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An Economic Evaluation of the Technologies to Power a Hydrogen Steel Production Process Under a CO_2 Emission Limit

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ABSTRACT

Decarbonising the steel industry is among the ultimate climate challenges.

This study analyzes how the cost optimal mix of technologies to meet the demand of a green-steel manufacturing process using direct reduction with hydrogen and electric arc furnace (HDR-EAF) changes under progressively lower CO_2 emission limits.

The modellization was done thanks to the PyPSA framework and includes renewable generators, different hydrogen production techniques and burners technologies, as well as a carbon capture system.

It is shown that a big reduction in CO_2 emission is possible with a little increase in CO_2 price and a totally green production of steel can be achieved.

Keywords: green steel, direct hydrogen reduction, renewable energy resources

NONMENCLATURE

Abbreviations	
BF-BOF	Blast furnace – basic oxygen furnace
HDR	Hydrogen Direct reduction
EAF	Electric arc furnace
CC	Direct Carbon capture
SMR	Steam methane reforming
VPSA	Vacuum pressure swing absorption
PyPSA	Python for Power System Analysis
tls	Ton of liquid steel

1. INTRODUCTION

To meet the 2050 goal of zero net emissions set in the Paris agreements and to keep the increase in global temperature below 1,5°C compared to pre-industrial levels, CO_2 emissions must be drastically reduced. The industry sector is the biggest contributor, consuming a third of primary energy and emitting a quarter of energy-related greenhouse gas. In particular, the iron-steel production process is one of the most CO_2 intensive, responsible for 9% of global greenhouse gas emissions [1, 2].

The steel industry is one of the most important industries today. Steel is widely used, from buildings to transport and shipping. The total amount of steel produced in 2021 reached 1.95 billion tons [3] and is set to continue to increase by 2050.

However, the steel industry is an energy-intensive, high-volume kind of industry that relies mainly on coal. Today 70% of steel is produced through CO_2 intensive processes like the blast furnace route (BF-BOF) [4], technology. This process uses mainly coal to generate the 18 GJ/tls and causes emissions of approximately 1870 $kgCO_2$/tls [1].

Companies around the world started to develop low-carbon steel-making routes like direct reduction of iron ore (DR) where a gaseous reducing agent such as natural gas or a mix of natural gas and hydrogen is used. This process could become green with the implementation of carbon capture and storage but there is also the possibility of replacing natural gas with a 100% hydrogen stream, leading to a reduction in emission of 91% [5]. The use of hydrogen would also increase flexibility of the electrical grid and would help develop the hydrogen infrastructure also for other type of industries [6].

For the aforementioned reasons the current work focuses on a green-steel production. The steel plant is composed by a fluidized bed for the direct reduction of iron ore with hydrogen and an electric arc furnace for the smelting of the sponge iron. The steel plant can be powered by carbon-intensive and renewable technologies. The aim of this analysis is to find the CO_2 price at which the different configuration of the plant become economically viable under different CO_2 constraints.

2. METHODOLOGY

The goal of this analysis is to find the cost-optimal setup of the steel plant studied in this work. The corresponding optimization problem reads [7]:

$$\min_{g,\bar{g},f,\bar{f}} \left(\sum_{n,s} C_{n,s} \cdot \bar{g}_{n,s} + \sum_{l} C_l \cdot \bar{f}_l + \sum_{n,s,t} O_s \cdot g_{n,s,t} \right) \quad (1)$$

