FROM A PINK UNICORN TO A SLOTH AND BEYOND

Reflections on decarbonising the steel industry published in Steel Times International and Green Steel World 2021-2024.

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When it comes to decarbonising steel production

there is no Silver Bullet!

"A silver bullet" is a widely used metaphor for something that efficiently solves all aspects of a problem. It emanates from folklore saying that silver bullets are the only means to kill werewolves who seem to have plagued people in ancient times. For some reason WWF does not seem to think that werewolves constitute an endangered species why I have to pose with this blank cartridge for once without a cuddly WWF-toy. Photo: Veronica Gyllenram.

When I had graduated as bergsingenjör (MSc) in 1983 one of my first assignments, working for the legendary professor John-Olof Edström at the department of Production Technology, Mining and Steel Industry, KTH, Stockholm, was to do techno-economic calculations comparing the new process alternatives that had been suggested to solve the cost crisis in the steel industry. Agglomeration of iron ore to sinter or pellets and agglomeration of coal to coke were the main steps that the new processes tried to omit saving both capital and operational costs. The results were conclusive for a 29 year old engineer when I proudly presented them at the conference "New Routes to Iron and Steel under Indian Conditions" hosted by Tata Steel in Jamshedphur in 1988. In my mind at that time, without doubt the blast furnace would be replaced by the Kawasaki process, the Sumitomo process, the KR process, HiSmelt, Elred, Inred, Plasmasmelt, Coin or any of the other proposed processes.

How wrong I was – India, please forgive me!

What happened was that...

... the blast furnace process developed in many ways by for example economies of scale resulting in bigger and bigger furnaces and more plants built with the same design; raw material development resulting in lower slag volumes, injection technology decreasing the coke rate etc. The large number of blast furnaces on the market secured well-functioning supply chains of technology, raw materials, skilled labour and research staff.

At the same time the new processes struggled with problems like unexpectedly high refractory wear, high maintenance costs and underfinanced development budgets and in the end the few that survived became niche processes.

What happens now?

With today's focus on reducing greenhouse gas emissions, we have a number of tasks to attend to. To begin with we must take better care of the materials that we have already produced. A limited amount of the steel we need in the future can be produced from scrap with low emissions. But our methods to collect and sort scrap are still primitive to say the least and we lose quality by increasing levels of tramp elements and we lose the value of alloys when they become tramp elements or end up in the slag. To continue, we have to reduce methane leakage wherever we can. Whether it is a coal mine, a natural gas well or different types of transport systems, leakage can be avoided and often in a profitable way according to research. Recent publications from Princeton also talk about hydrogen leakage as a problem since it tends to slow down decomposition of methane in the atmosphere. Who saw that coming?

But I guess the main problem today is to find a way to remove the oxygen from iron ore without adding to the greenhouse gases in the atmosphere and just like in the seventies we have an abundance of ideas and processes put forward. If we consider replacing 1.3 billion tons of iron production in blast furnaces emitting some 2.4 billion ton of CO2, we must look at high volume processes and today we have two: the blast furnace process and the DR-shaft furnace. Yes, we will see fluidised beds and perhaps electrolysis cells, but in my mind, they will not play a major role before 2050 and probably not even after that. Even more fantastic ideas exist that I do not dare to mention, getting large funds, but these processes will not be silver bullets and will probably turn out to be blanks. I can be wrong like in 1988 but I do not think so.

To eliminate fossil CO2 emissions to the atmosphere in the near future I think we have three alternatives, 1: Carbon Capture and Storage (CCS), 2: biogenic reductants and 3: hydrogen. They are all limited by resources like CCS-storage capacity and cost, biomass availability and cost and available low emission electricity and cost. In order to be feasible, applying CCS demands a close to 100% CO2-gas. That can be obtained in a new DR plant today with limited modifications but will require redesign of the blast furnace. Biogenic reductants and hydrogen still have to prove their feasibility in large scale production. The complexity of these problems and that there is no simple solution was the reason why I wrote my first debate article ***"Between a pony and a pink unicorn".*** People with deep knowledge about the decarbonisation topic encouraged me to continue.

Finally, decarbonisation of ironmaking is dependent on the quality of iron ore. Not all ores can be beneficiated to a very low content of unwanted oxides, so called gangue. In the traditional blast furnace followed by an oxygen converter the gangue is removed in the blast furnace with low losses of iron and the steelmaking in the converter can be done efficiently with low slag volumes. That makes this process less sensitive to the ore quality. In the direct reduction process the gangue stays in the direct reduced iron and cause losses and costs in the subsequent electric arc furnace. There are ideas to introduce an extra melting step after the DR furnace but that will take time which I discuss in my second debate article ***"Betting on a winning horse"*** a year later in September 2022.

If we are serious about greenhouse gas mitigation and resource conservation, we must have a scientific approach to the work with effective and efficient measures, realistic expectations on technology development and search for what actually makes a difference and not only sounds and feels good. I covered that in the articles ***"Not all cows should be holy"*** and ***"Avoiding a bears service to the climate"*** late 2022.

One of the lessons learned from earlier crises is that it may not be enough to just replace old plants and technology with new. Sometimes you have to rethink the entire supply chain and find optimal combinations of processes and locations which I discuss in an article in January 2023, ***"Local production of strategic goods"***.

The market is like a game where you have to use your skills to compete. Resilience may be a key factor so you can manage unwanted and unexpected surprises. In ***"The grand quest for green steel"*** from February 2023 I use a Monopoly analogy to illustrate how we have to deal with technology, market, finance and legislative "cards". By the way, a number of companies asked Kobolde to develop the game and hopefully we will have a computer version ready late 2024 or early 2025.

In April 2023 I took on the dystopic vision that our methods might not give the desired results and that we might miss the 2050 goal altogether, in the Dickens pastiche ***"A steelmaking carol"***. Some vigilance against greenwash might be necessary to avoid the message from ***"the ghost of steelmaking yet to come"*** to materialise.

In the end I believe that we will come to our senses, create competitive routes and attracting private capital. It will not happen without complications as is discussed in ***"It's all about survival"*** in January 2024 and ***"Moving towards climate neutrality with the speed of a three-toed sloth"*** from June 2024.

In the Carbon Capture summit in Amsterdam in June 2024 I summarised the routes that I believe will be dominant in the near future and how to develop them as shown in Table 1.

Table 1 Dominant process lines 2030-2050.

	Ore + DRI in BF + BOF	**Scrap + DRI in EAF**	**DRI in EAF**
Ores	Medium-High gangue	Low-Medium gangue	Low gangue
Reductants	1. Coke 2. Natural gas for DRI	1. Natural gas 2. Biosyngas 3. H2	Natural gas
DRI production location	Natural gas exporters	1. Natural gas exporters 2. Available biomass 3. Available green electricity	Natural gas countries
Steel production	BF-BOF Close to market	EAF Close to market	DR+EAF close to market
DR process CCS	If demanded by BF plants	1. If demanded by EAF plants 2. Yes: CCU 3. No not necessary	If demanded by steel customers
Action needed	Decrease leakage coal + NG Develop supply chains Develop CCS capacity for DR Develop CCS capacity and technology for BF	Decrease leakage NG, H2 Develop supply chains Develop CCUS capacity	Decrease leakage of NG Develop CCS capacity

As can be seen I believe that massive production of low emission DRI with natural gas and CCS will be a key for lowering the emissions in the blast furnace. The gas exporting countries with both gas and available carbon storage facilities will play a decisive role. Blast furnaces will be here for a long time. In the long run we might see oxygen blast furnaces and smelters but that will take some time.

In the end of this booklet, I have added two articles under the headline "Walk the talk". In ***"FerroSilva - combining iron production with a carbon sink"*** and ***"FerroSilva - Creating a new industrial eco-system"*** from June 2023. In these I together with my two co-entrepreneurs describe our project FerroSilva where we will produce DRI using a syngas from gasified forest residue, capture the biogenic CO2 for offtake and secure the supply of clean raw material for Ovako. We start with 50 kton/y with a plan to scale up to 500 kton when the design is more mature.

It has been great fun writing these articles and responding to comments from the readers of Steel Times International and Green Steel World. I am grateful to Matthew Moggridge and Thijs Elshof for publishing my thoughts. I am also grateful to my friend Pelle Berglund at Znapshot who always find time for me and my cuddly toys, weekdays and weekends like.

With my reflections I never intended to criticise anybody or anything. I just wanted to open for new perspectives and rake the arena for real discussions on how to solve the problems avoiding wishful thinking and holy cows.

Having said that. It bothers me that we do not recognise that we actually have all the tools we need to decarbonise the steel industry by 2050. It is possible provided we do not insist on going for a perfect non existing solution and that we are willing to work in steps and perhaps also redesign our supply chains. When we have unlimited amounts of low emission electricity at a reasonable price, we may set very high ambitious goals and perhaps we also may become sustainability puritans, but until then we have to deal with numbers of less than perfect solutions that each anyway move us closer and closer to the goal.

Thanks for reading this far in the booklet. Hope you will enjoy the reflestions in the following pages. There will be some repetition in the papers out of necessity. The topic is important so perhaps you can forgive me.

Finally, your comments are most welcome and please direct them to
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Stockholm in June 2024

Rutger Gyllenram

BETWEEN A PONY AND A PINK UNICORN

Steel Times International, October 2021.

What the industry is promising the politicians right now is something between a pink pony and a unicorn said my friend who was trying to figure out how the electricity grid in Sweden should cope with all the new projects using vast amounts of electricity.

Between a pony and a pink unicorn?

Direct Reduced Iron – or DRI – is viewed by many as a cast iron solution to the decarbonisation of the steel making process. Along with the use of hydrogen as a reductant, it's as if the whole thing is sown up, especially now that the Hybrit initiative in Sweden has delivered a consignment of fossil-free steel to car maker Volvo. But nothing is that straightforward and plenty of challenges still lie ahead. By **Rutger Gyllenram***

"WHAT the industry is promising right now is something between a pink pony and a unicorn!" The statement belongs to a young but already senior consultant at one of the major consultancy firms designing the future Swedish power grid. The discussion was about the sustainability and realism in large-scale production of DRI using hydrogen as a reductant; hydrogen produced from water by electrolysis demanding vast amounts of electric power, preferably 'green' electricity. The venue was Stockholm in April 2021.

Some years earlier, companies had started to promise fossil-free steelmaking by producing DRI with hydrogen as reductant and water as the off gas. The pressure on the steel industry to transform in order to make it possible to live up to the Paris agreement had been massive and since scrap resources are limited, a solution had to include iron ore reduction. Hence the idea was quite logical, the reduction of iron ore using hydrogen. While never

Rutger Gyllenram. Photo by Pelle Berglund, Znapshot.

used successfully on an industrial scale, it has been known since the 19th century. After the first steel company declared its ambitions, others followed and soon the technology suppliers also joined in. Today, one auto manufacturer after another declare that they want to use what they call 'green steel'. The ambition of all the actors to live up to the Paris agreement is commendable, but not without complications for them and their investors, quite often the taxpayers, as we will come back to.

Choice of reductant and assessing the technical risk

Low fossil or fossil-free DRI can be produced with three alternative reduction gases which all have advantages and drawbacks: natural gas with subsequent Carbon Capture and Storage, CCS, hydrogen gas and finally syngas of biogenic origin. The principles are shown in **Fig 1**. If CCS follows the syngas alternative, this process can also be considered climate negative.

Reduction with reformed natural gas, MIDREX and Energiron, accounts for the majority of today's gas-based DRI production and is by far the process type

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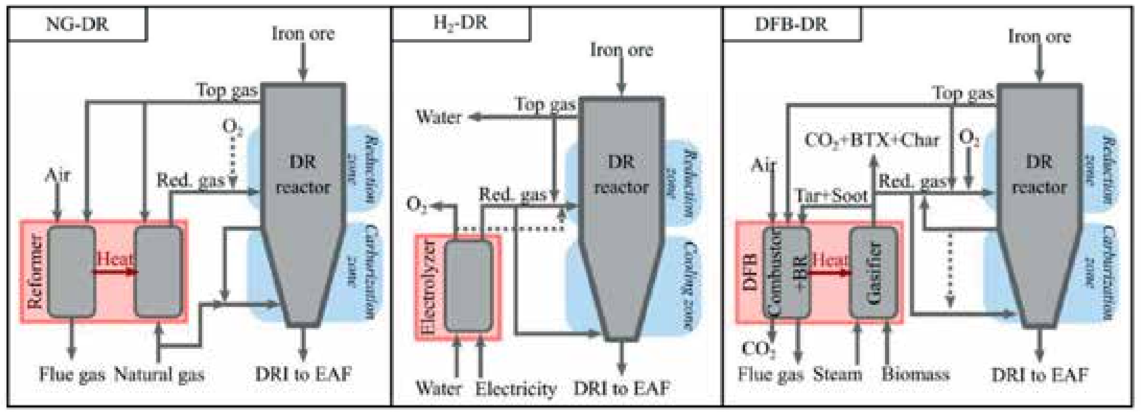

Fig 1. Pissot S et al, Production of Negative-Emissions Steel Using a Reducing Gas Derived from DFB Gasification, Energies 2021, https://doi.org/10.3390/en14164835

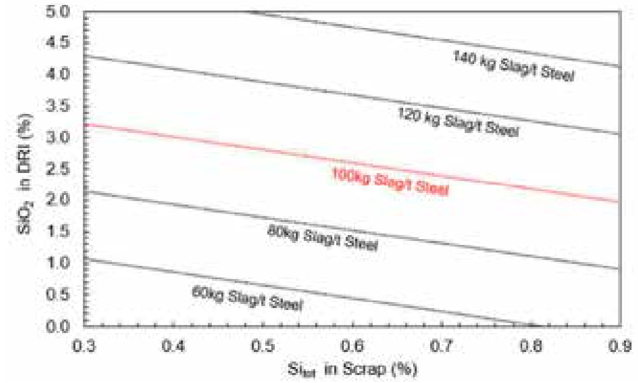

Fig 2. Gyllenram R et al, Driving investments in ore beneficiation and scrap upgrading to meet an increased demand from the direct reduction-EAF route, Mineral Economics 2021, https://doi.org/10.1007/s13563-021-00267-2

> "Natural gas based direct reduction with CCS as implemented by Emirates Steel is today the best example of low fossil iron production."

closest to becoming fossil free.

Since the reformed gas contains one third CO and two thirds H_2, compared with the 100% CO from blast furnace coke, the existing process provides the lowest CO_2 emissions of proven ironmaking technologies. Some of the natural gas is used for reduction and after separation of CO_2 in the top gas, a fraction that is CCS-ready is obtained. Other natural gas is burned with air to supply the necessary heat for reforming. The resulting flue gas contains nitrogen and is, therefore, not suitable for CCS unless nitrogen purification takes place. A future solution may be to burn this natural gas with oxygen instead and thus avoid mixing with nitrogen to make this CO_2 CCS-ready. The challenge is apart from making all the CO_2 CCS ready, to provide enough CCS capacity to handle the large volumes that may be produced in the future. The concept has been tried on a small scale by Emirates Steel and now a much larger implementation must be evaluated.

Reduction with hydrogen mainly entails challenges in three areas: electricity supply, heat balance and product properties. Hydrogen production requires large amounts of fossil-free electricity at a level that may affect the entire electricity balance of a steel-producing country. Furthermore, hydrogen reduction, unlike reduction with reformed natural gas or syngas, requires additional heat supply in order not to stop. This makes the process more complex than the others, which can cause problems when scaling up. Finally, reduction with hydrogen gives a carbon-free product that must either be carburised in a separate step or melted together with large amounts of carbon in the arc furnace in order not to suffer large iron losses.

Reduction with syngas of biogenic origin can be a solution where there are large amounts of biomass available as by-products from industrial forestry. Gasification is a known technology and

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Four necessary investment areas in the DRI supply chain to make a change this decade

1. Investments in ore beneficiation and pelletisation to replace sinter feed by pellets. Pellets lower blast furnace coke consumption today and pave the way for a transition to low fossil DRI production.
2. Investments in DRI-production for the blast furnace route. DRI used in the blast furnace lowers coke consumption and paves the way for replacing blast furnaces with intermediate melting furnaces when that technology is ready.
3. Investment in DRI-production for the metallics market offers a solution to scrap shortage.
4. Investment in development of DR-technology so all of the CO_2 can be captured and sequestrated.

> "For the steel industry to turn from blast furnaces to DRI from hydrogen, about 100 new mega size nuclear plants need to be built." [The New Yorker magazine].

otherwise the process is similar to reduction with reformed natural gas. The challenge here, however, is to scale up the gasification process to the volumes required. Today, forest by-products have a relatively low value and some are left to decompose in the forest. A future challenge may be competition from the production of biofuels.

Coping with both DR-grade and BF-grade pellets

A low amount of slag is absolutely crucial for the economy of steel production in an electric arc furnace. This can only be achieved with low levels of acid oxides in the iron raw material, primarily gangue in DRI and steriles in scrap. **Fig 2** shows the slag volume for 100 tons of steel with 50 tons of scrap and the rest DRI for different gangue contents in DRI and a different level of silica from dirt in scrap. A reduction of silica in DRI of two percentage points may result in savings of 12 USD/ton steel. What drives the production cost is increased energy consumption, increased consumption of lime and dolomite, increased losses of iron to the slag and reduced productivity. Forecasted growth of DRI production has led the mining companies to review their ore resources and processes to meet a possible increase in demand for DR pellets.

It is, however, a known fact that not all ores can be beneficiated to DR-grade, and technology suppliers are now working on an intermediate stage where a submerged arc furnace or resistance furnace is used to melt DRI from BF pellets under blast furnace-like conditions. In this new process, a blast furnace type slag will be separated with low iron losses and low consumption of slag formers as a result and the melted iron can be further processed in an electric arc furnace or a basic oxygen converter. The challenge here is to avoid high temperatures that make silicon in the slag evaporate and dissolve in the iron. If that happens nothing is gained from this process route compared to the traditional melting of DRI in an electric arc furnace.

Investments at low risk – now!

The development of an electric smelting process for DRI with a high silicon content will probably take most of a decade to be considered proven technology. In the meantime, the focus must necessarily be on introducing improvements in the blast furnace process in order to reduce coke consumption. There are three important areas where low risk investments are needed: further enrichment of ore to reduce the levels of gangue, expansion of pellet capacity to increase the pellet ratio and thereby reduce the amount of slag in the blast furnace, and finally production of DRI from BF-pellets to charge the blast furnace with material pre-reduced with natural gas. Although not solving the entire CO_2 problem, these investments, while being profitable, prepare the raw material supply chain for new technology when it is ready.

The more you work with DRI as a means for decarbonisation, the more obvious it becomes that the supply chain will be divided into an ore stage, a reduction stage and a steelmaking stage that do not need to be co-located. This opens up for DRI producers who are not integrated with a steel plant. They may be owned by a steel company, a mining company or completely independent. The critical conditions that will determine the location of fossil-free DRI producers for the world market are, in addition to port capacity, probably the availability of natural gas, electricity and biomass, and finally if CO_2 is produced, a geology suitable for storage through CCS.

Political risk

Unlike the terms 'fossil-free' and 'fossil-

negative' which can be explained scientifically, the term 'green steel' is based entirely on values. It is impossible to predict how limited resources like scrap, electricity, biomass and geological formations for CCS will be viewed in the public eye 10 or 20 years from now. An assumed price premium based on 'greenness' introduces a significant risk in an investment calculus and in a longer perspective steel products will probably have to compete entirely on product quality and production cost, including those related to CO_2 emissions.

A major question is whether an attributional or consequential perspective will be applied on DR production in the future. The concepts are fetched from life cycle assessment, LCA, methodology and means taking the actual emissions from producing DRI into account or selecting the emissions that are emitted as a consequence of the DRI production. An example is whether a DR plant with an adjacent wind park can use wind-power emissions for the hydrogen production as is the case with an attributional perspective or if emissions from coal combustion should be used since the wind power produced could have replaced fossil energy.

