an even more ambitious expansion of renewable production, going beyond the replacement of current fossil electricity generation. At the same time, the emergence of a new hydrogen sector that could flexibly use large amounts of electricity would help boost the profitability of renewable energy production from fluctuating sources, such as wind and solar, since it would pay for surplus electricity that would otherwise be left unsold.

As the share of renewable electricity production from fluctuating sources such as wind and solar increases, it becomes increasingly difficult to balance supply and demand at all times. Currently, this balancing is achieved to a large degree by dispatchable fossil fuel-powered plants that allow adaptation of energy supply to demand.

8. Geo-economic aspects

Switching steel industry dependence from coal to hydrogen is not just a technological and financial challenge, it might also impact the way the steel industry is organised at regional, European and global level. Historically, the ease of access to coal was an important aspect in determining the location of steel industry plants. Steel mills were thus often set up in close proximity to domestic coal fields, or – for steel mills relying on imported coal – next to port facilities.

Australia is currently exporting large quantities of iron ore to China, where it is processed using local coal resources – and generating considerable air pollution. Decarbonisation of the Chinese steel industry would ultimately require large investments in renewable energies. However, since Australia has significant low-cost renewable electricity potential, both wind and solar, it is conceivable that, at the same time as switching from coal to hydrogen, the entire first processing step – the reduction of iron ore to iron – could be shifted from China to Australia, to take advantage of cheap local renewable energy and furthermore saving transport and labour costs.

In Europe, coastal areas often have more favourable conditions for generating wind energy, while southern areas have more favourable conditions for producing electricity with photovoltaics. In Sweden and Norway, cheap hydroelectric power could facilitate hydrogen production. Another option is production hydrogen from solar energy in southern Europe or Northern Africa and shipping it to industrial clients in central and Western Europe. This is being aimed at by recent agreements signed by Germany and Morocco as well as The Netherlands and Portugal. This illustrates that at least part of the additional electricity generation capacity required for decarbonising the European steel industry could ultimately be set up in partnership with countries where conditions for renewable energy production are even more favourable.

9. Transport and distribution of hydrogen

As a new form of fuel, hydrogen will also bring about changes to the way the energy is transported between producers and consumers. Hydrogen can be produced in large quantities in direct proximity to large hydrogen consumers such as steel mills – provided that there is a sufficiently strong grid connection to bring in the required electricity. Hydrogen can alternatively also be produced at sites where there is easy access to large amounts of relatively cheap electricity, such as major nodes of the national grid. It is also interesting to produce it at sites where the availability of electricity is undergoing particularly drastic changes, such as locations where large offshore wind parks connect to the national electricity grid, where hydrogen production can play an important role in balancing electricity supply and demand.

Hydrogen can be transported through pipelines from major production sites to larger customers. Pipelines can provide an interesting alternative to bringing energy from producer to consumer, where grid capacity would otherwise be insufficient. Pipelines for transporting hydrogen have been in use for almost 80 years. There are currently about 1 500 km of hydrogen pipelines in operation in Europe, however, most hydrogen is produced at the site of demand at present.

Hydrogen can also be produced in a more distributed manner in regional, smaller production sites. For example, hydrogen as a fuel for vehicles could be produced directly at refuelling points, minimising the cost of transporting it to the customer.

Hydrogen can also be injected into the existing natural gas distribution networks at moderate concentrations of up to 12 %. This option is especially interesting in regions where the production of hydrogen exceeds demand.

Hydrogen, like many other fuels and chemical gases, needs to be handled with due care. It is already used today for many applications in the chemical industry. As the use of hydrogen expands into new sectors of industry such as the steel industry, safety protocols might need to be further updated to take due consideration of any concerns.

10. Alternative approaches

Besides using hydrogen for decarbonising the steel production processes, alternative approaches are being proposed and explored:

- One route is to combine traditional steel mills emitting CO_2 with carbon capture technology and subsequently utilising or storing the captured carbon. Estimates, however, indicate that carbon capture and storage (CCS) would only be viable at a cost of €100 per ton of CO_2 emitted. This would then increase the price of a ton of steel by up to €185, roughly the same order of magnitude as the cost of switching over to hydrogen at current prices. However, CCS technology is still in an early stage of development, and is raising concern as to the possible environmental effects of injecting large amounts of CO_2 into underground caverns. Furthermore, as the price of hydrogen continues to drop, the CCS route for decarbonising steel production will look increasingly unattractive.
- Another proposed process – still in its infancy – is direct electrolysis of molten iron ore – but this has so far only been tried out in laboratory conditions. Besides a number of technical difficulties that still have to be overcome, estimates indicate that it might require up to 40 times more electricity per ton of steel than using electricity to first produce hydrogen, and

then inject the hydrogen into a blast furnace. This technology would thus still need major breakthroughs to put it within the range of market readiness.

11. Conclusion and timeline

Replacing coal with hydrogen seems a promising option for decarbonising the steel production process. While it would initially increase the price of steel, the cost of hydrogen is expected to fall significantly as soon as hydrogen is mass-produced. To provide a useful contribution towards reaching net-zero emissions by 2050, the lessons that will be learned from the first pilot projects currently being set up will be essential. These pilot projects could allow optimisation of the efficiency and safety of this technology by the middle of the decade, and then be followed up by demonstration projects at commercial scale between 2025 and 2035. At that point, the price of green hydrogen will likely have come down so much that hydrogen-based steel production may also be economically advantageous.

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