$$s.t. \sum_{s} g_{n,s,t} - d_{n,t} = \sum_{l} K_{n,l} \cdot f_l \quad (2)$$

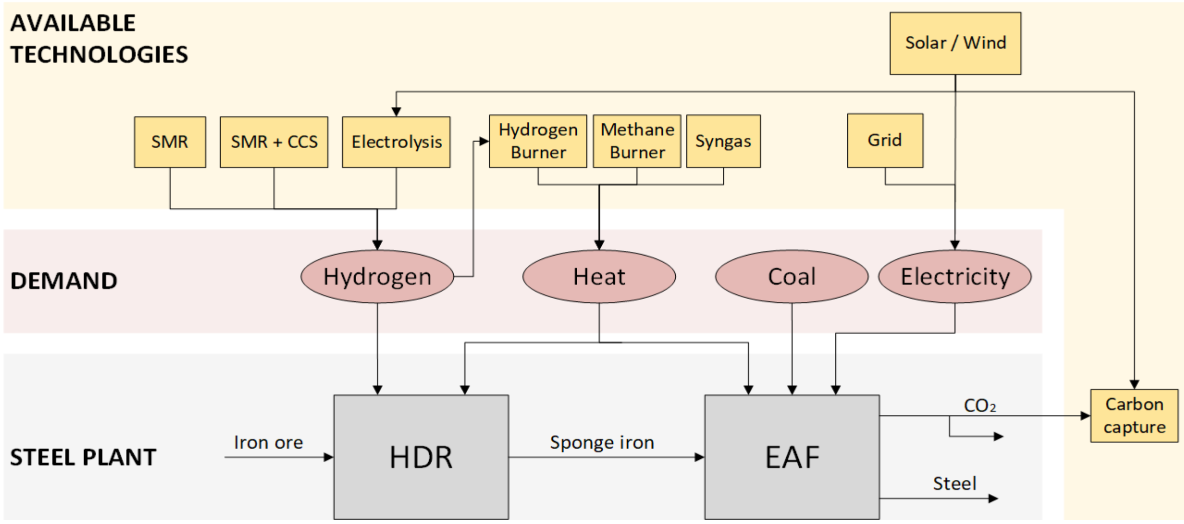

Fig. 1 Steel plant scheme and available technologies

$$G^{-}_{n,s,t} \cdot \bar{g}_{n,s} \leq g_{n,s,t} \leq G^{+}_{n,s,t} \cdot \bar{g}_{n,s} \qquad \forall\, n,t \tag{3}$$

$$soc_{n,s,t} = \left(1-\eta^{l}_{n,s}\right) \cdot soc_{n,s,t-1} + \eta^{u}_{n,s} uptake_{n,s,t} \qquad \forall\, n,t,s>1 \tag{4}$$

$$0 \leq soc_{n,s,t} \leq \tau_{n,s} \cdot \bar{g}_{n,s} \tag{5}$$

$$|f_l(t)| \leq \bar{f}_l \qquad \forall\, l \tag{6}$$

$$\sum_{n,s,t} \frac{1}{\eta_{n,s}} \cdot g_{n,s,t} \cdot e_{n,s} \leq CAP_{CO_2} \tag{7}$$

$$\bar{g}_{n,s,t}, g_{n,s}, \bar{f}_l, soc_{n,s,t} \geq 0 \tag{8}$$

Constraint (2) ensures that the demand is met at all times. Constraints (3) - (6) define the bounds for dispatch of generators (wind, PV, electrical grid), storage (gas, H_2, CO_2, battery, synthetic gas) and links. The potential generation $\bar{g}_{n,s}(t)$ describes the resource availability in case of fluctuating renewable generation facilities. Constraints (4) ensures the consistency of the state of charge, where in Equation (4), $uptake_{n,s,t}$ refers to the net energy uptake of the storage unit given by

$$uptake_{n,s,t} = \eta_1 \cdot g_{n,s,t,store} - \eta_2^{-1} g_{n,s,t,dispatch}$$

Upper bounds for CO_2 emissions are defined in Equation (7).

The steel plant equipment is composed by a fluidized bed that requires thermal energy for pre-heating the ores to 800-900°C and hydrogen as an agent for the reduction, and by an EAF where the sponge iron is sent, that requires electrical energy for creating the arc but also thermal energy for starting the process and coal as a carbon additive. To mimic the plant, four demands are considered (electrical, thermal, hydrogen and coal) according to [6]. Each demand can be met by different types of technologies (*Fig. 1*).

For the electric load there is the possibility of a connection to the national electric grid or to build solar panels and wind turbines capacity. The cost of electricity from the national grid and the availability of solar irradiation and wind speed are real time series for different locations in Germany with hourly resolution [8].