The environmental product declarations, EPDs, developed for products today use attributional methodology and as a consequence are used by companies planning for fossil-free steel. Consequential analysis, on the other hand, is often used at the societal level and that may be a reason for meeting much more arguments with this perspective once an enlightened debate starts on how resources are used. In late September two articles indicate that the discussion has started. An article in The New Yorker makes the comment that for the steel industry to turn from blast furnaces to DRI from hydrogen, about 100 new mega size nuclear plants need to be built. In the same week three economists claimed in the Swedish paper Ekonomisk Debatt (Economy Debate) that investing in hydrogen-based production in northern Sweden was 'environmental nationalism'. The researchers applied a consequential perspective and suggested that fossil-free electricity from Sweden could be exported to substitute electricity made from coal elsewhere in Europe. Regardless of the quality of facts and arguments in the two articles, they highlight the fact that what is 'green' is dependent on the perspective you apply. The problem is that perspective

> "Hydrogen production requires large amounts of fossil-free electricity at a level that may affect the entire electricity balance of a steel-producing country."

preferences may change over time. Investors should consider what a gradual transition from an attributional to a consequential perspective on green production over the next 10 years may do to the investments.

Meeting the Paris agreement

There is no single solution that will turn global steel production fossil-free by 2050. Natural gas-based direct reduction with CCS as implemented by Emirates Steel is today the best example of low fossil iron production. As mentioned earlier, in this kind of process about 50% of the CO_2 in the off gas is CCS-ready which might, with some effort, increase to 100%, but again that is allowing for a speculation. Some of the research projects going on with hydrogen today are promising, but they are just that: research or pilot projects. How they perform in competition with

FACT BOX

Three necessary missions to promote investments

1. Agreeing on a minimum price on CO_2 emissions on major markets.
2. Stabilising the demand and prices for pellets and DRI within the supply chain.
3. Stabilising production, transport and trade conditions in regions with large resources of natural gas and geology suitable for CCS.

DRI from natural gas and a hypothetical 100% CCS 30 years from now is yet to be seen. Reduction with syngas from biomass combined with CCS is finally a very attractive option since it may offer a carbon sink i.e. negative CO_2 emissions.

The elephant in the room, the large installed base of fairly new blast furnace plants, must initially be handled with traditional efficiency improvements aiming at lowering the coke and coal consumption. In this work a transition to pellets instead of sinter to lower the slag volume, which saves coke as a fuel for melting, and charging DRI to save using coke as a reductant, will have an immediate effect on global CO_2 emissions. At the same time, building up this infrastructure paves the way for phasing out the blast furnaces when they have become obsolete and new technology is available.

What is needed is agreements within the supply chain to start this transition involving steel companies, DRI producers and ore product suppliers to create the necessary market stability to allow for the investments to take place. Furthermore, huge diplomatic efforts have to be made to stabilise the political situation in countries with vast amounts of natural gas. The MENA and other natural gas-rich regions may become hot spots for fossil-free DRI production, but that demands making the regions less of hot spots in other aspects. Countries like Iran and, to some extent, Venezuela may prove to be important factors in decarbonising the steel industry, but then mutual trust must be restored. Difficult, yes, but the incentives have never been higher.

To conclude: Yes, DRI is an important tool to decarbonise the steel industry, avoid pink unicorns in the shape of wishful thinking and the elephant in the room may lead the way forward, even if it is pink. ■

BETTING ON A WINNING HORSE

Steel Times International September 2022

There are a lot of promising projects going on but they will take time. Which one is the winning horse? Instead of waiting there is much to do and since we do not know what will work and where problems will arise, we should not discard any alternatives just because we do not fancy them.

Betting on a winning horse

The winds of change are blowing in the steel industry and we are now offered long lists of new processes that are being developed to save the planet. It's like betting on horses. Who will win and can the steel industry change? By **Rutger Gyllenram***

"OUR industry has changed very quickly in the past." The words are from Professor Chris Pistorius from Carnegie Mellon University, the venue was AISTech 2022 in Pittsburgh, USA and the context was the Brimacombe memorial lecture that, at the end, addressed decarbonisation in the steel industry. I guess we all agree when Pistorius states that it is encouraging to see how the steel industry embraces new technology, noting examples of how the Bessemer process took over from the puddling process in little more than 10 years around 1865, the BOF process taking over from open hearth and continuous casting replacing most of the ingot casting in just a number of decades after the second world war.

It is, however, fair to note that it took several years after Sir Henry Bessemer presented his invention before the first Bessemer charge succeeded. Furthermore, both using oxygen instead of air in the converter process, as in the BOF, and designs for continuous casting, were suggested by Bessemer but could not be realized in his time for technical reasons. The three technologies all increased the productivity and decreased the costs so the driving force for change was immense. The impact on society of the transition was also remarkable with smaller plants and whole communities closing and bigger plants growing.

Rutger Gyllenram. Photo by Pelle Berglund, Znapshot.

WHO WILL MAKE THE PELLETS AND DRI IN THE FUTURE?

Finally, we may ask if the changing iron and steelmaking map opens for more forward and backward integration in the industry. One of the main challenges for the mining industry in supplying the steel industry with pellets is to balance supply with demand with various quality premiums fluctuating. The dilemma of having one industry taking the cost and the other the benefit of ore beneficiation and pelletising is illustrated in Fig 3 taking iron yield as an example. DRI as a product has more potential customers and might offer a more stable demand and stable prices. So will mining companies start to make DRI, DRI producers beneficiate and pelletise ore or will things stay the same?

Fossil free steel or fossil CO_2-emission free steel

And now it is time to change again in a multitude of ways. A roadmap for the global steel industry to reduce emissions of carbon dioxide (CO_2) and other greenhouse gases includes multiple steps along the steel life cycle. The development of Life Cycle Assessment, LCA, has made emission data transparent upstream and downstream from a producer together with the producers' own emissions making it possible for anyone in the supply chain to make informed decisions.

In **Fig 1** production steps are shown from the mine to the end of life of a steel product followed by recycling. Necessary actions to achieve a fossil free steel production like fossil free electricity production, producing fossil free reductants, electrification, improving resource efficiency, all central to decarbonisation, are pointed out. The main questions that we need to ask ourselves are found at the bottom: do we need more stakeholder incentives, research, public information or regulations to make this happen?

For a mining company the emissions from mining, beneficiation, agglomeration and transportation are important areas for abatement of CO_2. Much can be done with electrification but using hydrogen, biofuels or other measures are necessary for some operations. The public discussion today is to a large extent focused on fossil-free reductants which will dominate discussions

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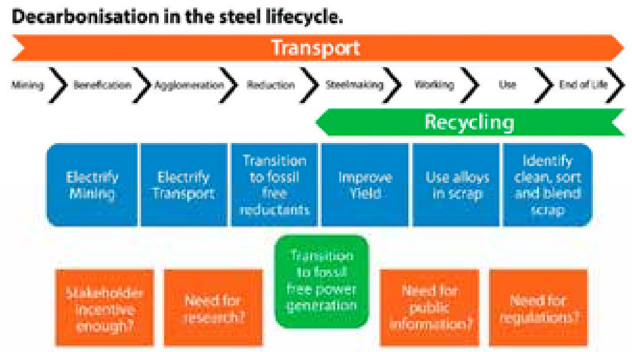


Fig 1. Decarbonisation in the steel lifecycle, from Worldsteel RAMCO meeting, Nov 18 2021. © Rutger Gyllenram Kobolde & Partners AB 2021

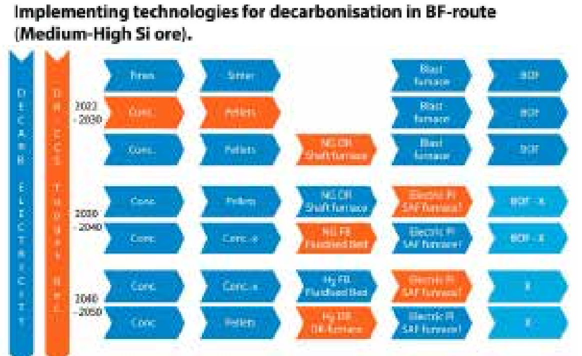


Fig 2. Implementing technologies for decarbonisation in the BF-route (Medium-High Si ore). From Worldsteel RAMCO meeting Nov 18 2021. © Rutger Gyllenram Kobolde & Partners AB 2021.

and development in the coming decades. The yield issue is to a large extent related to the amount of gangue from ore that is processed in the furnaces which is discussed later.

Finally, the steel with the lowest CO_2 emission comes from recycling but although the amount of available scrap is expected to increase in the decades to come, it will always be a limiting factor, determined by the amount of steel that goes into the use phase, the life time of the products and the collection rate. Therefore, closing blast furnaces to migrate to scrap-based production may do well for a single company, but can only work as a global solution in a rate to match an increased availability of scrap. Although scrap comes as a raw material almost free of burdens, a lot can be done to lower the total emissions for steel by utilising alloys in scrap and avoiding tramp elements like copper.

The transition of the entire steel industry to production without using fossil coal or natural gas will most certainly take the best part of this century and be limited by a number of critical factors. It will have to take place in several steps with intermediary solutions. One is Carbon Capture Utilisation and Storage (CCUS) where CO_2 is either used for products or liquified and stored, sequestrated in geological formations. Sequestrating fossil CO_2 will abate the fossil emissions. Sequestrating biogenic CO_2 will create carbon sinks. Both are probably necessary to reach the climate goals set for 2050. Whether we shall call steel produced from fossil reductants followed by CCUS 'fossil free' steel or 'fossil CO_2-emission free steel' or something else we may leave to academia?

Today, when we look for solutions to decrease greenhouse gas emissions from steelmaking by either replacing or modifying the blast furnace process, three questions spring to mind:

- Will we see the same rapid conversion to new processes and technical solutions to meet the climate challenge as in the introductory examples? Indeed, a lot is going on but when will they reach the market?
- Where will new ironmaking capacity be built? Will the availability of energy, the scale-up status of new ironmaking processes and availability of CCUS infrastructure draw a new iron and steelmaking map?
- What kind of immediate actions and long-term roadmaps can investors demand from steelmakers?

Processes and technical solutions

The last time we had this enormous interest in new iron and steelmaking technology was after the energy crisis of the 1970s. A big number of processes challenged the blast furnace by not demanding agglomeration of ore and/or coal. In economic evaluations the new process suggestions all outperformed the blast furnace process but at the end only a few survived to serve in niche applications. In hindsight one might conclude that the time and effort needed to develop a completely new process was underestimated and the projects ran out of funding or underperformed mainly due to low productivity, high refractory wear and difficulties in process control. On the other hand, the suppliers of blast furnace technology showed a great ability to improve, modify and scale up the process. Without questioning the good will of the steelmakers, one may conclude that the only thing that has changed is that this time, the cost of emitting greenhouse gases has been added to the equation. Is it a game changer for alternative ironmaking processes or will the blast furnace adapt? The chief objective of the EU-financed ULCOS project is to decarbonize ironmaking and it came along with other things, such as blast furnace top gas recycling which was implemented at the LKAB experimental blast furnace in Luleå, Sweden. After almost a decade of silence, it seems that the ULCOS ideas are again on the table.

Probably we can divide technology candidates to abate emissions into three categories:

1. Established, ready-to-implement, technologies profitable from the start.
2. Technology that needs to be scaled up and given the right economic conditions.
3. Development projects where function and profitability still need to be proven.

The A group includes lowering slag volumes in furnaces, replacing air with oxygen in combustion and replacing coal and coke with other reductants in the blast furnace and applying CCUS wherever possible. In group 2. we have, for example, top gas recycling, hydrogen and biogenic syngas reduction to avoid carbon, electric pig iron furnaces to melt high gangue DRI and fluidised bed reduction technology to avoid agglomeration. All very promising, but yet to be proved. In group 3. we have, for example, electrolysis projects that probably have a long way to go to the market so we will leave them out of the discussion for now.

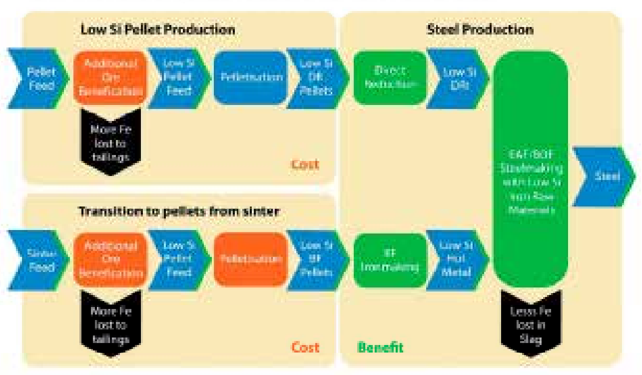


Fig 3. Cost benefit of decarbonisation thru ore beneficiation. After "How to Satisfy Steelmakers – What's in it for the Miners?" Fastmarkets Global Iron Ore 2021, © Rutger Gyllenram Kobolde & Partners AB 2021. Available at https://vimeo.com/526605624/6b72216f40.

A new iron and steelmaking map

A century ago, steelmaking plants were generally co-located with energy resources, close to a stream and a forest. Ores were by far the resources easiest to transport, easier than, for example, charcoal that is more voluminous. Coking coal and steam coal were denser and were more suitable for locations with blast furnaces producing close to 4Mt/yr of pig iron. Gas-based DR plants emerged more than 70 years ago and have now reached module sizes of more than 2Mt/yr of DRI often found in coastal locations where sea bound DR-pellets and local natural gas are the main resources.

For the new process installations that we discuss today we might, at least initially, be restricted by the availability of key resources. Regarding reductants, hydrogen production needs electricity, limited by available production and grid capacity, biogenic syngas needs a supply of biomass which is voluminous and finally, CCUS infrastructure may be limiting for processes emitting fossil or biogenic CO_2. These locations may, however, be excellent incubators and profit centres for new processes that are limited in module size depending on how far they have come in scaling up.

The debate has already started and regions with constant wind, sun and CCUS capacity are mapped. We will probably not see liquid natural gas or hydrogen shipped for iron ore reduction purposes due to liquefaction and transportation costs other than to bridge over-supply or technology gaps. The commodities transported long distances will be iron ore, DRI and steel. It has been suggested that countries like Chile and Australia will become hubs for hydrogen-reduced DRI while the MENA region may supply DRI from natural gas with CCUS.

What will happen to existing integrated plants with blast furnaces and basic oxygen furnaces? Eventually they will surely be equipped with electric arc furnaces when the availability of scrap and low gangue DRI allows for that. Until then they might continue production reinventing the blast furnace process with top gas recycling, CCUS and other measures or outsource the reduction and replace the blast furnaces with electric pig iron furnaces.

Immediate actions and long-term roadmaps

Ore products are either intended for the blast furnace – basic oxygen furnace route, BF-BOF; or direct reduction via the electric arc furnace route, DR-EAF. Although both routes benefit from a low gangue content in the ore, the blast furnace is less sensitive since it operates with a basicity (CaO/SiO_2) around 1 whereas the EAF operates with a basicity of around 4.

For mining companies with ores that cannot be beneficiated to DR-quality it is essential that either the blast furnace is adapted to new demands on CO_2 mitigation or that projects on electric pig iron furnaces with the same slag chemistry as the blast furnace succeed.

Bearing in mind that the possibility of beneficiating a certain ore depends on mineralogy and that getting permissions to build tailing dams has become increasingly difficult for some mining companies, it must be noted that decreasing the amount of gangue melted in any process should be given the highest priority in order to decrease energy use and improve yield.

Most fossil-free projects, planned for implementation this decade, are aimed at DRI production based on DR-pellets followed by an electric arc furnace. When talking about replacing the impacts from blast furnaces on a larger scale we must, therefore, look at what to do with the majority of ores which are of medium-to-high gangue content.

A possible timeline for material and process development to decarbonise steelmaking using medium-to-high silica iron ore is shown in **Fig 2.** The first row shows the situation today where sinter with a high silica content is reduced in the BF and decarburised in the BOF. In the second row the ore is beneficiated to a lower silica content and agglomerated to pellets. This will normally decrease the slag volume in the BF and lower the coke consumption and CO_2 emissions. In the third row, pellets are reduced to DRI to reduce coke consumption and CO_2 emissions in the BF. Even if natural gas is used it will decrease the emissions. If CCUS in the DRI production step is applied, the reduction will be even higher. This might be how far we get this decade, and what happens the next we can only guess. Maybe we can replace blast furnaces with electric pig iron furnaces and DR-shafts with fluidised beds, and use hydrogen made without emitting CO_2 but we do not know.

Aut Caesar, aut Nihil!

Caesar or nothing, the famous proverb of Cesare Borgia often interpreted as all or nothing, comes to mind in today´s discussions when incremental improvements of existing technology are viewed as 'less green' and, therefore, less attractive than new processes solving all our problems in an unknown future. Since we do not know when the shift will come, we have to muddle through with what we know and can do today to make whatever small steps that are possible. At the same time, we have to work hard to make the game changers ready to enter the market. It might be sooner or later. When they are ready the shift might be fast.

Which horse to bet on? Probably a herd of horses that moves fast and saves as much CO_2 as possible already today with existing technology and has prospects of achieving ambitious goals in the future. ■

Fig 1.

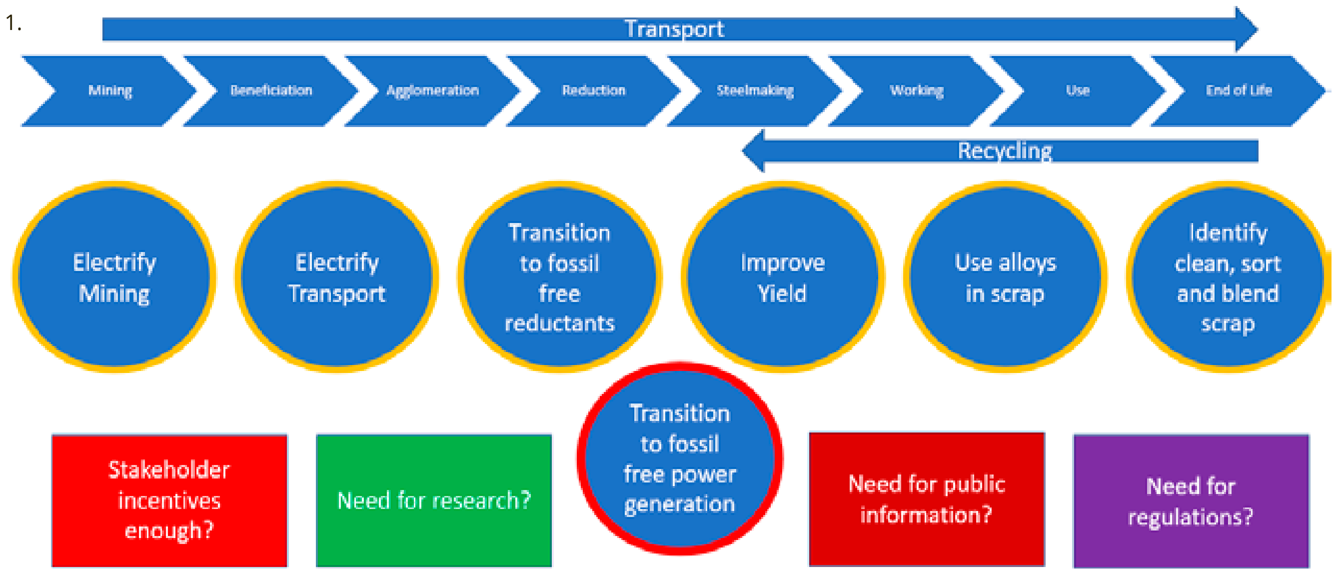


Fig 2.

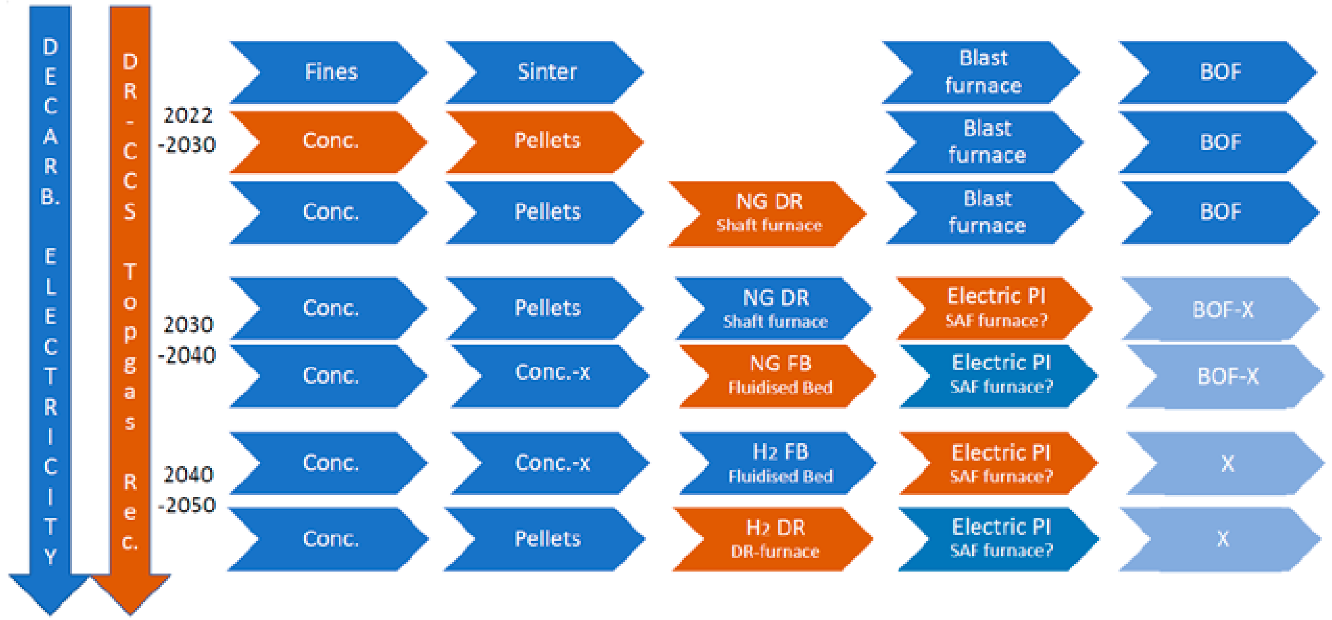
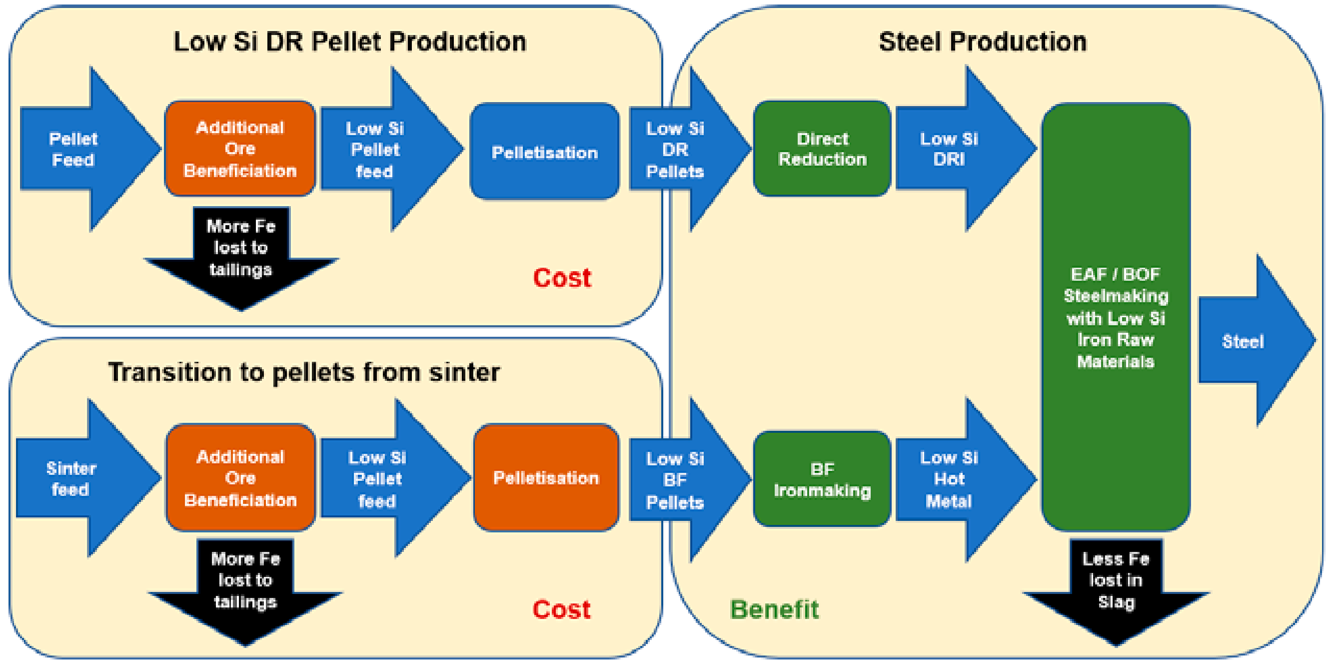


Fig 3.



NOT ALL COWS SHOULD BE HOLY

Green Steel World November 2022

When working for decarbonisation of the steel industry we must avoid wishful thinking, think out of the box and accept that we have to work with some processes that we do not fancy until there really are alternatives.

Rutger Gyllenram and cow-worker. Photo Pelle Berglund, Znapshot.

Not all cows should be holy

By Rutger Gyllenram

Meeting a holy cow

In 1988 when I was 29, I went on my first trip to India, a country that I since then have loved but never understood. My mission was to talk at the conference "New routes to Iron and Steel under Indian conditions" in Jamshedpur, with a presentation focussing on new smelting reduction processes to replace the blast furnace that by many then was considered obsolete. Going there I passed Varanasi where I changed train. The platform was busy with lots of noise and people hasting to their trains and luggage carts manoeuvring in the crowd. Suddenly everything slowed down and it became silent. A cow drifted majestically down the platform making everybody to stop and give way. I assumed it was a holy cow and have not thought further about it until recently when it seems I again meet holy cows, now in conference rooms in the form of opinions disguised as axioms not to be questioned.

Where will we be in 2050?

We all agree that we have to go net zero on climate gas emissions but not all actions that look promising will lead to this. We have now more than 50 climate initiatives setting up goals and devising roadmaps affecting the steel industry, all developed, I believe, in good faith and to a large extent built on research and communicated results from development projects. The same goes for roadmaps presented by some of the major steel companies. That is all well and good but what is missing are critical reviews of these suggested roadmaps that all industrial projects should undergo before they are financed or even proposed. Sustainability contains three pillars: economy, social aspects and the environment, and looking at a global scenario for 2050 with the roadmaps presented, the steel industry might, at that time, not have made any net achievement in any of these three areas.

The obstacles that we have to overcome

Let us focus on three major conditions ruling the ironmaking in the steelmaking industry:

1. **Reducing iron ore to iron is simple.** It can be done by gas reduction with carbon monoxide, pure hydrogen or a mix of the two; smelting reduction with carbon in an iron melt reducing molten iron oxide; and finally with electrolysis of molten oxide. There are a number of processes at various technology readiness levels, TRLs, and suppliers willing to deliver.
2. **Reducing iron ore without emitting carbon dioxide to the atmosphere is not complicated.** It can be done by applying carbon capture and storage of the carbon dioxide or avoid using carbon. Again, the TRL is there, although rarely proven in industrial scale.
3. **Choosing technology when designing a new net zero plant or decarbonising an existing plant is achievable if the production cost can be estimated with some accuracy.** Assuming that the TRL of the process alternatives are known and iron ore and coal are imported by ocean freight, the choice depends mainly on the intended production volume and availability of resources such as natural gas; biomass; sun and wind for new electricity capacity and sufficient transmission networks; and finally, CCS-capacity. The trick is to match local conditions with technology and timing in order to produce steel at a cost in the same range as the best net zero producers.

What makes everything difficult are the two main obstacles today; namely the political and technical uncertainties, where the political uncertainties are the most damaging and may prolong the process of decarbonising the steel industry by decades. Meeting demands to decrease greenhouse gas emissions is difficult enough but has become even more difficult since the demands have been coupled to a number of ideas of what you should and should not do in the process. They seem to be very difficult to leave out in discussions and they are here called "Holy cows".

Five holy cows that may make us miss the decarbonisation targets for 2050

Holy cow no 1: "Hydrogen reduction and electrolysis will soon become main reduction processes for net zero steel"

This seem to be the general opinion today and we will no doubt see some good examples of hydrogen ironmaking where the conditions are right. Preconditions are high volumes of "green" electricity at low price. Estimations of the amount of electricity needed to transform only a part of the global iron production suggests it is a niche process and current prices for electricity makes hydrogen reduction in continental Europe a daring project.

Ironmaking by electrolysis is interesting but its competitiveness is primarily not depending on what takes place in the reaction zone but how to create sufficient economies of scale and reasonable maintenance costs. In my mind it has no place in any roadmap at the moment since these questions are not answered.

Holy cow no 2: "We should not invest in blast furnace plants after 2030"

This is probably the most counterproductive cow. To begin with it sends a message to technology suppliers and plants not to invest in development of blast furnace technology. Several development routes for the blast furnace can drastically reduce the greenhouse gas emissions without CCS and even make them close to zero by using CCS.

One advantage of the blast furnace, apart from its energy efficiency, is that it operates with a low slag basicity compared to the electric arc furnace. This makes the blast furnace better suited, compared to the direct reduction route, for iron ores with high gangue contents. These ores are common in for example Australia. An alternative that has been proposed is to have an intermediate melting step between the DR-furnace and the steelmaking process by using electric pig iron furnaces working with the same low basicity. The technology was developed more than a century ago and is today used for ferroalloy production. All plants for iron except one operating under very special conditions have been closed due to high production costs compared to the blast furnace. Further developed, the electric pig iron furnace might become a reasonably efficient iron making process depending on local conditions. It may however prove less competitive and have higher emissions than an improved blast furnace equipped with CCS.

Continuing to downplay the blast furnace will finally leave the blast furnace technology as it is and keeping the emissions from a large part of the global iron production as they are today, possibly for the rest of the century.

Holy cow no 3: "It is possible to keep the present ironmaking structure by applying new technology"

It is remarkable to see that the roadmaps presented by companies often are very conservative regarding the production sites. Blast furnaces are replaced with hydrogen DR-reduction and electric pig iron furnaces providing pig iron to the oxygen converters of the integrated plant. As argued above different regions have different preconditions to operate processes and the ideal place for a DR plant regardless of reduction gas might not be the same place as one once hosting a blast furnace. In earlier technology shifts we have had huge restructuring of the steel industry. Why should this be different?

Holy cow no 4: "CCS can only be an intermediary solution and should be avoided"

At the moment CCS is the only solution we have, to deal with carbon dioxide emissions from iron ore reduction on an industrial scale. Downplaying it sends the message that any solution involving CCS is intermediary and not economically sustainable. A reasonable reaction to that message is to adopt a "wait and see" strategy which would be counterproductive if the ambition is to decrease emissions as soon as possible.

Holy cow no 5: "Customers are willing to pay more for net zero steel"

Probably correct for some customers, maybe a majority, but this is a case of wishful thinking. Assuming higher prices may have catastrophic consequences for early movers in net zero steelmaking if the assumption is proven wrong. In developing countries, the ability to pay more is most certainly lower and the assumption wrong. Hesitant steel producers might lay out smoke trails just showing a will to decarbonise or greenwash existing production.

And in that way, we can go on fighting holy cows. The basic idea behind the cow is seldom totally wrong but the reasoning contains a great part of wishful thinking and lack of critical analysis based on science and established facts. The reasons why the holy cows may make us miss the decarbonisation targets for 2050 and not deliver on sustainability goals are threefold:

1. Hesitance to invest in "accepted" uncertain solutions and public resistance against proven solutions make companies wait to start the transformation.
2. Erroneous roadmaps make governments and companies invest huge amounts in technology and plants that later are proven not competitive and obsolete thereby wasting tax payers' and shareholders' money.
3. Downplaying an improved blast furnace and CCS for both blast furnaces and DR-processes as important factors in decarbonising the steel industry hinder technological development necessary to reach climate goals.

Conclusion

What puzzles me as a process metallurgist is why we do not develop the methods further that are known to work, and start reducing emissions now?

The lowest hanging fruit is to produce DRI/HBI with natural gas and CCS. The cost for separation and liquefaction of all carbon dioxide from a MIDREX and Energiron is well under the cost for carbon allowances and should be achievable in a short time perspective. Since countries with natural gas generally have a geology suitable for CCS the cost for storage could be kept low or even nil as is the case with Emirates Steel. High gangue HBI produced in this way can be charged in blast furnaces to reduce their emissions and low gangue HBI can be used to make up for the scrap shortage caused by the transition from integrated plants to EAF plants.

The ULCOS-project financed to a large part by the European tax-payers came up with the oxygen blast furnace with top gas recycling. It was tested at the LKAB experimental blast furnace in Luleå giving positive results. After that the development stopped and the present status is unclear, but certain is the fact that we have lost more than a decade of development. A further development of this technology is probably the biggest contribution to decarbonising the global steel industry, that European companies can make.

Steel is an important material due to its versatility and low cost compared to other materials, and is essential for building construction and infrastructure. In developing countries, the blast furnace process will be the normal route for many years. However, it may be possible to improve both new and existing installations once the technology is available.

How to finally get rid of holy cows

If we really want to achieve the targets set for 2050, politicians and their entourage must reconsider their instrumental view and stop telling companies how to achieve the goals and restrain themselves to decide targets. The important thing is the size of the reduction of greenhouse gas emissions performed - not how to reduce.

Rutger Gyllenram is a Swedish process metallurgist, founder and CEO of Kobolde & Partners AB, Stockholm, working with raw material and process assessments as well as standardization in the field of sustainability. He is engaged in the FerroSilva project aiming at producing DRI from syngas of biogenic origin combined with bio-CCS and is also active as independent debater in the field of sustainability.

AVOIDING A BEAR'S SERVICE TO THE CLIMATE

Steel Times International December 2022

We must work with concepts that drive resource conservation and emission abatement on a global scale and avoid suboptimisation and greenwash. This article touches on my favourite subject "recovering alloys in scrap".

Avoiding a bear's service to the climate

Why demands on 'recycled content' should not be used for steel, and what to do instead. By **Rutger Gyllenram***

IN the Rumi fables written in the 13th century there is a story about a man that helps a bear, and in return, the animal decides to protect its helper from evil. When the newly adopted protégé was fast asleep an insect settled on the forehead and immediately the bear killed it with a strong blow of its paw. Unfortunately, the man also died and the concept 'a bear's service', meaning an act with good intentions but fatal outcome, was born. We still use that expression in our daily life in many languages around the world; acting with good intentions with unintended, negative, results is evidently part of human nature and a close companion in our history. The relevance to circular economy and the concept of 'recycled content' is that an uncritical use may lead to more greenhouse gas emissions, not less, and that there are other concepts that better support decarbonization and circularity. Demanding a certain recycled content for steel might turn out to be a bear's service to the climate.

The steel life cycle

In order to optimise the environmental properties of a product, you have to look at its entire life cycle and the continuation of the used materials into the next. This is studied in Life Cycle Assessment (LCA) projects and used in Environmental Product Declarations (EPDs). For buildings the standard EPD, EN 15804, divides the assessment into a number of modules (as shown in **fig 1**). Module A describes the process that starts with virgin and recycled material as well as reused products, leading to a building that is ready to use. Module B describes the operations, environmental loads, and resource use during the building's life time, and module C shows the deconstruction stage where materials are recovered for either reuse or recycling, if not deposited as waste, which is almost never the case for metals. Building a bridge from stainless steel means having a high environmental burden in module A compared to other materials which becomes lower in module B when taking maintenance and product life into account.

The environmental value of reuse, including refurbishment or formatting of a product, and recycling including remelting, is calculated in module D, where calculation rules make sure greenwashing is avoided.

*Founder and CEO, Kobolde & Partners AB

Rutger Gyllenram with a not so dangerous bear.
Photo: Pelle Berglund, Znapshot

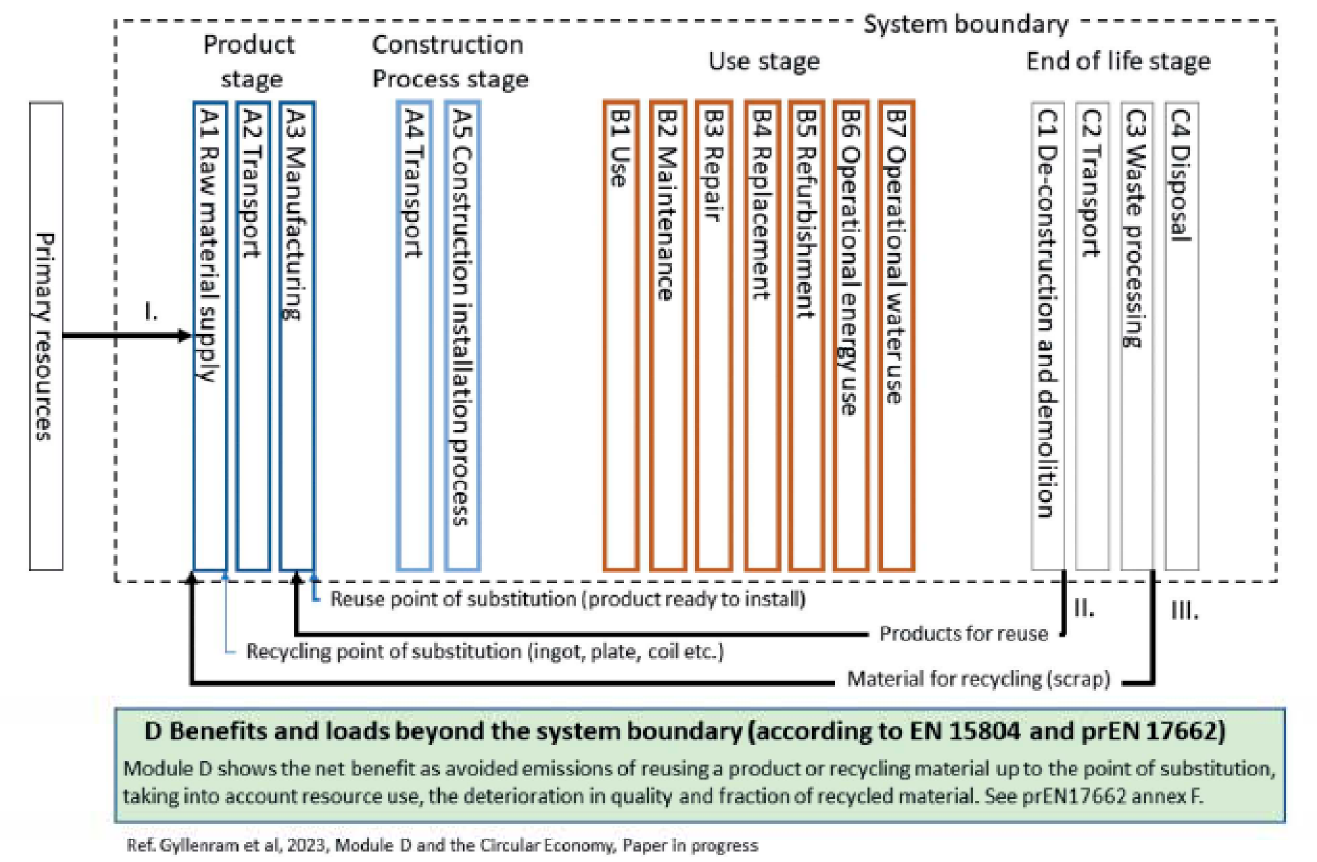


Fig 1. The life cycle of steel as it is modelled in the draft standard for steel and aluminium, outlined for buildings and civil engineering structures but applicable to most uses of metals in products. The steel is produced from a mix of primary and recycled material, used in a product and at the end of life either recycled or reused. The value of reuse and recycling is calculated in the so-called 'module D', taking into account any degradation of quality and loss of value

For both reuse and recycling, module D should take into account any deterioration in quality due to circulation. Since remelting is avoided in the reuse case, the gain is higher than for recycling if the quality can be kept at a reasonably high level. The quality of recycling is included in the model but unfortunately seldom analysed in depth.

What is discussed, however, is that using virgin material has a higher environmental impact than using scrap – and regardless of the fact that in a growing global economy both virgin and recycled material are necessary for the economy – the 'recycled content' measure is used as an index for good environmental performance while it at best is irrelevant, and this will be discussed further on.