Regarding the thermal load, combustion of methane, hydrogen or syngas is possible. Methane is burnt through traditional gas burners; the syngas is produced from H_2 and CO_2 thanks to a Fischer-Tropsch process and burnt with the same burners as methane. For the combustion of hydrogen, the traditional gas burners need to be retrofitted [9].

Hydrogen production is possible through steam methane reforming, steam methane reforming with carbon capture and storage of CO_2 or green electrolysis. SMR is the most common technology for industrial hydrogen production, using an endothermic reaction of methane and water; electrolysis is powered by renewable sources, namely the electricity produced with solar and wind capacity.

The coal demand is needed to secure a carbon supply to the melted iron, and it cannot be substitute with greener alternatives.

A carbon capture technology of vacuum pressure swing absorption, already proven to work in a real steel plant, can also be implemented in order to reduce unavoidable emissions [10, 11].

For each element efficiency, capital and marginal cost and CO_2 emission factors are considered. The data

Technology	Capital Cost [€/MW]	Marginal Cost [€/MWh]	CO_2 emission factor [ton/MWh]	Efficiency [-]	Lifetime [year]
Wind generator	47152	1.35	-	-	30
Solar generator	21898	0.01	-	-	40
Grid	-	Time series	0.36	-	-
Electrolyzer	24000	24	-	0.68	30
SMR	41122	20.1	0.33	0.76	30
SMR+CCS	47702	20.1	0.29	0.69	30
Syngas production	112000	-	-	-	25
Methane burner	-	20.1	0.20	0.95	-
H_2 burner	2008	-	-	0.95	25
VPSA	-	439 *	-	8.78 *	-
H_2 store	52	-	-	-	20
CO_2 store	126	-	-	-	25
Battery	5680	-	-	-	25
Syngas store	1000	-	-	-	100
Coal	-	-	0.34	-	-

Table 1: Cost and technological assumptions (Data for VPSA is in €/ton and ton/MWh)

were taken from [12] when available. Additional data was taken from [13, 14, 15, 16]. Cost and technological assumptions are given in Table 1. Capital costs are annualized.

The model is studied under different CO_2 emission limits, from no limits (i.e. 721000 ton of CO_2/year) to 0 net ton/year emitted, with a decrease of 50000 t/year for each scenario.

One additional scenario, with the technology mix of the case with no CO_2 emission limits but equipped with a carbon capture technology to reach zero net emissions was considered. This was done to see if the use of just a carbon capture technology would be cheaper than the use of the other technologies combined.

The model is implemented in the Python for Power System Analysis (PyPSA) framework.

3. RESULTS

3.1 Electric production

In the *figure 2* is shown the electrical energy that needs to be produced to meet the plant demand. At first, by reducing the allowable CO_2 emissions the electricity from the grid is reduced, since is the cheapest route to decarbonize the system. After the phasing out of the grid energy from solar, and particularly wind, starts to be produced. The steep increase in production is given by the use of electrolyzers that need to be powered.

From 250 kton of CO_2 and lower there is a small increase in production due to the use of carbon capture, since the VPSA system requires electrical energy.