Steel recycling in the circular economy

Steel is an 100% recyclable material which means that all collected steel scrap from industry, that is 'new' or often called 'prompt' scrap, or 'old' scrap, can be used in the production of steel. Scrap circulated within a plant belongs to a third category and is called 'home' scrap – this scrap is normally not reported in scrap statistics. Since the price of scrap is in the range of hundreds of euros per ton, the recycling rate is high – and with few exceptions steel stays in the circular economy. Losses occur for steel that are hard to recover, for example sunken ships and piping in the ground, material contaminated by radioactivity, material used in a way that it is consumed, and finally oxides in slag and dust. Even rebar, which for a long time was used for backfilling together with the surrounding concrete, is nowadays liberated and recovered for remelting. According to scrap dealers in Sweden, about 40% of traded scrap is prompt scrap and the rest is old scrap.

Alloys in scrap

Steel gets its properties from its chemical content with alloys and impurities, casting conditions, hot and cold forming, heat treatment, surface treatment etc. These operations together add to the performance as well as the environmental burdens of the steel. When reusing a steel product all these properties may be recovered in a new function whereas remelting may make use of only the iron and alloy content, but often only the iron is taken into account. In the same way alloys may give steel desired properties, the same elements may in other cases be considered unwanted 'tramp' elements. Furthermore, alloys have significantly higher carbon footprints than iron since they come from ores with lower metal content than iron and often use more energy-intensive processes for extraction. Carbon footprints that are double or 10 to 20 times that of iron or even higher is not uncommon and the same goes for alloy prices.

When it comes to valorising the alloy content in scrap, the business is about separating and sorting at the scrap processing end and storing and blending at the steel plant. Information about the scrap average chemical composition together with lot sizes play important roles in optimising alloy recovery. Most important, however, is the ambition to actually make the alloys in scrap recoverable and to use the recovery potential of scrap alloys in full. Scrap with a known chemical analysis within narrow limits has a much higher environmental and economic value than scrap with just a maximum level for certain tramp elements.

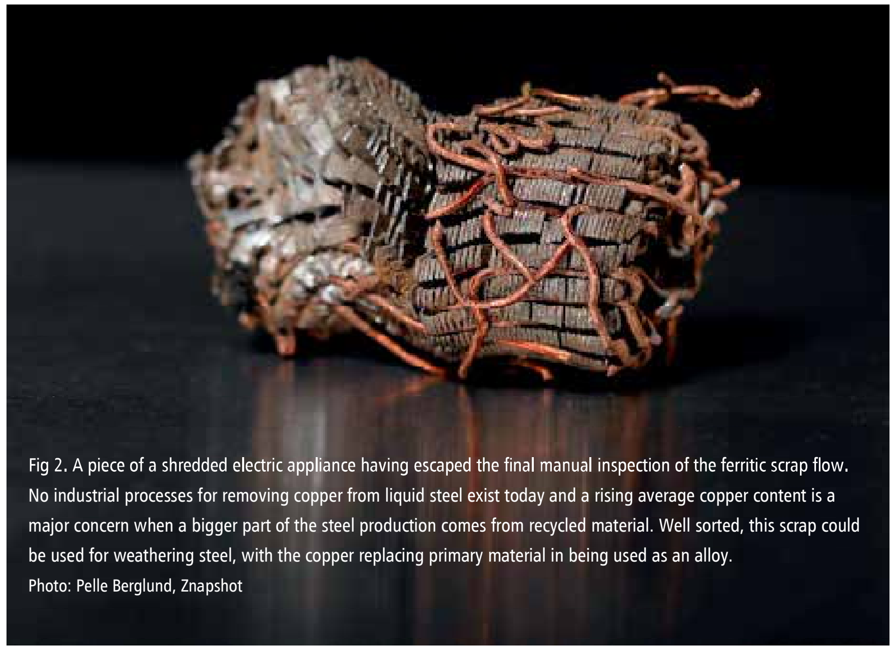


Fig 2. A piece of a shredded electric appliance having escaped the final manual inspection of the ferritic scrap flow. No industrial processes for removing copper from liquid steel exist today and a rising average copper content is a major concern when a bigger part of the steel production comes from recycled material. Well sorted, this scrap could be used for weathering steel, with the copper replacing primary material in being used as an alloy.
Photo: Pelle Berglund, Znapshot

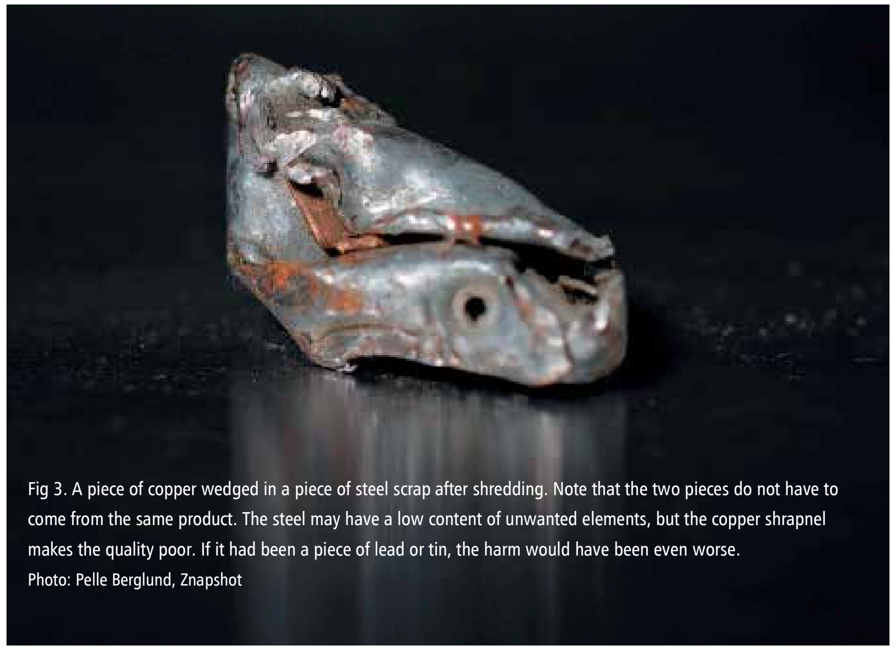


Fig 3. A piece of copper wedged in a piece of steel scrap after shredding. Note that the two pieces do not have to come from the same product. The steel may have a low content of unwanted elements, but the copper shrapnel makes the quality poor. If it had been a piece of lead or tin, the harm would have been even worse.
Photo: Pelle Berglund, Znapshot

Prompt scrap

For prompt scrap, the analysis of the scrap flows is normally initially known, but keeping scrap from different steel qualities separate requires scrap management to be included in the factory design. Unfortunately, that is often a detail that is omitted when trying to decrease the investment cost of a new plant. There is an abundance of examples where end cuttings in steel rolling mills, cuttings from steel coils in the automotive industry, and turnings from machining plants in the foundry industry end up in single scrap streams where alloys are difficult to recover due to widely varying chemical analysis and combinations of alloys that do not fit the steel products for which the scrap is used. Keeping track of scrap chemistry is seldom a priority down the production line where it is sometimes viewed as a problem and not an opportunity.

Old scrap

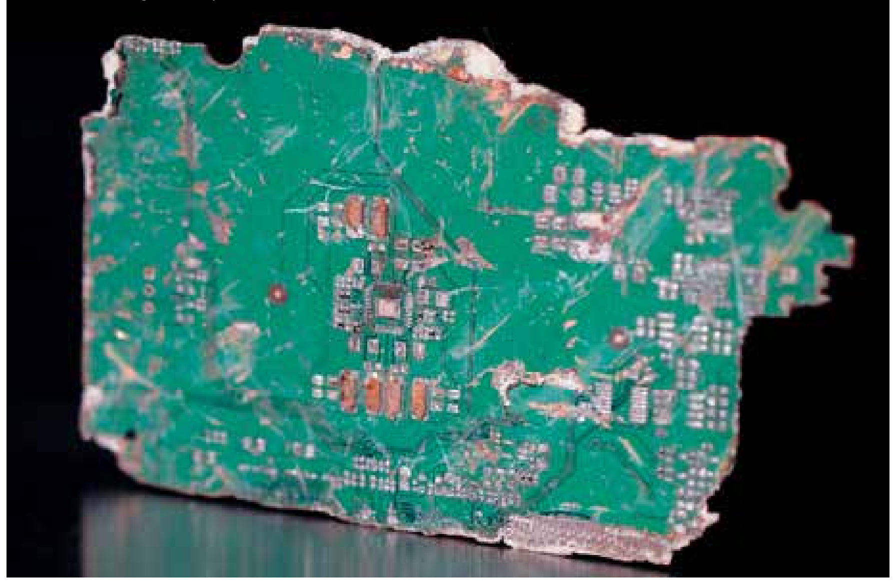
Old scrap is collected from discarded constructions, products or packaging and sorted according to one of many scrap classification systems. The sorting is done by skilled personnel often with an XRF, a hand-held instrument with which the chemical analysis of larger objects can be measured. Complex products like cars, are shredded and the resulting scrap is then automatically sorted in one magnetic and one non-magnetic fraction.

The non-magnetic flow is much smaller than that of the magnetic and contains scrap with higher metal/alloy value, and in modern shredding plants is then processed by copper, brass, different kinds of aluminium and different kinds of stainless steel being separated into different flows for further processing, which makes use of the full value of the content.

The magnetic fraction contains all ferritic steels like unalloyed steel with less than 1% of alloys and alloyed steel with nickel, chromium, molybdenum typically under 10%, ferritic stainless steel like the drum in a washing machine or the inside of a dishwasher, which typically contains more than 13% chromium. Non-magnetic metals may be trapped in ferritic steel parts and then go with the magnetic stream. The biggest problem is probably copper wire from motors that are wound up around iron kernels or wedged in a scrap piece. Examples of where copper goes with the ferritic flow are shown in **Fig 2** and **Fig 3**; with **Fig 1** showing a motor where the copper was part of the product and **Fig 2** representing a situation where two pieces of different origin are wedged together. This scrap is well-suited for the production of weathering steel that is alloyed with copper but in most steel qualities, copper is a tramp element and not valorised. The scrap piece shown in **Fig 4** may be non-alloyed steel, high strength steel with high manganese content, or ferritic stainless steel with high chromium etc. Such scraps increase the uncertainty of the chemical content and the loss of valuable alloys.

Fig 4. A piece of shredded scrap from the magnetic flow. It may come from a car roof and have a very low alloy content, be a high strength side of the car with high manganese, be part of the inside of a dishwasher with high chromium etc. The alloys cause concern in the following steelmaking process and may all end up as tramp elements which are unwanted. Well sorted, the alloys in the scrap piece could have come to use.
Photo: Pelle Berglund, Znapshot

Fig 5. A piece of a circuit board found in the ferritic scrap flow. If the solders are made of lead and tin, the circuit board constitutes an impurity hazardous to some steel qualities.
Photo: Pelle Berglund, Znapshot



Finally, the circuit board in **Fig 5** that also was found in a ferritic flow contains lead and tin in the solders which are detrimental in certain steel qualities.

With new technology, the magnetic flow can be processed where individual parts are identified with laser technology and directed into different streams for optimal alloy recovery and avoidance of tramp elements. The environmental benefit of such sorting both from a carbon footprint and a resource conservation perspective is evident, but costs for the new technology are still an obstacle. The EU directives for vehicles, appliances or waste are still focusing on weight and not the recycling value so little help is in place at the moment, but hopefully the next generation of directives will look in this direction.

Why is 'recycled content' a concept of the past that should be avoided for metals?

1) There is only a certain amount of scrap to make scrap-based steel from, and when it runs out, only steel from iron ore remains. Scrap from end-of-life products in society is used directly and there are no large reserves of unused scrap. This means that insisting on only buying scrap-based steel does not improve anything. It is irrelevant. It may however increase transportation and add to emissions from that sector.

2) Not buying steel from virgin sources in the western world may divert virgin production to countries with less efficient ore-based steel production. This may be detrimental when fossil-free ore reduction processes emerge.

3) In many cases, although not all, it has just been a way of making a virtue of something companies have done for a long time for cost reasons, which does not indicate a real interest in circularity. This makes the label less trustworthy and valuable and indicates complacency. Using a concept without real environmental impact and not fostering continuous improvement is, perhaps, the most serious flaw.

Preparing for the product label 'reuse and recycling ready'

How do you design a product that avoids the problems of poor recycling of alloys discussed above? It is a million-euro question that companies engaged in meeting circularity, climate goals, and other demands from society must ask themselves. If we invent the concept 'reuse and recycling ready' ensuring a smooth prolongation of the products' life and recycling of the alloys as alloys, what should it include? It is likely that we must look at the entire life cycle with repair and maintenance and then the end-of-life operations. For reuse, you need to make the product deconstruction-friendly, and for recycling you need to decide whether the product needs laser sorting or may do well with just magnetic separation. Deciding on that and dealing with labelling and documentation might be a first step. The second step would then be to make reuse and recycling work in practice with reuse-product management and different waste management streams – and finding entrepreneurs taking on the task. And sorting out the financing. That would be a real service to circularity and the climate. ■

LOCAL PRODUCTION OF STRATEGIC GOODS

Steel Times International January 2023

It is a pleasant thought that we can develop new technology and implement in our existing plants so we can go on as before except that we avoid emissions. Very simple calculations show that we have to invest very wisely in order to keep our production profitable and resilient to competition from competitors with other sources of energy and access to carbon storage.

Rutger Gyllenram with a raw material producer in the cloth-supply chain and a bunch of grapes – or is it green DRI?
Photo: Pelle Berglund Znapshot, DRI grapes: Emirates Steel and Therése Gyllenram

Local production of strategic goods

Must steel companies necessarily do their own iron ore reduction? **Rutger Gyllenram*** offers a story about David Ricardo, wine, cloth and green DRI

IT is easy to like David Ricardo (1772-1823), one of the great economists from the early 19th century. Apart from laying the ground for a system with independent central banks, that today is a role model in many countries stabilising the economy, he spoke out against slavery which he thought was a stain on the character of the nation. He also opposed protectionism during the Napoleonic war, making food more expensive and, therefore, life harder for the less fortunate. Ricardo's perhaps most famous work is *On the Principles of Political Economy and Taxation* published in 1817 where he, among other things, presents the theory of competitive advantage advocating free trade. His example of production of cloth and wine in England and Portugal, where the latter had better conditions for vineyards and the former better conditions for manufacturing of textiles, is well known and his basic idea was that it is beneficial for both parties to specialize and trade.

*Founder, CEO, Kobolde & Partners

Although not being an economist, I have always found it puzzling that we in the steel industry, for such a long time, have claimed it to be necessary to keep a full-scale steel industry in almost every country sometimes leading to operations with very poor profitability. I was once told that 'the steel industry is the bedrock of our nation's industry' when performing a due diligence at an integrated plant in urgent need for money and with very little prospect of ever becoming profitable. In a country building up its basic industry and infrastructure, an ambition to keep the steel industry working within the country is understandable.

In addition, the uncertainty that lies in long complicated supply chains may be a concern for companies of all countries in unstable times. Maybe, therefore, the prevailing model for ore-based steelmaking is still integrated reduction and steelmaking plants. The key questions are if that is an optimal solution when the steel industry now aims to decrease the emission of greenhouse gases to very low levels and if the industry is ready to try new supply chain models?

Although the entire steel life cycle contains steps that emit greenhouse gases, it is the iron ore reduction that is the greatest emitter and that at present is under scrutiny. Scrap-based steelmaking has lower emissions, but since available scrap is limited by the flow of obsolete products in society, increasing scrap-based steelmaking is not a possible solution. The dominant reduction furnace today is the blast furnace where iron ore is reduced and smelted to pig iron and blast furnace slag from iron ores of varying quality, coke, coal and limestone. Producing direct reduced iron, DRI, in a shaft furnace with a reduction gas is the main alternative to the blast furnace today. The product is solid in contrast to the liquid pig iron from the blast furnace and since the gangue from the ore stays in the DRI the ore quality is more of a concern in the DR process.

There are in principle only two ways to decrease emissions from iron ore reduction:

1. Applying carbon capture usage or storage, CCU/CCS (CCUS)
2. Replacing fossil carbon with 'fossil free' reductants and fuels.

This decrease must now start in a world where the energy and raw material availability sets limitations to our choice of technology. We are coming from a world where raw materials, like ore and coal, have been transported over the oceans at low cost and processed in standardised, energy-efficient processes. Steelmaking sites have to a large extent been chosen from a market perspective. We might be heading for a world where we are more restricted by existing industrial structures, available raw materials and energy supply than we want to acknowledge and production sites may become, to a larger extent, dependent on the raw material situation and the resulting process selection.

Decarbonisation with CCUS

In the ULCOS project, mainly financed by European taxpayers and completed in the first decade of this millennium, CCUS was the main method chosen. A blast furnace design was developed using oxygen instead of air as blast and with capture of CO_2 in the top and recycling of the CO to tuyeres in the middle of the shaft to ensure heating of the burden. The concept of top gas recycling, TGR, was tested in the LKAB Experimental Blast Furnace and found promising, but plans to scale up the concept were never realised. As an alternative to the blast furnace, ULCOS also proposed a DR furnace with hydrogen made from natural gas using CCUS for the generated CO_2.

It seems, that for a number of years, CCUS as a general method for decarbonisation in the steel industry was put aside partly due to technologies avoiding fossil carbon and partly due to arguments that CCS cannot be considered a long-term solution since carbon storage needs geological formations with certain characteristics that may be in short supply. It seems, however, that CCUS again is considered a necessary constituent in a decarbonisation roadmap. Especially storage or permanent usage of CO_2 of biogenic origin that creates a carbon sink to make up for fossil emissions that cannot be avoided. It is hard to tell the reason for this

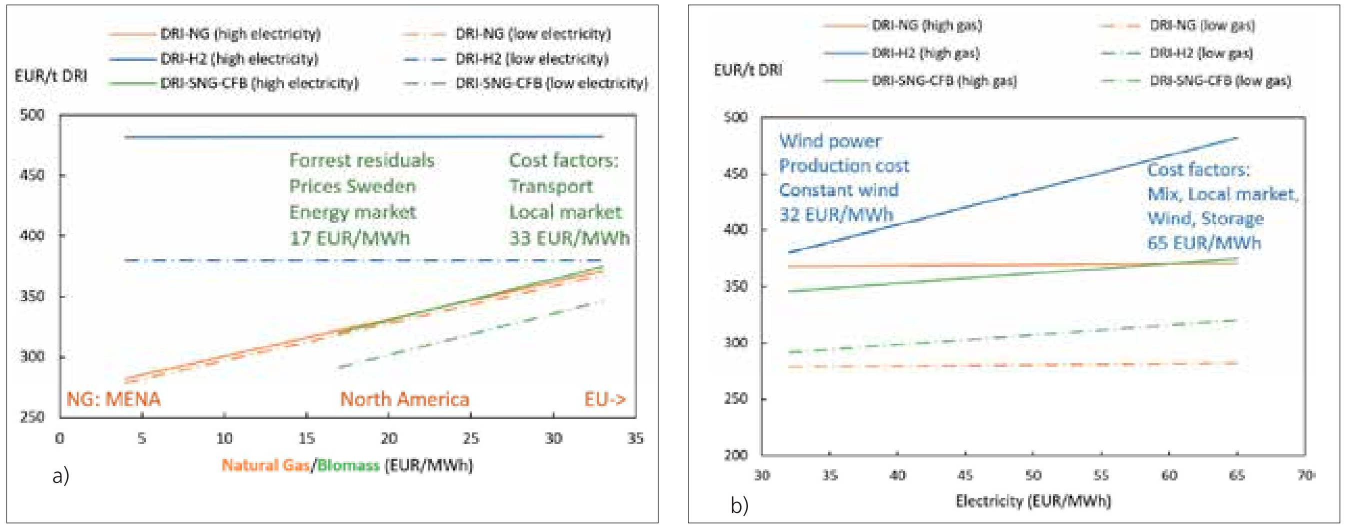


Fig 1. Tentative estimation of the cost of low fossil DRI production with: natural gas + CCS (amber), hydrogen (blue) and biogenic syngas + CCS (green) as a function of a) the cost for natural gas and biomass and b) the cost for electricity. The same cost for iron ore is assumed for the alternatives. Calculations based on the FerroSilva pre-study and first presented at the Worldsteel 57:th RAMCO meeting 2022.

sudden acceptance, but it is sad to realize that we have lost a decade of development that would have come in handy now.

Geographic areas considered suitable for storage of CO_2 are often, but not exclusively, regions with oil and gas resources which means that these both have access to a reduction agent for DRI production and the means to store the resulting CO_2.

Replacing fossil fuels with hydrogen, biogenic material and electricity

The most drastic move and the one frequently advocated today is to replace reduction in the blast furnace process with a gas based direct reduction furnace followed by smelting in an electric furnace. Choice of the smelting and steelmaking operations depend, among other things, on the ore quality. But the important necessary requirement when replacing melting in the blast furnace with melting in an electric furnace is that the electricity used has a very low carbon footprint since the blast furnace is highly energy efficient.

Gas based direct reduction is today performed with a reformed natural gas which is a mix of hydrogen and carbon monoxide. As an alternative, direct reduction can be made with pure hydrogen or a syngas of biogenic origin with an analysis similar to that of reformed natural gas. Hydrogen production in an electrolyser is restricted by the available amount of low fossil electricity and the transmission capacity; production of syngas on the other

hand is restricted by the available amount of biomass within a reasonable transport distance.

With top gas recycling still very much on hold, the suggestions put forward to increase productivity and decrease CO_2 emissions in the blast furnace are manyfold. Injection of biomass or hydrogen, use of biocoke or using electricity to improve the heat balance with electricity are some. A well-established method is to charge scrap or DRI in the blast furnace down to the limit where the coke charge is reduced to the minimum level determined by the need for furnace permeability. Supplying low fossil DRI to the blast furnace market as a complement to iron ore may prove an efficient way to partially decarbonise this dominant process. Iron ore is to a large extent traded across the globe. DRI production included in the supply chain may be done at the mine shipping side, the receiving port plant side or as a stopover service between the mine and the plant.

Production of low fossil DRI to be used in blast furnaces

So far, we do not have published reports on costs for full scale production of DRI with very low greenhouse gas emissions and, therefore, have to rely on estimations. A tentative calculation was made in the FerroSilva project aiming at producing DRI from DR pellets and a syngas from forest residue. A full paper with all the assumptions will be published in 2023, but the main cost figures are shown in **Fig 1**. The model assumes that all CO_2 from the natural gas process is captured and stored as well as that from the biogenic gas thus, in the latter case, generating a 'carbon sink credit'. It is provided here as a basis for discussion and to give an indication on how to understand strengths, weaknesses, opportunities and threats in a SWOT analysis.

Fossil free reduction with hydrogen

is sensitive to the electricity price, and electrolyser efficiency is definitely a weakness, but it has its strength in that it does not rely on CCS. Promising development in electricity and hydrogen production is an opportunity, but the dangers of handling hydrogen and possible complications from the endothermic nature of reduction with hydrogen may be considered a threat.

The main strengths of DRI production with syngas of biogenic origin are that it can use forest residue that otherwise would have been left in the forest to rot emitting methane, and that the biogenic CO_2 can be either used or stored to create a carbon sink. A weakness is the voluminous nature of wood chips that may limit transport distances and that it is a material with varying properties that may be challenging. The rising interest worldwide in harvesting this material is an opportunity, but political ambitions in some regions, like in the EU, to restrict the use of bioenergy, for instance, is a grave threat.

DRI production with natural gas has the advantage of being low cost, well established, apart from a necessary complete capture of CO_2, and with adjacent possibilities of CCS in natural gas-rich areas. The main weakness is the fact that leakage normally occurs in natural gas processing and that methane is a strong greenhouse gas. The opportunity is the vast amounts of natural gas that is available in certain regions, making possible production sites numerous, but in the case of a stopover service the main threat is the unwillingness of companies to lose control over the supply of critical raw materials.

Will we have a reduction stopover service in the future?

Since **Fig 1** does not include transport of the DRI and since production conditions vary, the main conclusion is that all processes may be profitable at the mine side or the plant side of ore trade routes, but only reduction with natural gas may have the cost situation making it possible to have a stopover service for ore reduction covering the costs of extra unloading and loading. Furthermore, it is hard to imagine that we can transform the entire steel industry in such a short period that lies ahead of us without using the cheapest, most developed route available for us and that is direct reduction with natural gas with CCS. This may be a real business opportunity in the MENA region and other natural gas rich parts of the world.

From a decarbonisation perspective, as some companies have already identified, a stopover service for reduction is probably a faster way to start the road to the carbon neutral world than to invent completely new process lines and force through new fossil free electricity production. There are, of course, a number of questions that have been left out in this article, like transport and the advantages of charging hot DRI, but they are probably minor details in the big picture.

Sitting in our software lab at Kobolde, almost on the border to the arctic world, it is presumptuous to say that many companies worldwide are wrong in choosing to adapt their processes' layout to keep integrated plants fully integrated. However, I am worried that transition to the suggested paths is unnecessary, slow and costly and may not only make us miss the goals set out to meet the Paris agreement but might cause us to miss abatement of greenhouse gases altogether.

Eventually, we should decide at which level we need to have local production of strategic goods to ensure undisturbed supply chains and to what extent we can rely on a rule-based world order where we can focus on doing what we do best and have competitive production conditions. Building trust and stability may prove as important as providing new technology. Like wine and cloth, all in the spirit of David Ricardo. ■

This is the third and final article in a series about the conditions for DRI-production as a means to decarbonise steel production. The others are "Between a pony and a pink unicorn" STI October 2021, and "Betting on a winning horse" STI September 2022.

REDUCTION AS A STOPOVER SERVICE -
A KEY TO FASTER DECARBONISATION OF STEEL PRODUCTION:

1. Produce low fossil merchant DRI/HBI where natural gas is cheap and CCS possible.
2. Create diverse and stable supply chains involving many (all?) stakeholders.
3. Create market conditions where both the DRI carbon footprint and composition matters.

THE GRAND QUEST FOR GREEN STEEL

Green Steel World February 2023

It seems to me that the awareness that some new technologies might not work or that resources will not suffice, is non-existent. In my mind we must be much more resilient and work with technologies that we know deliver until new proven processes are in place.

Rutger Gyllenram with players from China, India, Australia and the MENA region. Players: WWF. Visual game design: Katarina Hamilton.
Photo: Pelle Berglund, Znapshot

The grand quest for green steel ...
The game is on, but who are writing the rules?

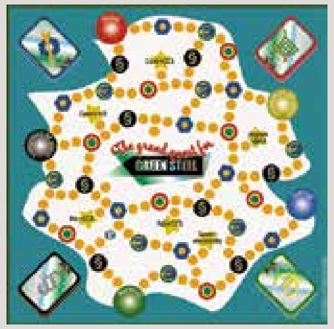
By: Rutger Gyllenram.
Research: Wenjing Wei, Kobolde & Partners AB.

Not all cards are good

Among the bright memories I have from my childhood, one is when the family came together to play a game of Monopoly. You walked around a gamepad where you could buy streets and railway stations, build houses and hotels. On some spots you had to pick up a card that could be either good or bad. You never knew what to expect.

Although I now look very much like the iconic millionaire from the box, I can still remember the joyful feeling of getting a card saying I had won some money in a beauty contest and of course the subsequent scorn from my siblings. But I also remember the despair from getting a card saying I had to renovate all houses and hotels at a huge cost. The rules came with the game, easy to understand, and equal for all and the same goes today when again picking up the box for some real estate gaming with my wife and children half a century later.

Trying to understand what is going on in the steel industry, I cannot help viewing how decarbonisation is managed as a new type of game where companies compete, as they have always done, but where greenhouse gas emissions have become both a cost factor and a product quality feature.



In our imaginary game, a player can start as either an integrated blast furnace plant (BF), integrated direct reduction plant (DR), minimill, startup or a mine. The goal is to reach the "GREEN STEEL-patch" in the middle with a product where cost, carbon footprint and quality determine the competitiveness. Furthermore, the players are supposed to pass one or more decarbonisation stations marked as yellow stars with the text "Coal+CCS", "NG+CCS", "Bio+CCS", "Hydrogen", "Green electricity" or "Improve yield" indicating the decarbonising technology steps that may be taken by the player. Here NG stands for natural gas, Bio for biogenic syngas and CCS for carbon capture and storage.

Finally, there are a number of cards to pick up ruling on the legislative framework, technology, market and finance, when stepping on the assigned dots. Some cards may be good and some bad just as in Monopoly.

The points that I want to make using this game metaphor are:

1. Steelmakers must be prepared for all types of surprises and must avoid wishful thinking. In this case, a player will surely get both encouraging and disappointing cards.
2. Furthermore, players must be aware that in real life the playbooks are constantly edited by a number of sometimes competing playwriters and they may not be equal for all. What is considered green steel today may not be green tomorrow and what is not considered green steel today may be green tomorrow. Nobody knows.
3. Finally, a game is just a game, and a responsible company must go beyond the rulebook to contribute to the intentions of the Paris agreement. We must not fool ourselves to think that just calling something green will actually result in a global decrease in greenhouse gas emissions over time. The concept is a tool to meet the end, not the end.

Roadmaps

There is a lot going on showing how to reach the green steel goal. Without providing an exhaustive list we can note that roadmaps have been developed for the world by the International Energy Agency, IEA, on the request of the Group of Seven, G7, for China by Rocky Mountain Institute, RMI, and for India by the Energy and Resource Institute, TERI. The European Union is now working on a roadmap for Europe in the Green Steel for Europe project. Companies may develop individual roadmaps according to a framework set up by the Science Based Target initiative, SBTi, and alignment of this work is at present addressed in the Net Zero Steel Pathway Methodology project, NZSPMP performed by SBTi and a consortium of companies and organisations. In addition, the UN campaign "Race to Zero" promotes breakthrough technology roadmaps across many industries including steel. Finally, an evaluation of the work going on has been published by the think tank E3G studying the six largest steel production regions China, Europe, India, Japan, South Korea and the US.

As technology develops and experiences are gathered these roadmaps must be revised on a continuous basis, for countries as well as for companies. An openness, to successes as well as problems and failures, is therefore of the greatest importance for the world to move forward. Recognising failure may be the best contribution to global success. Faking success is a sure path to global failure.

Technology

Decarbonisation efforts must, to be sustainable, take the entire life cycle into account. As shown in Figure 1 the steel life cycle starts in the mine, continues in production, and uses steps and goes on forever in the reuse and recycling cycles of steel. Four main areas for decarbonisation can be identified and are here described briefly.

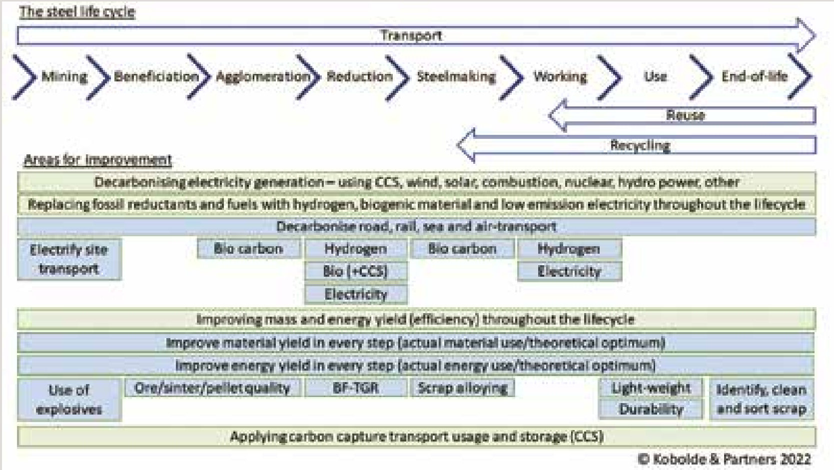


Figure 1. The steel life cycle and possible decarbonisation. The main areas, in green, are decarbonising the grid mix, replacing fossil fuels and reductants, improving the material and energy yield and finally applying CCS to the greenhouse gas flows that cannot be avoided. Examples of possible topics/applications to address are given in the blue boxes.

Decarbonising electricity is of concern not only to the steel industry since electrification is seen as one of the main ways to decarbonise society. This means that we not only have to decarbonise the existing production, but we also have to build new capacity with low emissions. As long as we still have large parts of the electricity mix in the grid coming from coal combustion it does not really make sense to replace coal as an energy or reduction source in metallurgical processes.

Replacing fossil fuels and reductants involves electrification and the use of hydrogen and biomass. Electrification of transport is a major issue not only in the steel life cycle. Using hydrogen and biofuels are other alternatives to fossil fuels.

Hydrogen is an alternative to fossil reductants and is at present also used as fuel in reheat furnaces. Biomass can be gasified to biogenic syngas used for reduction or turned into biocarbon used in processes like agglomeration and steelmaking. Using electrolysis for ore reduction is yet in the test scale but electric pig iron processes are again proposed as alternatives to the blast furnace. Furthermore, electric reheat furnaces may replace furnaces using fossil fuels.

Improving mass and energy yield is an ever-ongoing activity throughout the steel life cycle saving both money and the environment and some areas may be pointed out.

Although the biggest improvements in mines come from replacing diesel and using low fossil electricity an improvement in precision may result in **less use of explosives** and less material to move around. Ore beneficiation causes yield losses and is a cost to the ore producer but improves yield thereby saving more money and reducing environmental burdens in later process steps.

There is still a lot to do in the traditional processes. By using oxygen instead of air and applying top gas recycling in the blast furnace a considerable reduction of coke use can be achieved, and an off-gas obtained ready for CCS. Another example is that scrap upgrading and sorting at the end of the life of a product can be improved to make it possible to decrease the need for virgin alloys in scrap-based steel production.

Finally, the yield in the use stage is for example improved by lightweight constructions getting more functional value per kg of steel or by more durable steel with a longer lifetime and a possibility to reuse when the economic life of construction comes to an end. A higher quality may however result in a higher carbon footprint of the steel per kg but a lower carbon footprint over the product's entire life cycle.

Applying carbon capture, transport, usage, and storage, here just called CCS, is dependent on the ease with which pure CO2 can be captured and the transportation and storage possibilities available. Storing CO2 of biogenic origin creates negative carbon emissions often called carbon sinks.

The outlined possibilities above differ in impact, cost, and risk. Developing and implementing new technology is costly and takes time and there is always a possibility that it will take longer time to reach the planned performance than anticipated.

Any stakeholder must be prepared for surprises good as well as bad.

The regulatory framework

Let us for this discussion define the regulatory framework as the rules affecting the decarbonisation of the steel life cycle, originating from either product ecology with life cycle assessment, LCA, or GHG reporting on an organisational level. The two approaches differ in scope and data granularity and give different results when applied.

The standard ISO14044 is considered the basis for LCA and is a normative reference in ISO and CEN standards used for both multi-impact assessments like ISO 21930 and EN 15804 for building products, and single-impact standards that focus on GHG emissions like 14067 for all types of products. A new multi-impact European standard for steel and aluminium products, prEN17662, will be published in 2023. These standards make it possible to take emissions in the entire life cycle of a product into account when making an assessment. Other standards like the general ISO 14064 and EN 19694 and the 14404-series for steel production give guidance on quantification and reporting at the organisational level.

Most product standards apply the book-keeping approach making it for example possible to use the actual impacts from raw materials and resources. This means that buying for example wind electricity from an adjacent plant gives a low carbon footprint even though the main supply to the grid comes from coal combustion.

- A game-changer in the decades to come would be if standards start prescribing a mandatory use of a market mix of resources or in the most extreme case a consequential approach where the highest carbon footprint in the market should be used.

Companies around the world all experience a certain amount of political uncertainty. The European commission and parliament are very active in the field of decarbonisation which can be both good and bad depending on their level of understanding of the different topics. For example, we do not know how the Product Environmental Footprint, PEF, system will be applied for some steel products, what will be the demands from the new Construction Product Regulation, CPR, or how the new Ecodesign directive will work. A key question discussed at the moment is if protected forests are a better carbon sink than sustainably managed forests generating both material and residuals that can be used for bio-syngas and bio-carbon. Such a decision must be based on facts and not emotions.

A negative game-changer for the steel industry would be policies restricting companies from harvesting sustainably managed forests.

Ways to calculate and report GHG emissions for products have been developed for a long time starting in 2004 with the Greenhouse Gas Protocol. The World Steel Association, worldsteel, has been working for a long time to develop an LCA methodology for steel and gathering data for databases both for organisations and products. Eurofer is evaluating methods to use for the classification of near zero steel and other steel organisations like the American Iron and Steel Institute, AISI, the Global Steel Climate Council, and GSCC, have their methods. The list continues with the United Nations Industrial Development Organisation with the IDDI project and the not-for-profit organisation Responsible Steel, and there are many more.

A feature of some methods is using a sliding scale when classifying steel emissions depending on the scrap ratio. Ore-based and scrap-based industries do not agree on the merits of this procedure. At the end that dispute has to be solved and it is hopefully not impossible.

An interesting methodological twist is the mass balance method where all improvements after a certain date in an entire production volume are attributed to a fraction of the production which is then labelled green steel. The rest of the production volume is attributed to the original emission level and sold to customers less motivated to "buy green".

All the technologies presented in figure 1 matter and it is of the greatest importance that any accepted carbon footprint classification system for steel or products made of steel honour them.

Furthermore, a prerequisite for GHG mitigation in the steel industry is that labels should benefit only companies that invest in decarbonisation and obtain very low carbon footprint values, avoiding greenwash.

The systems use a variety of methodologies and system boundaries making results from different systems hard to compare and data not suitable for assessing an entire life cycle without additional information.

Financing

The transition to green steel or near zero steel or whatever we want to call it will need fabulous amounts of money. At present, the tax payers in Europe and the ETS fund have paid much of the investments in Europe. In the long run, it is important that the capital markets can assess the different projects and that more private money can come into the system.

SASB standards for sustainability info, the Task Force on Climate-related Financial Disclosures, Equator principles, Glasgow Financial Alliance for Net Zero, Climate Action 100+ and Climate Bonds Initiative are all examples of an active investor sector in this field.

Critical issues are whether the interest will keep, and enough funds will be available, and if occasional occurring project failures will scare off investors, public and/or private.

Customer demand

In the end, it is anticipated that green steel will be more costly than traditionally produced steel even though GHG emissions are punished according to the European ETS system, similar mechanisms, or tolls. Different ways to create demand are suggested in a number of initiatives like the First mover Coalition, FMC, the Industrial Deep Decarbonisation Initiative, IDDI, and SteelZero from the Climate Group.

A high willingness-to-pay, WTP, for green steel is crucial and is dependent on the trust that customers have for the system and that they can tell the difference between possible competing labels.

The nightmare for producers that have invested heavily to produce green (near zero) steel is that customers still expect them to sell at the same prices as producers using the traditional blast furnace route.

Conclusions

I am not saying that any of the efforts made today to promote solutions to decrease the carbon footprint of steel are wrong. What scares me is that very few actors on the market, if any, declare a plan B. What happens if the new processes do not deliver on the promise when expected? It is, to my knowledge, not even discussed.

Another distressing factor is that companies investing huge amounts in new processes and having high production costs may face a difficult market due to eased customer demands on carbon footprint and redefined rules for green steel.

We need an open discussion on how we shall meet the demands set by the Paris agreement facing different scenarios, which means getting both good and bad cards, and how we shall formulate a playbook equal for all, that is accepted globally and that leads to the goal.

A STEELMAKING CAROL

Steel Times International, April 2023

I am deeply concerned that we might reach 2050 without having achieved anything if we let the green initiatives and all the labelling systems have their say without reflecting on if they help us reach our goals.

A Steelmaking Carol

Charles Dickens was a remarkable man who experienced hardship in his early years when his father was put in prison due to insolvency. Charles had to quit school to work but resumed his studies some years later and became a fantastic writer and observer of mankind. His novella *A Christmas Carol* was published 180 years ago and is the inspiration for this article on the endeavour of decarbonizing the steel industry by 2050. By **Rutger Gyllenram***

The ghost of steelmaking past

With the introduction of the Bessemer, Thomas and Siemens-Martin processes in the second half of the 19th century, it became possible to decarburize blast furnace iron in liquid form. The amount of manual work decreased, the economies of scale increased and thus productivity and profitability. For small ironworks in Sweden, it was a disaster and entire communities disappeared. Many probably swore by Henry Bessemer, but the few companies that had enough capital and opportunity, invested in the new technology and grew. The death of mills did not go unnoticed by the politicians and legislation was demanded to prevent the transformation of the industry from taking place. That did not happen and it took until the energy crisis at the end of the 1970s before a similar crisis appeared.