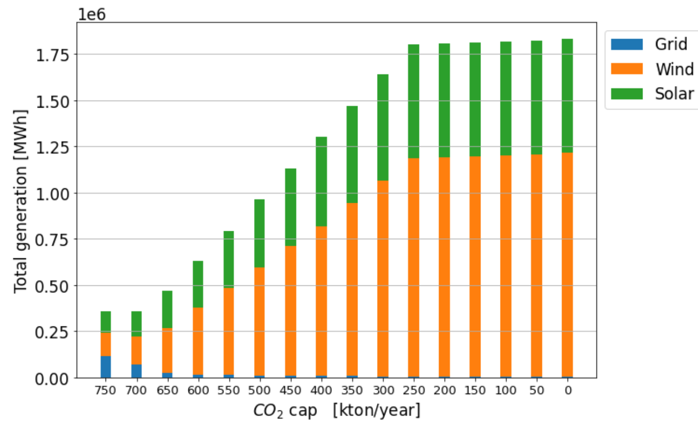

Fig. 2 Electricity production

3.2 H_2 production

In *figure 3* the production of hydrogen in MWh for the different scenarios can be seen. For low CO_2 limits the production is entirely from SMR since the reduction in CO_2 emissions is done by phasing out the grid. From 650 to 300 kton of CO_2 the steam methane reforming is replaced by electrolysis. With a limit of 250 kton a year and lower, the production of H_2 is done thanks to SMR with CCS and it increases due to the use of hydrogen burners.

3.3 Thermal production

As can be seen in *figure 4* the thermal energy is almost entirely produced by methane burners. Being expensive, hydrogen burners come into play for low CO_2 limits, when it is the only option left to use, other than the carbon capture to lower the emissions. The demand is constant.

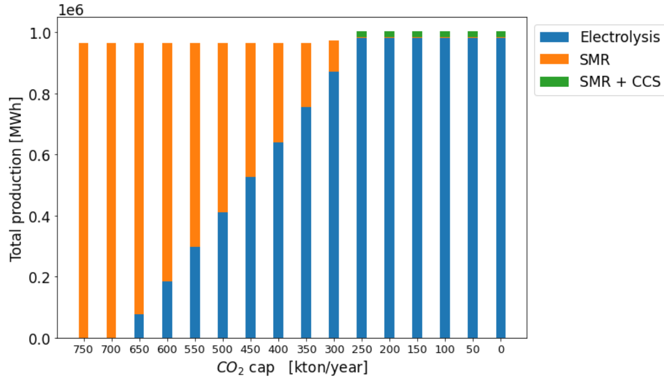

Fig. 3 H_2 production

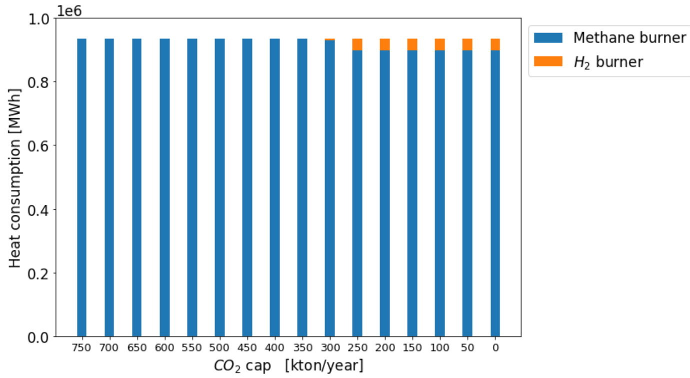

Fig. 4 Thermal production

3.4 Total cost

The costs of the system are shown in *figure 5*. The cheapest configuration is composed by SMR for hydrogen production, gas burners for heating, and the electricity is bought from the grid and generated with few solar and wind.

With the lowering of the emissions more expensive technologies are used, more and more electricity is generated with renewables. SMR is replaced by electrolysis with just a slight increase in price. Below 250 kton of CO_2 a year the increasing cost is given by the carbon capture technology and mainly the CO_2 storage. This is also the reason why a system with zero net emissions that relies on carbon intensive technologies with carbon capture (column 'CC' in the plot) is more expensive than a system built with a mix of renewables and green technologies.

3.5 CO_2 price

For each simulation a price per ton of CO_2 is obtained. The CO_2 price indicates how much it costs to remove an additional ton of CO_2 from the atmosphere in that particular configuration of the plant. As shown in *figure 6* with no constraints on CO_2 emissions the price is zero. With the decrease of CO_2 emission limits there is a first steep increase in the price due to the phasing out of the grid and implementation of renewables, being the cheapest way to reduce emission at early stages. Between a CO_2 limit of 650 and 350 kton a year SMR is replaced by electrolysis and the CO_2 price reaches a plateau (around 104 €/ton). Behavior given by the fact that SMR has a lower capital cost but a higher marginal cost then electrolysis and so switching between the two technologies does not resolve in a big increase in the total cost. The price to pay to remove an additional ton of CO_2 is constant since it can be removed by producing hydrogen with more electrolysis.