This time the politicians were more active and gave extensive support to investments in the steel industry to secure jobs. Blast furnaces were shut down and replaced by electric arc furnaces and certainly jobs were created, first when the new plants were built and again when they were dismantled to be shipped to where they could be operated at a profit. A complete waste of money. Now that the steel industry is once again facing great stress and demands for change, do we have anything to learn from this story?

As cruel as it may sound, the first lesson should be that there is a time for everything and when the conditions that made a place a successful industrial location disappear, in the long run the industry will also disappear. Trade secrets, skilled employees and niche products may be sufficient conditions for survival and prosperity, but new technology alone will not help if it can be applied with greater success elsewhere. Furthermore, it is interesting to note that when investment in new steelmaking processes took off, they had reached what we call today a top technical readiness level (TRL). Sir Henry Bessemer may have invented the Bessemer process, but it was after long trials that it finally succeeded when Göransson, who was manager at Högbo mill north of Sandviken, could take it into operation. The Thomas and Siemens-Martin processes had similar stories: they were developed in England, Germany and France and were introduced on a wide scale in Sweden where they were first proven.

Another lesson is that process development takes time. Bessemer's ideas to use oxygen instead of air in steelmaking and to replace ingot casting with continuous casting took until the mid-20th century to be implemented for steel. To continue, the energy crisis led to extensive development programmes worldwide to replace the blast furnace with processes that did not need agglomerated raw materials. After 50 years, there are few implementations of new reduction technology, and the blast furnace is still the dominant reduction process. A successful story is, however, the natural gas-based direct reduction process that has gone from moderate sizes of 100 kt/yr to the mega modules we see today of 2.5 Mt. It is impressive, but has taken more than 50 years to scale up.

What the ghost of steelmaking present can tell us

Today, more than half of the world's production of steel is made in China, and India has announced that it will increase production drastically. The blast furnace is the dominant reduction process for iron ore followed by natural gas-based direct reduction. Scrap is the other ferrous raw material and the amount available for steelmaking is greater in industrialized countries than elsewhere although the amount of available scrap is continuously increasing. When it comes to greenhouse gas emissions the relation between the three processes can, for the sake of discussion, be set as roughly 2kg, 1kg and 0.5 kg CO_2-eq/kg steel.

Just a few years ago, the issue of greenhouse gas emissions was only mentioned in passing in the steel industry. Projects like EU-funded ULCOS, aimed in the first decade of this millennium to develop low greenhouse gas emission alternatives to ironmaking processes; their most successful project was the oxygen blast furnace with top gas recirculation and carbon capture and storage (CCS) which was tested with good results on a pilot scale. Then, many of us experienced that the lid was put on. Instead, projects with direct reduction using hydrogen were introduced and were funded by the EU. These projects are now reaching demonstration level in the one million ton scale but are reported not to be profitable with present hydrogen prices.

Today, the debate about the development of the steel industry, at least in the Western world, is dominated by the issue of reducing greenhouse gases, and those who bring it to the agenda are mainly politicians, financiers, customers and the steel companies themselves. Organizations such as the UN, IEA, WTO, WEF, OECD, worldsteel and the G7 are committed to developing systems to drive development towards low emissions steelmaking. Organizations of investors and customers as well as steel makers and non-profit organizations are also engaged in developing calculation systems, roadmaps, threshold values or different types of labels. Today, it is almost a full-time job to follow this development and to understand the effect different systems or programmes can have on the market and on the steel production companies.

A dilemma suddenly arises here. It's quite simple. If we are to reduce emissions to 0 by 2050, we should look at what is emitted when producing each ton of steel and report this. If it is below a certain value, it can be considered close to 0. If you as a producer want to sell steel that is close to 0, you must invest in processes that do not emit greenhouse gases. Supply blast furnaces and direct reduction plants with carbon capture and usage or storage, CCUS, or switch to hydrogen or biogenic syngas as a reducing agent. It will, however, take time since the fossil-free processes are probably not ready for the market in full scale yet. Much can be done to reduce emissions to some extent, but few if any can reach close to 0 immediately, and politicians and customers must understand that.

The final question is: are we right to assume that all companies must survive the transition to close to 0 steel? It was not like that in earlier crises and if we twist the labeling systems so it becomes easier for a company with higher emissions to get the same label as a company with lower emissions, are we then working for decarbonization? Finally, when governments subsidize investment in new technology to save jobs, are we sure the plants can be run with a profit in the long run and the jobs will stay or is it just a waste of money?

Meet the ghost of steelmaking yet to come

In *A Christmas Carol*, Ebenezer Scrooge is, after confrontation with the ghosts of past and present Christmases, given the opportunity by "The ghost of Christmases yet to come" to – in a dystopic way – see into the future in order to make what we can call life-changing decisions. Let's think about what we might experience if we were visited by "The ghost of steelmaking yet to come" and escorted to the "Greenish Steel Conference 2050" just in time for the inauguration speech:

"Dear delegates, as we gather here today, we can state that we have put a successful year behind us. After extensive negotiations,

*Founder and CEO, Kobolde & Partners

the number of definitions of greenish steel has now been reduced to 300, which is three less than last year. Since both steel manufacturers and steel customers are involved in the design of each of the programmes, a greenish steel label that satisfies consumers can be guaranteed.

"The number of research projects for fossil-free steelmaking has now reached 2000 and the number of pilot installations of the five leading alternative processes for pig iron and DRI in operation has reached five i.e., one of each. Additional plants are planned when it is judged that it is possible to compete with traditional plants producing greenish steel.

"Projects to relocate steel facilities to areas with conditions for them to be operated without heavy losses are happily underway among many of our members. They represent great manufacturing potential for greenish steel once they are in the right place.

"Scrap exports have now completely ceased from the USA and the EU as they closed their ore-based works, which is why the countries that previously used this scrap raw material have switched to sponge iron production in rotary kilns. Admittedly, this results in higher emissions of greenhouse gases than the previous ore-based production in the EU and the USA, but through a new calculation formula, this DRI can also be assessed as greenish.

The question of who should pay for the capture and storage of carbon dioxide as well as the extra cost for hydrogen production has now entered a decisive phase. Since all products are greenish even without CCS or hydrogen, there is no possibility of passing this cost on to the consumer. We expect to be able to have a conference on this and come to a decision around 2060-2070.

"This concludes my introductory remarks. Unfortunately, greenhouse gas emissions increased last year, so today we are 30% above the 2020 level, but in 2051 we expect the rate of increase to decrease."

Epilogue

A Christmas Carol by Charles Dickens ends happily with Scrooge realizing that there are values other than money. In the business world, unfortunately, it's just a beautiful thought. A company's task is to increase capital for its shareholders. Nothing else. However, laws and regulations, other stakeholders such as employees, public opinion, and, of course, customer requirements are considered, all of which affect the company's profitability and long-term survival. It is natural for management to wish for regulations that favour their existing plants and way of production regardless of the impact on the climate.

Transition to near zero will hurt

Earlier crises have forced companies to rethink their supply chains and their business ideas, and some have been forced to close. Cash injections from governments in the wrong projects have only prolonged the pain since the laws of business economy are what they are. If we really want to meet the goals of the Paris agreement, we must brace ourselves and realize that the transition to near zero steel making will hurt, but not having a transition will hurt even more. Then, maybe even this carol can have a happy ending. ■

IT IS ALL ABOUT SURVIVAL

Steel Times International, January 2024

There is hope if we apply pure business logic to low emission iron and steelmaking. We need private capital for investments and that will only be available if the business cases are sound. We must continue to learn and adapt, and learn and adapt and learn and adapt. Then there is perhaps a possibility that we can have reason to be optimistic.

The author (right) with WWF-meerkat "Sur-Vival" (left) looking out for threats and opportunities on the horizon.
Photo: Pelle Berglund, Znapshot.

It is all about survival

It is easy to forget that climate change is only one of the threats experienced by countries, companies and individuals. All major risks must be addressed and relevant resources allocated in an optimal way by each and every one to secure survival. By **Rutger Gyllenram***

I guess it was in Disney's *The Lion King* that many of us became acquainted with the meerkat Timon and this charming species. Being a very social mammal, it lives in colonies which jointly look out for predators like eagles, lions and snakes, standing in a monumental pose. A hypothetical proposal by a chief meerkat saying: 'today we only look out for snakes', would probably be promptly rejected.

Taking part in *Steel Times International's* conferences is always a pleasure and this autumn I had the honour to moderate a session as part of the Future Steel Forum conference in Vienna, with some interesting revelations. A speaker from one of the many green initiatives asked the audience to approach the podium and join one of four groups. To the right were those who did not find decarbonization really important and to the left those who found it ultra important with two groups in between. I was appointed leader of the right group and was initially only accompanied by one person. I asked the delegate for the reason for the choice and got the reply: 'my country is at war and we have other priorities'. Then the speaker asked the audience to think of their children or other young people and where they would have positioned themselves. Contradictory to what the speaker and I anticipated, the main part of the audience started to move towards groups to the right and quite a few to my corner. Again, I asked "why?" and got the answer: "they have other problems that they worry about". Regardless of the validity of this single observation I think that the decarbonization movement, of which I proudly am a part, must take a much wider view on climate change and not believe that decreasing greenhouse gas emissions can be singled out and treated as

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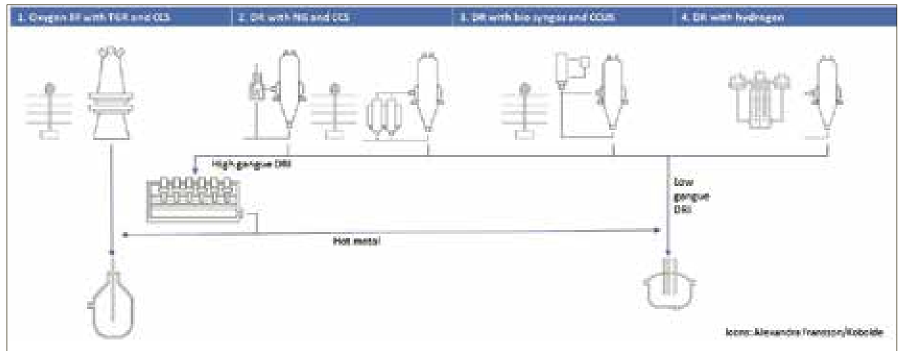


Fig 1. Four processes with relatively high TRL using the reductants coal, natural gas, biomass and hydrogen from electrolysis. The use of fossil reductants requires efficient carbon capture and storage for the process to reach near zero status.

a separate problem embraced by everyone. Furthermore, as a metallurgist, I must accept that the situation only to a minor extent can be solved with new processes, and that we should be open to new supply chains and perhaps investment logic. The overarching challenge is that we will not attract the necessary private funding unless we can manage market uncertainties and make investment offers for low emission steel projects with risks in parity with those for traditional iron and steelmaking.

In 2030 no one will talk about green steel

Today it seems that many, or even most, companies have a plan for how to reduce the carbon footprint of their steel products by a certain amount until 2030 and have an ambition to be near zero by 2050. The first goal can be reached by increasing energy and material efficiency, electrification, using 'green' or 'blue' hydrogen, scrap instead of ore etc. Compared to what afterwards lies ahead, this step is easy, and acquiring some sort of green steel label requires limited effort thanks to the total confusion so generously provided to the market by an abundance of green initiatives. An example is that charging scrap on a blast furnace lowers the carbon footprint for the produced iron but since the amount of available scrap in the world is limited it does not affect global warming. Another problematic feature that we see today is the mass balance method according to which a certain emission reduction can be attributed to a fraction of the steel production that then can be marketed as having a near zero emission, at least for a period of time.

Do not get me wrong, I really think that companies should be rewarded for whatever step they take to decrease emissions and a sales manager that cannot offer 'green steel' today will have to look out for a new job. However, if we are serious about the second step reaching near zero, we must not confuse incremental improvements with decarbonizing the entire production.

Today's many disparate 'green steel' definitions may make the concept lose its meaning and cease to be used and instead the actual carbon footprint for a product will be calculated at production based on LCA standards and declared as one of many properties together with yield strength and hardness in Declarations of Performance, DoPs. Such measures do not create disadvantages for producers who make extensive investments and reach close to zero emissions and may take over.

Competitive low emission iron and steel will become the new normal

Since the reduction of iron ore answers for the biggest part of the CO_2 emissions from the steel industry the focus now is on those processes, albeit not saying that the following steelmaking step does not matter. Just like after the energy crisis in the 1970s, a large number of reduction processes are now proposed and probably like in the 1980s, very few will survive the pilot plant stage. However, those who can use existing infrastructure and engineering resources definitely have an advantage. **Fig 1**

At present, we can see four alternative reductants and process lines for large scale, near zero emission ironmaking as shown in **Fig 1**:

1. In the oxygen blast furnace with top gas recycling, CO_2 with low nitrogen content which is suitable for liquefaction, transport, and storage can be captured. Traditional blast furnaces are erected today in large numbers but may be altered at the end of the campaign life which could be 15-30 years. Lower coke consumption and increased productivity are arguments for using the oxygen variant and modifying existing plants.

2. Direct reduction using natural gas in either MIDREX or Energiron plants is the dominant way to produce Direct Reduced Iron, known as DRI, today. In order to capture 100% of the CO_2 , heating and reforming should probably be done without burning top gas with air which might require some process redesign. As an alternative to natural gas a syngas from coal could be used.

3. Using biomass to produce a syngas for direct reduction offers the possibility to create a carbon sink when the biogenic CO_2 is either stored or used as a raw material for chemicals.

4. Hydrogen produced with electrolysis of water offers a possibility to reduce iron without the use of coal and emission of CO_2.

Availability of low gangue ore for DR-pellets is sometimes said to be an obstacle for the transition to low emission steel. One possibility is to introduce the smelter as an intermediate step to melt DRI to hot metal with low iron losses compared to the electric arc furnaces. The ore quality is probably not a show stopper.

Three factors will decide if these processes will be able to compete with traditionally produced steel and become the new normal for steel by 2050:

I. Availability of technology and management to avoid methane leakage in coal, oil and gas extraction as well as available infrastructure, management and financing of CO_2 storage for alternative 1 and 2.

II. Possibility to obtain economies of scale in engineering, construction and production of iron from iron ore for all alternatives.

III. Availability of private funding based on trust in proven technology and diverse supply chains.

Whereas fossil fuels are in abundant supply, electricity and biomass resources will probably make alternative 3 and 4 niche processes compared to 1 and 2, at least until 2050. If however, processes and reductants are chosen where they have the best possibility to become competitive, there is in my mind no reason not to believe that low emission iron and steel will become the new normal and all processes find locations where they can excel. The key is probably to have an open mind and common business sense when deciding what to do and where.

Decarbonization will be put in perspective

For countries, companies, and individuals, threats like security, political stability, economic growth, climate-change consequences and other issues are more integrated and complex than the eagles, lions, and snakes that the meerkat has to take on. Furthermore, there is another problem with the metaphor. Whereas the available countermeasures to threats used by animals probably have not changed much over the past millenniums, the technical, geoeconomic, and geopolitical landscapes change constantly and with that the available toolboxes for us humans. Adapting to these changes and finding new ways to solve problems may prove to be a painful process. As an example: a natural reaction for countries to threats to the local industry is to provide subsidies for research, development and finally investment covering some of the CAPEX. However, support to invest in plants with an OPEX that cannot compete on an international market over time may make companies end up as loss-centres and major suppliers of used equipment. It happened in Sweden in the 1980s. It can now happen again in many countries.

The next few years will offer new insights. For example, we will have the first full scale hydrogen reduction plant at H_2 Green Steel in operation. That is a brave project and experiences will be really important globally. Other technologies that we can see rising to higher Technical Readiness Level, (TRL), will be the use of biomass as a source for reduction gas and smelters as a means to use high gangue DRI to feed BOF-converters with hot metal. But the real revolution would be the development of technology to avoid methane leakages from oil, gas and coal extraction together with making Carbon Capture and Storage, (CCS), an easy-to-use service to avoid CO_2 emissions and finally to experience a new spring for nuclear energy, fission, and fusion.

Before we have results from all these projects in place, we must rely on rough estimates for OPEX to assess the competitive strength of the different production alternatives, and we will be less able to plan for an optimal use of limited resources like engineering capacity and capital.

And yet, we have to keep looking on the horizon, understanding where we are in the process of technical development, and figuring out how to best abate emissions of climate gases in a grand plan for survival. ■

MOVING TOWARDS CLIMATE NEUTRALITY WITH THE SPEED OF A THREE-TOED SLOTH

Steel Times International, Future Steel Forum 2024

The industry is a part of the civil society and politicians must seek acceptance for spending the tax payer’s money on mega projects. Should we perhaps let one or two companies take the lead provided all can share information instead of all running into the same problems? Are there other ways to decarbonise that consume less of public funding?

Moving towards climate neutrality – with the speed of a three-toed sloth

The European Union and the EU member states are spending immense sums on supporting the transformation of the iron and steel industry to become carbon neutral by 2050. Yet it feels that we are moving too slow, and at the same time voices are heard saying that we move too fast and need money also for other purposes in order to sustain social stability and a functioning democratic system in Europe. Is it time to rethink the decarbonization pathway in the EU? Is it better to now do what we can with existing technology at reasonable costs rather than waiting for the perfect solution?

By **Rutger Gyllenram***

The troubled author Rutger Gyllenram (left) with a WWF three toed sloth (right) and a decarbonization calendar. Photo: Pelle Berglund, Znapshot.

Living in South America, the three-toed sloth is a friendly herbivore that spends most of its life in the trees, trying not to be noticed so as to avoid predators. With a maximum ground speed of 250m per hour when in a hurry, I guess the sloth is not a formidable symbol for speed. Yet it is the animal I have chosen to symbolise the present state of decarbonization in the steel industry in this contemplation starting at the breakfast table just before Easter.

A headline slaps me in the face 'Klimatomställningen riskerar att gå för fort' which is Swedish for 'Actions to reach climate neutrality risk going too fast'. Malte Lohan, the director-general of the European Industry organisation Orgalim is interviewed in the Swedish morning paper Svenska Dagbladet. The essence of the article is that ill-considered decisions create opposition that in the end may make the transformation to a low-emission society come to a halt. "What is the point of trying to show that Europe can become climate neutral if our social democracy breaks down in the process?"

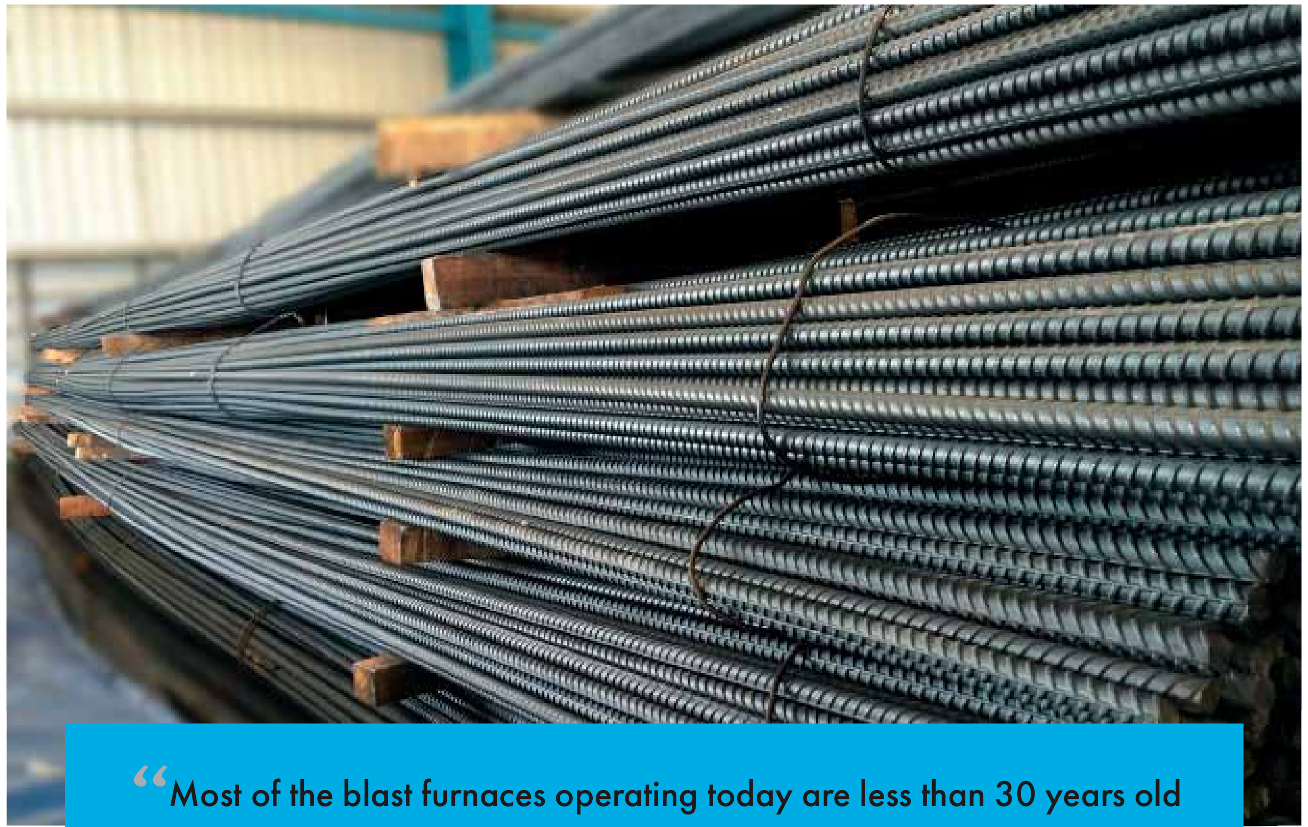
I turn to my flow in Linkedin and read: 'Green steel is possible and even affordable, but still unlikely' in an article by Clyde Russell from Reuters giving an Asian perspective. The message is that a voluntary green steel premium is sustainable only in applications where steel represents a minor part of the product value like, for example, a car. For buildings, the steel intensity is higher, and with that – the price sensitivity. Furthermore, countries where urbanisation and construction of infrastructure consume a large part of the available capital for development are less inclined to pay a premium. The conclusion is that some sorts of carbon taxes are necessary, but may not be applicable everywhere.

I recall my visit to a hydrogen seminar given by VDEh Steel Academy in Dusseldorf early in March. I learned that hydrogen produced at the border with France is 'questionable since the imported electricity comes from nuclear power plants', and that the green steel definition developed by VDEh does not take CCS into account to decrease the reported emissions 'since CCS is not allowed' and that Germany, on the other hand, plans to import blue hydrogen from Norway, which is produced from natural gas using CCS. I admit that I may have misunderstood something in this, in every

> "In my mind it is better to start making improvements in existing technology, although they may not result in total climate neutrality, rather than waiting for the perfect solution that we perhaps cannot sustain."

*Rutger Gyllenram is a Swedish process metallurgist, CEO and founder of Kobolde & Partners AB and co-founder of FerroSilva AB. Kobolde works with raw material and process assessments for the mining, metals and steel industries and is active in ISO and CEN standardisation of carbon accounting and CCS as well as LCA methodology for steel and aluminium. Neither Rutger Gyllenram nor Kobolde & Partners have customers or any other interests in the fossil or nuclear industries.

FUTURE STEEL FORUM 2024



“Most of the blast furnaces operating today are less than 30 years old and will probably be in operation well after 2050”

way excellent, event but it all seemed rather confusing. In Sweden, we are experiencing a growing resistance to closing functioning nuclear power plants and to using available electricity production capacity for ‘state-subsidized DRI production’. As an observer, I wish for more fact-checking and an open minded debate from both sides but can only note the anger and dissatisfaction.

Questions arise: Have decision makers overplayed their hands when it comes to redesigning the society to meet climate goals? Is it now time to reconsider the positions and instead redesign the suggested decarbonization paths? To make a stop to that, they must put three green holy cows on hold: ‘no CCS’, ‘no nuclear power’ and ‘no fossil fuels’ can any longer dictate the agenda. In Voltaire’s words, governments today are letting ‘perfect be the enemy of good’. In my mind it is better to start making improvements in existing technology although they may not result in total climate neutrality rather than waiting for the perfect solution that we perhaps cannot sustain.

It seems that Germany is now looking again at using CCS and Sweden has given up the resistance and started a CCS programme. The last nuclear plant in Germany shut down in 2023 and closed plants can never be restarted. Sweden will hopefully continue operating functioning nuclear plants and the present Swedish government has new installations on the agenda. If and when they will materialise is written in the stars. That leaves us with the resistance to fossil fuels, especially coal, combined with a problematic love for hydrogen.

While most of the many steel decarbonization experts that have entered the world arena in recent years believe that hydrogen reduction will totally dominate the market in 2050, I must report a dissenting opinion. Do not get me wrong. When we have new technology and can produce an abundance of fossil-free energy at low cost, we have every possibility to use electricity in different ways to produce iron including reduction with hydrogen from electrolysers. Until then we have to stick with the world we have. When I evaluate the financial conditions for some of the existing fantastic decarbonization projects I think of the famous words of French general Pierre Bosquet when he was in Crimea in 1854 and saw the British light brigade being obliterated, fearlessly attacking a well-fortified Russian army: “C’est magnifique, mais ce n’est pas la guerre”, meaning “It is magnificent, but it is not war”. We are in my opinion using brilliant engineers and good money to build plants that will probably never be able to run without state subsidies and that may have to close in a few years. And full heartedly betting on a process that still does not exist, i.e. DR with 100% H_2 in other than pilot plants without published test results, does not seem like the normal way to invest having made a proper risk analysis.

Rejecting the use of fossil reductants and only accepting their use as some sort of transition towards the fossil free society leads as I see it to higher emissions. Let me take three examples for the sake of discussion with the caveat that they may contain misunderstandings on my side of what some companies are planning or doing:

1. Having the opinion that coal mines should close as soon as possible leads to less investments in, for example, the abatement of methane emissions. In the long term, coal mining might move to places with less capability or ambition to abate these emissions.

2. Believing that blast furnaces will be phased out as soon as enough cheap hydrogen is available leads to less investments in abating the emissions in the blast furnaces in a transition period that could well span the rest of this century.

3. Claiming that DR processes are hydrogen-ready and using natural gas ‘only’ while waiting for affordable green hydrogen may lead to CCS not being applied, although the waiting time may be long.

Most of the blast furnaces operating today are less than 30 years old and will probably be in operation well after 2050. Furthermore, new plants are erected on an almost yearly basis. The idea of closing them in the next decades and have them replaced by DR plants operating with hydrogen as reductant raises some serious issues regarding resource availability and I refrain from developing that case further except for one question. With today’s political climate, we have every reason to question the willingness of the voters in western democracies to pick up the bill for the global transition.

If we accept that we probably will have to use fossil reductants for the decades to come there is a lot to do in order to reduce emissions:

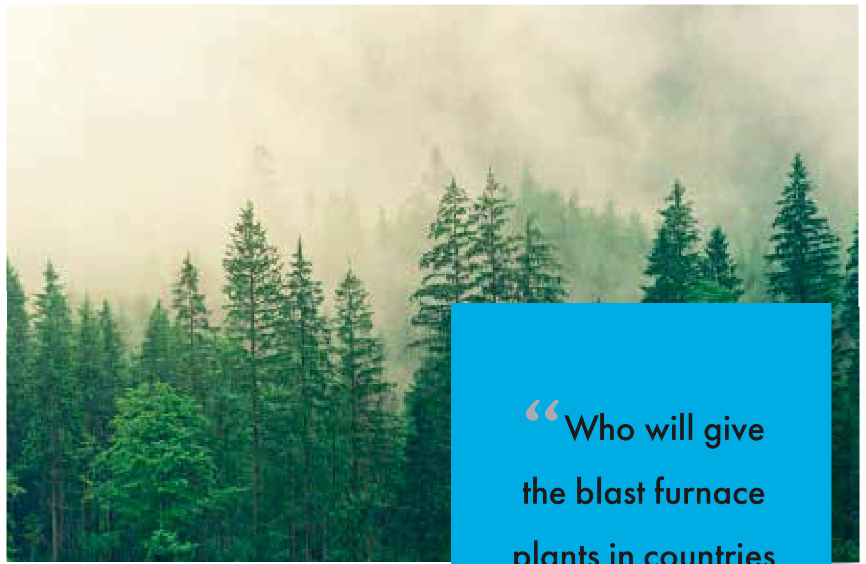
I. Securing safe coal mining with low methane emissions should be the first step together with avoiding leakages of natural gas.

II. The low hanging fruit is probably to improve the overall energy efficiency like blast production and improve the use of waste heat, but the main reduction comes from reducing the coke rate. We need just under 300 kg of coke per ton hot metal to secure the permeability in the furnace which means we can reduce and replace a little over 200kg and there are several ways to do that. Biomass, hydrogen, and oxygen enrichment are some examples. There are several projects doing this at the moment, most of them outside Europe.

III. Charging low emission DRI is a way to decrease the part of the coke used for reduction of ore. Normal DRI reduced with natural gas would create a small reduction and using low fossil DRI produced with natural gas and CCS would be better but the reduction would still be in the limit of the 200 kg mentioned in bullet II.

IV. Finally, CCS could be the natural goal for blast furnace plants. In the European Union, project ULCOS was developed with the best possible metallurgical expertise. After proving the concept in the pilot blast furnace in Luleå, nothing really happened. If Europe wants to lead decarbonization, the best contribution to the global endeavour would probably be to pick up where we stopped and make the oxygen blast furnace with top gas recycling and CCS the new normal, and the cheapest way to produce iron.

When writing this, I saw a presentation on my Linkedin feed from the advanced Korean steelmaker POSCO outlining its decarbonization pathway. The last slide is about the final step, which is DRI production with hydrogen. It has the text: ‘Intensive Government Support Needed’ and the last slide reads: “POSCO will do the best to realize ‘2050 Carbon Neutrality’”. South Korea is rich. Who will give the blast furnace plants in countries with a smaller GDP *per capita* some ‘intensive support’?



“Who will give the blast furnace plants in countries with a smaller GDP per capita some “intensive support”?”

In the low emission metallurgical landscape of tomorrow, many different reduction processes and raw materials will compete: coal with CCS, natural gas with CCS, syngas from biomass with biogenic CCU, hydrogen from electricity and in the end, perhaps even electrolysis. To reach a desirable end we need time and resources guided by solid knowledge and realism, not wishful thinking.

Come to think of it, the sloth-strategy of survival is ‘not to be noticed’. A lot that does not make it to the headlines is actually occurring in the industry following ordinary business logic and resulting in inventions giving lower GHG emissions. That gives some hope. The rest is hard work!

25 years to 2050 – and counting. ■

To walk the talk:
the FerroSilva project

FERROSILVA – COMBINING IRON PRODUCTION WITH A CARBON SINK

Steel Times international, June 2023

FerroSilva started as a project originating from the "Department of Processes at the Institute of Materials Science", at the KTH Royal Institute of Technology in Stockholm. In the spring of 2020, Peter Samuelsson and I won the KTH Innovation Prize with FerroSilva as the best proposal for reducing greenhouse gas emissions and in the spring of 2021, the Swedish Energy Agency decided to co-finance a feasibility study that was completed in the autumn of 2022.

Photo: KTH Innovation

In June 2023 we thought we had enough material to publish popular articles in Steel Times International and Green Steel World. We have been critical of the information from publicly funded projects being so limited so we decided to be quite open and publish our findings as peer-reviewed research articles that can be found on **www.ferrosilva.com.** In this article, Peter and I are accompanied by Göran Nyström who joined the team in an early stage.

The project is now undergoing the necessary initial phases and we see the number of FerroSilva-colleagues increase every day. Our aim is to have the first FerroSilva plant commissioned in 2027-28.

The management team at the Hofors site.
From left: Peter Samuelsson (management and process development), Göran Nyström (market and finance), Rutger Gyllenram (raw materials and logistics)
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FerroSilva – combining iron production with a carbon sink

With an expanding economy, demand for steel is increasing – making the optimal use of resources a priority. FerroSilva, a project involving multiple steelmakers, suppliers, and academics, offers the novel use of biogenic material as a reducing agent in DRI production – with plans to build its first plant and commence operations by 2026. By **Rutger Gyllenram*, Peter Samuelsson**** and **Göran Nyström*****

IT is not difficult to produce iron from iron ore; we have done that for a couple of thousand years. Fossil free iron production was the dominant way until the coking process was invented at the end of the eighteenth century, and charcoal blast furnaces are still used in some countries. However, high-volume, low-cost production demanded the unmatched energy efficiency of the blast furnace process and the smooth logistics of fossil coal – so the blast furnace/ basic oxygen furnace is the dominant process route for steel from iron ore. This position is now challenged by the need to decrease global emissions of carbon dioxide in order to avoid a climate catastrophe.

The transition to fossil free iron is a challenge

It is human to hope for a new metallurgical process that will solve all our problems immediately. However, abating emissions of climate gases is an issue not only for the steel industry but for all people, and replacing coal will make almost all other

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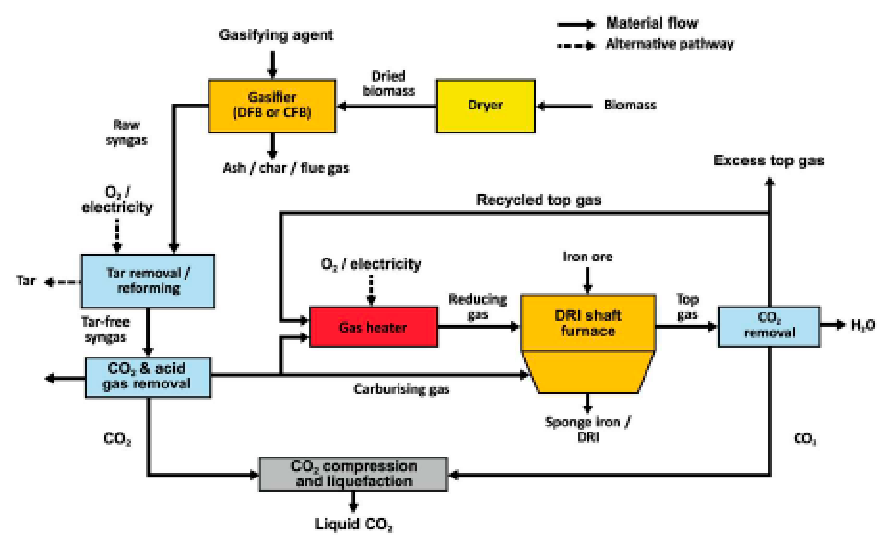


Fig 1. Simplified layout of the FerroSilva process. [Ilman Zaini et al 2023] link: https://doi.org/10.1016/j.

resources scarce for the decades to come, and process development will to a large extent depend on optimal use of limited resources. The transition to fossil-free steel will affect every aspect of steelmaking. Blast furnaces that are modified and combined with CCUS, will probably keep their position in order to make use of high gangue ores. Direct reduction from reformed natural gas combined with CCUS and followed by melting in electric arc furnaces using renewable electricity is one alternative and finally, making the reduction with hydrogen made from fossil-free electricity is another. They will all have their place in due time when technology reaches a high readiness level and new trade patterns are stabilised.

Biogenic material as a source of reducing agent

From both an economical and an ecological perspective, the optimal route would be to benefit from resources that are not used to their full potential today. Such resources include sawmill waste and forest residue, i.e., tops and branches. The latter is often not harvested but left to rot. Other biogenic resources can be found in the vast and diversified agricultural sector. The drawback of biogenic material is that it is voluminous, it often must be collected from large areas, and the available volumes are limited. There is however more biogenic raw material available than is normally recognised and logistic systems are being developed that can manage the material. The price is normally determined by the value of generated district heating and electricity which limits acceptable costs for transport and building up logistic systems. If, on the other hand, the product is a reducing gas that can replace natural gas or hydrogen, the value is higher and can cover more extensive harvesting and transport, which increases availability. The final advantage is that biomass generates biogenic carbon dioxide that does not require allowances and when stored, or used in products, creates a carbon sink.

Closing blast furnaces creates demand for DRI

When the number of electric arc furnaces increases and the number of blast furnaces decreases there is a risk of a shortage of high-grade scrap with low amounts of tramp elements. This was the major concern that made three Swedish steel companies, Ovako, Alleima and Uddeholm, team up with two providers of wood chips and saw dust pellets, Sveaskog and Lantmännen. Together with KTH Royal Institute of Technology and Chalmers University of Technology, M3Advice and Kobolde & Partners, and with additional financing from the Swedish Energy Agency, the consortium performed a feasibility study finalised in September 2022. This has now resulted in plans to build a first FerroSilva plant of 50kt of DRI at the Ovako Hofors plant with the intention to start production in 2026.

The FerroSilva process

The process is based on three technology building blocks, all of them in operation at full scale, but can be found across three separate industrial segments.

Gasification in a fluidised bed is nothing new and can be found at some companies in the pulp and paper industries. Often the aim is to produce heat or electricity. In this case the product is a biogenic syngas with a composition close to what is achieved when reforming natural gas. Today, there are the following designs available with a high technical readiness level; TRL, Dual Fluidised Bed (DFB), and Circulating Fluidised Bed (CFB), all with slightly different performances. The biomass is dried before it is entered into the gasifier where a raw syngas is produced as is shown in **Fig 1**. The tar is then removed and after that, carbon dioxide and acid gases. The carbon dioxide removal process is commonly used in refineries and petrochemical plants. The resulting gas is then either heated and injected as reduction gas into a DR-shaft

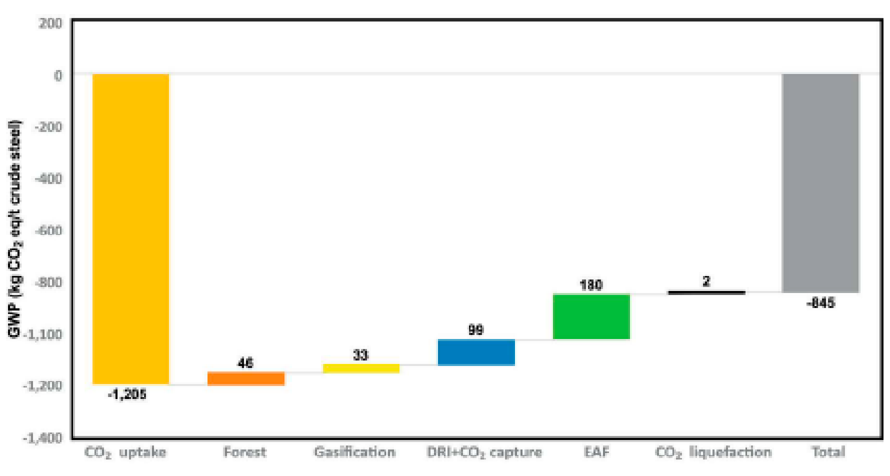


Fig 2. The global warming potential, GWP, from the life cycle assessment .
[Anissa Nurdiawati et al 2023] https://doi.org/10.1016/j.jclepro.2023.136262

of the same type as is used for reformed natural gas, or injected cold in the bottom as cooling carburising gas. Carbon dioxide and water is removed from the top gas and hydrogen and carbon monoxide is recycled as reduction gas. The high-grade iron ore pellets that are charged at the top of the furnace leave the shaft as DRI. The shaft furnace is like the ones already applied today in the natural gas processes. Finally, the captured biogenic carbon dioxide is compressed, liquified and transported to a partner for further processing. (**Fig 1**)

The key to efficiency is to use energy streams in the process. Approximately 1.4 tons or 3.7 m^3 biomass is used, equal to 3500kWh. Electricity use is 300kWh and biogenic carbon dioxide generation is approximately 1 ton per ton of DRI.

Life cycle assessment for steel using FerroSilva DRI

The three major environmental impacts that must be observed in the FerroSilva process form the Global Warming Potential (GWP) which in large part is about uptake and emissions of carbon dioxide and other climate gases, the soil carbon, and the biodiversity. For a company like FerroSilva, all these three are of great importance and demand close co-operation in the supply chain.

Working with certified forestry companies and following up on research and compliance with standards is part of the core business.

For carbon dioxide, the follow-up must include how the captured liquid gas is transported and processed to new materials or fuel. **Fig 2** shows the GWP, i.e., the carbon dioxide equivalents balance, for one ton of crude steel made in an electric arc furnace from FerroSilva DRI. As can be seen, the steelmaking and carbon dioxide liquefaction emits 360kg direct and indirect emissions (scope 1-3).