Between 350 and 250 kton of CO_2 the price increase again due to the switch to hydrogen burning, reaching the maximum value of 176 €/ton from 200 kton to 0. This last increase in CO_2 price is given by the use of carbon capture and it does not change since the cost of removing a ton of CO_2 remains the same once the carbon capture technology is built.

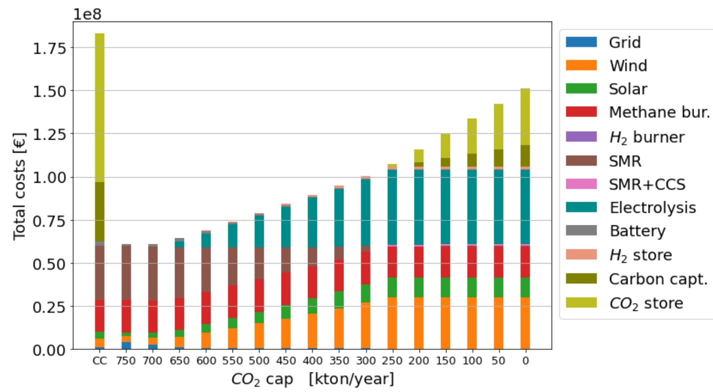

Fig. 5 Total costs

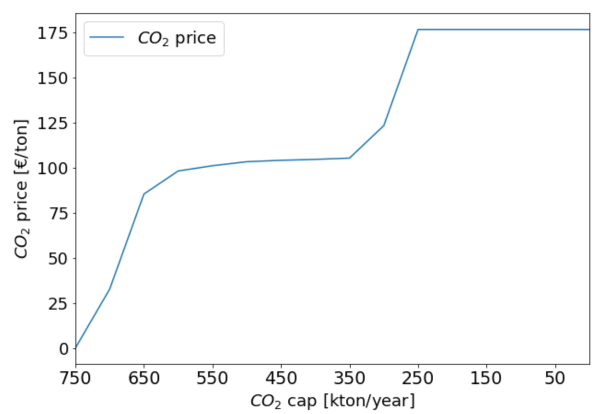

Fig. 6 CO_2 price

3.6 Influence of location on CO_2 price

The discussed steel plant is set in central Germany. Two additional locations, one in the south and one in the north of the country were considered. As can be seen in *figure 7* the trend of the CO_2 price is similar in every case, but the system reaches a lower price in the north thanks to the highest wind availability. The south is better for solar irradiation, but this doesn't compensate for the decrease in wind speed and the prices reach higher values.

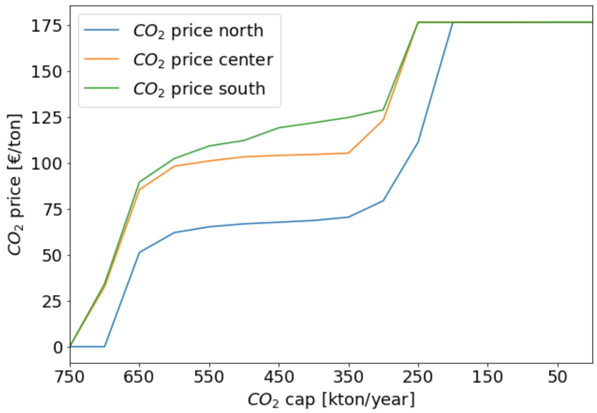

Fig. 7 CO_2 price depending on location

4. CONCLUSION

From this study is clear that the switch to electrolysis powered by renewables is the most essential step to take to decarbonize the steel industry.

Furthermore, ensuring a CO_2 price of around 100€/ton would lead to a reduction in overall emissions of around 60%. Increasing the price up to 176 €/ton would be enough to reach zero net emissions.

Further analysis could include a change in country and in renewable availability for the plant, as well as a sensitivity analysis regarding equipment costs and a coupling with other industries.

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