This leaves a carbon sink of 845kg if this carbon dioxide is brought out of the circuit or used to replace fossil carbon in any way.

Cost of the reducing agent

It is always tricky to compare production costs from processes that do not yet exist. Reduction with natural gas and 100% CCS of the generated CO_2, full-scale reduction with hydrogen or using biogenic syngas and CCU are here compared using published consumption figures and investment costs based on a reference case and estimated differences between the different technologies. As can be seen in **Fig 3** the price of the reduction agent has a huge impact on the production cost. The price in euros for natural gas and biomass per MWh is shown on the x-axis, and production costs in EUR/ton DRI on the y-axis. The thickness of the lines shows the difference in cost between in a price range for electricity between 32 and 65 EUR/MWh.

The calculations are made with varying energy prices, iron ore costs, and transportation. This means that distance to the mine or the market may change the differences in production cost between technologies. For FerroSilva, the calculation indicates that it is competitive at a medium natural gas price.

Building a first plant

The first FerroSilva plant is planned to be located within the production site of Ovako in Hofors. There are excellent rail and road connections and much of the needed utilities infrastructure are available in proximity to the FerroSilva plant, including the residential district heating, where residual energies from the

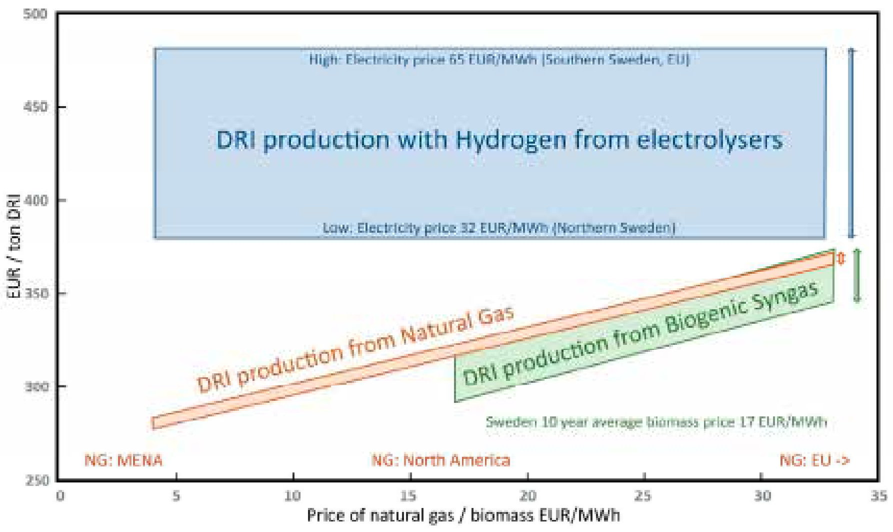
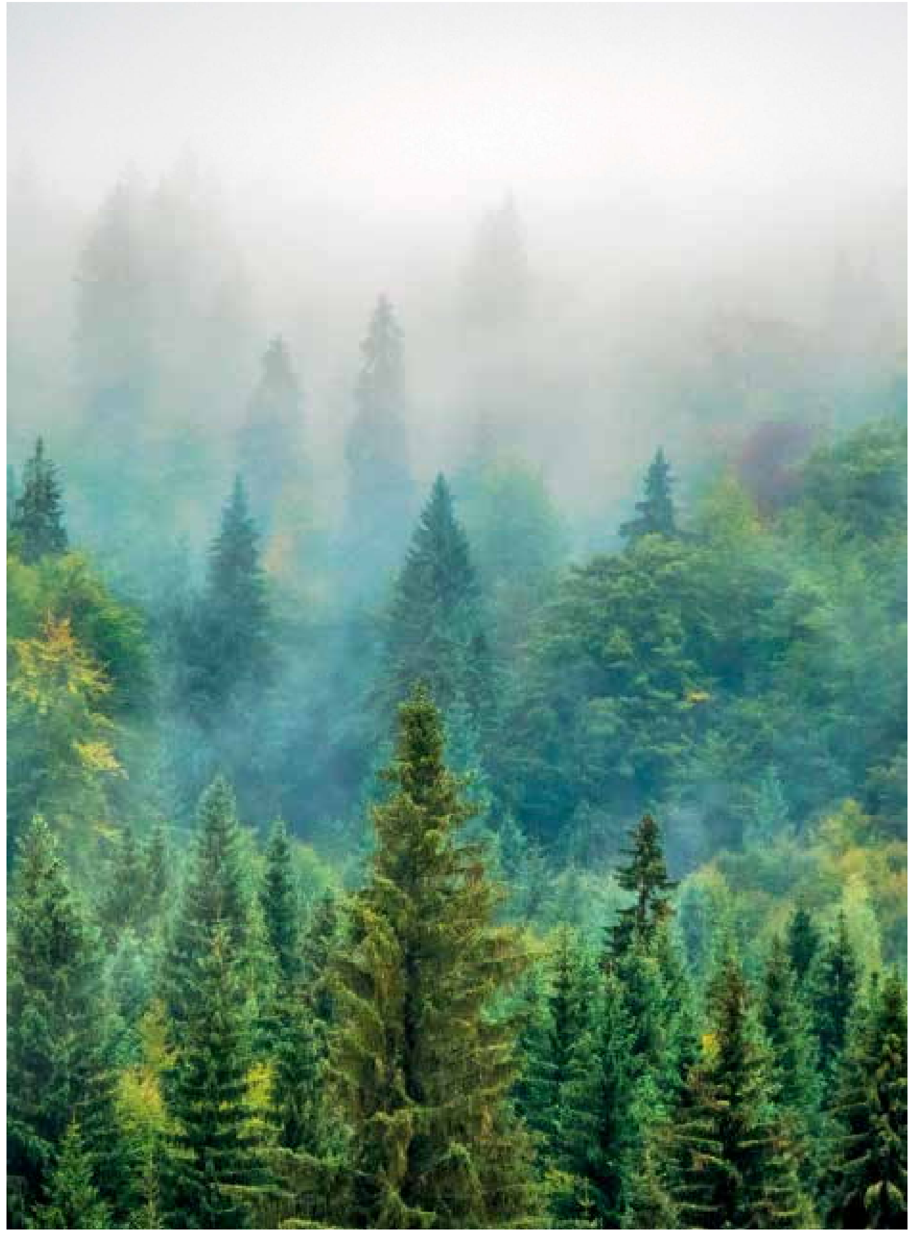


Fig 3. A comparison of production costs for DRI using natural gas + CCS, biogenic syngas + CCS and hydrogen. [FerroSilva feasibility study]



DRI production can be put to good use. Furthermore, the process for securing environmental permits will be substantially simplified, being within Ovako's industrial area rather than at a greenfield site.

The melt shop where the produced DRI will be used in steelmaking operations is located some 200 metres away from the FerroSilva plant. Liquid carbon dioxide will be shipped via rail to other users, such as the production of bio-methanol, that can be used for the production of aviation fuel, but also for further synthesis into products that today are reliant on fossil raw material; such as plastics, pharmaceuticals etc.

The way forward

With an expanding global economy, demand for steel is increasing and using our resources in an optimal way is necessary. A sustainable use of biogenic material with the FerroSilva process will no doubt play an important role in countries with a well-managed sustainable forest industry. The same is also valid for countries with a significant agricultural industry, where substantial quantities of residues are available. Contrary to the popular view, suitable bio resources, and thus residues, are available in many parts of the world and are not limited to the boreal and northern temperate forest ecosystems. After setting up the initial plant, the plan is to construct and commission an even larger scale plant and to further expand the geographical footprint of the FerroSilva technology.

For further information, log on to **www.ferrosilva.com,** or email **info@ferrosilva.com**

Fig 4. The FerroSilva plant in its suggested location at the Ovako Hofors site. [Design: Katarina Hamilton]

FERROSILVA – CREATING A NEW INDUSTRIAL ECO-SYSTEM

Green Steel World, June 2023

Photo: private

A concept like FerroSilva, starting with forest residue and ending with DRI, ship fuel and other products constitutes a new type of industrial eco-system. There is a lot to learn and we needed a lot of help as can be understood from this article. Karin Reuterskiöld and Dr Elham Yazdkhasti helped us navigate together with a number of other persons. It was amazing to see how generously people contributed with their time and competence once they realised the potential in the FerroSilva idea.

We asked artist and designer Katarina Hamilton to visualise a FerroSilva facility. It started with an idea phase where the terrain levels were created with coasters and booklets, conveyors with straws, buildings with matchboxes, a candlestick and tealights and finally plastic clips to represent trains. The result can be seen in the articles.

An image of the first FerroSilva plant. Building in a brownfield location has advantages with existing infra structure and services like in Hofors where the closeness to the customer that can take warm DRI directly from the reduction plant is an extra advantage. Layout: Katarina Hamilton.

FerroSilva - Creating a new industrial eco-system

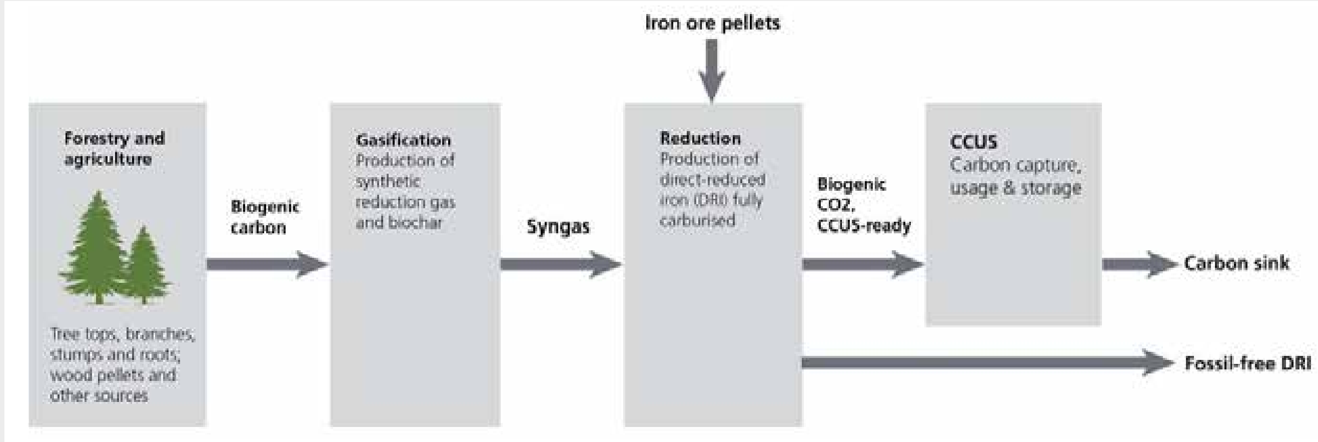
A new industrial ecosystem is emerging in the Swedish Bergslagen. Residual products from forestry and agriculture become syngas, which is used to reduce iron ore. The carbon dioxide is captured and becomes products or is stored in the bedrock. But this requires new types of industrial collaboration and well-developed logistics. FerroSilva is now planning its first plant of 50 thousand tonnes per year at the steelmaker Ovako's plant in Hofors.

By Rutger Gyllenram, Peter Samuelsson and Göran Nyström

Going for fossil free iron

The demand for steel with low emissions of greenhouse gases make many steel producers close their blast furnaces and replace them with electric arc furnaces that outside natural gas-rich countries are normally used for scrap. Since the amount of scrap is limited, this transformation must be combined with an increased production of sponge iron, so-called DRI. Today, DRI is mainly manufactured with reformed natural gas as a reducing agent, and by capturing and using or storing the carbon dioxide formed, so-called CCUS, the process can reach low greenhouse gas emission values. Reformed natural gas has a composition of approximately one-third carbon monoxide and two-thirds hydrogen. The DRI produced this way normally has a metallization degree of about 92% and a carbon content of about 2%. The carbon's main role in the DRI is to reduce the last portion of iron oxide to iron in the smelting step. DRI can be used together with scrap and has the advantage that it does not contain tramp elements such as copper.

An alternative to reformed natural gas is to use pure hydrogen as a reducing agent, which gives a DRI without carbon. A number of projects are underway in this area but very little has yet been published in terms of operating results. It is clear, however, that access to large amounts of electricity with low emissions and a well-developed electrolyser technology are requirements.



The FerroSilva business model. Residues from forestry and agriculture are gasified to form a syngas used for reduction of iron ore to fully carburized DRI. Biogenic carbon dioxide is captured and further processed to either chemicals or fuels unless it is stored in suitable geologic formations.

Possible scrap shortage?

The fact that some blast furnaces have already been scheduled to close down, completely new electric arc furnace plants are planned and that expansion of electricity production and technical development of hydrogen processes can take time creates a concern among today's scrap-based plants that the availability of high-quality scrap will become a limiting factor. This possible shortage is the driving force for three special steel companies, Ovako, Alleima and Uddeholm, to team up with the forestry company Sveaskog and the agricultural company Lantmännen, KTH Royal Institute of Technology, Chalmers University of Technology as well as M3Advice and Kobolde & Partners to form the FerroSilva project. With the goal to investigate the conditions for reducing iron ore with gasified biomass and with part of the funding from the Swedish Energy Agency, a feasibility study was carried out during 2021-2022 with very promising results.

The FerroSilva supply chain

The basic idea can be seen in the figure above, where residual products from forestry and agriculture are collected and gasified into a syngas with the same composition as reformed natural gas. This is then used as reduction gas in a shaft furnace which produces a DRI with the same properties as in production with natural gas. Around 1 ton of carbon dioxide is formed per ton of DRI and this is collected for further transport to a facility that can further process it into methanol to be used as a starting point for other chemical products or as fuel.

The FerroSilva startup team from left Dr Peter Samuelsson, Göran Nyström and Rutger Gyllenram. Peter is driving the work to build FerroSilva's first factory in Hofors, Rutger focuses on issues related to production, raw materials, logistics, environment and research and finally Göran drives marketing and investment matters.

FerroSilva energy use is 300 kWh electricity and 3500 kWh biomass equal to about 1.4 tonnes or 3.7 m3 with a biomass density of 380 kg/m3.

Starting with 50-thousand tonnes DRI per year

The first FerroSilva plant will have a capacity of 50 thousand tonnes of DRI per year and will be located inside Ovako's industrial area at the place where the old blast furnace stood many decades ago. Building on a brown-field site has great advantages as the land is prepared, almost all infrastructure and services are in place and the customer for the produced DRI is only about 100 m away.

The ambitious plan is to start production in the second half of 2026 ramping up to a productivity of 50 thousand tonnes of DRI per year in 2027. The process concept has the advantage of utilizing existing mature technology put together in a new way. Despite a rather small plant size the production is sufficient to provide the copper free raw material necessary to meet the high quality demands on Ovako steel. A preliminary design of the plant is shown in the initial figure. Biomass and pellets are delivered by rail from the raw material suppliers to material bins on the left in the picture and then further transported with conveyor belts to the gasification plant and DR shaft. The product is taken directly by electric truck to the steel mill. The liquid carbon dioxide is planned to be temporarily stored in tanks before being loaded into railway cars for transport to a nearby plant for methanol production or, in case of surplus carbon dioxide, stored in the bedrock.

Building a Bio-DRI Eco-system for the future

Using biomass to generate a reduction gas means that it becomes profitable to use a significantly larger part of the residual material that arises from forestry and agriculture. Unlike the production of district heating, FerroSilva demands a steady stream

In addition to the technical team, FerroSilva is supported by Karin Reuterskiöld, left, from Forever Sustainable in questions regarding sustainable finance and Dr. Elham Yazdkhasti, right, from the Swedish University of Agricultural Sciences/Kobolde who is coordinating FerroSilva's efforts in what we call bio-sustainability.

of biomass throughout the year. Collection of forest by-products for 50 thousand tonnes of DRI uses 0.3% of the residual products that are not collected today and if all of Sweden's iron reduction of 3 million tonnes took place with gasified forest by-products, only 19% of the unused amount of biomass would be consumed. Even if the material is there, the utilization places great demands on the logistics and on the collection taking place in a way that does not damage biological diversity and depletion of soil-bound carbon. How to utilize ash from the FerroSilva plant will be considered.

Likewise, a network of partners to take care of carbon dioxide for usage and storage must be developed. It is still early days in this management but to make methanol from carbon dioxide, large quantities of hydrogen are required, and according to the present plans this will be produced in a brownfield site not far from Hofors in order to produce e-fuels from the FerroSilva biogenic carbon dioxide. But as they say "early days". The FerroSilva team, presented in the figures above, is however now experiencing an intensive period to say the least.

Going for 500 thousand tonnes of DRI

The natural gas-based direct reduction plants being built today normally have a capacity over 2 million tonnes of DRI/year. It took almost 60 years to go from the first facilities of 50-100 thousand tonnes to today's sizes. For hydrogen, there is talk of building facilities of 1-2 million tonnes of DRI after initial pilot trials. In that comparison, 50 thousand tonnes seem extremely limited, but considering that a complete logistic system from the forest to the methanol factory is to be built up, the size feels manageable. Once the new industrial eco-system has been established, a next step of 500 thousand tonnes is planned.

Meeting the goals of the Paris agreement

If the biogenic carbon dioxide captured in the FerroSilva process is used for products or to replace fossil fuels, a so-called carbon dioxide sink is created. These reductions are necessary for us to have a chance of meeting the requirements of the Paris Agreement. It is clear that we have underestimated the amount of forest and agricultural by-products available as the supply is a function of the price to cover the collection. It is therefore the hope of the FerroSilva team that the technology can be used in all countries with certified forestry and agriculture and become an important factor in meeting the climate goals for 2030 and 2050. The important thing is to remember that it is not about a process solution, but about the building of a completely new industrial ecosystem that requires cooperation between different industries and financial actors and with governments raking the arena.

Some peer reviewed and conference papers covering the DR-EAF line and topics in the FerroSilva project which all can be found on the FerroSilva and Kobolde webbsites:

1. Gyllenram, R.; Ekerot, S.; Jönsson, P.: Lubricating the recycling Machine, Revue de Métallurgie 109, 349–358 (2012) DOI: https://doi.org/10.1051/metal/2012017

2. Gyllenram, R.; Sikström, P.; Hahne, R.; Tottie, M.: Classification of DRI/HBI based on the performance in the EAF. A help for steelmaker's procurement of metallics. Proceedings / METEC & 2nd ESTAD 2015, European Steel Technology and Application Days : Düsseldorf, Germany, CCD Congress Center Düsseldorf, 15 - 19 June 2015

3. Arzpeyma, N.; Gyllenram, R.; Jönsson, P. G.: Development of a Mass and Energy Balance Model and its Application for HBI Charged EAFs, Metals 2020, 10, 311; doi:10.3390/met10030311

4. Arzpeyma, N.; Alam, M.; Gyllenram, R.; Jönsson, P.G. Model Development to Study Uncertainties in Electric Arc Furnace Plants to Improve Their Economic and Environmental Performance. Metals 2021, 11, 892. https://doi.org/10.3390/met11060892

5. Gyllenram, R.; Arzpeyma, N.; Wei, W.; Jönsson, P. G.: Driving investments in ore beneficiation and scrap upgrading to meet an increased demand from the direct reduction-EAF route, Mineral Economics 2022-06, https://doi.org/10.1007/s13563-021-00267-2

6. José Juan Bolívar Caballero, Ilman Nuran Zaini, Weihong Yang: Reforming processes for syngas production: A mini-review on the current status, challenges, and prospects for biomass conversion to fuels, Applications in Energy and Combustion Science 10 (2022), https://doi.org/10.1016/j.jaecs.2022.100064

7. Anissa Nurdiawati, Ilman Nuran Zaini, Wenjing Wei, Rutger Gyllenram, Weihong Yang, Peter Samuelsson: Towards fossil-free steel: Life cycle assessment of biosyngas-based direct reduced iron (DRI) production process, Journal of Cleaner Production 2023-03, https://doi.org/10.1016/j.jclepro.2023.136262

8. Ilman Nuran Zaini, Anissa Nurdiawati, Joel Gustavsson, Wenjing Wei, Henrik Thunman, Rutger Gyllenram, Peter Samuelsson, Weihong Yang: Decarbonising the iron and steel industries: Production of carbon-negative direct reduced iron by using biosyngas, Energy Conversion and Management, 2023-04, https://doi.org/10.1016/j.enconman.2023.116806

Rutger Gyllenram.
Photo by Pelle Berglund,
Znapshot.

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