

Feasibility study of low-carbon ammonia and steel production in Europe

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Abstract

As stipulated in the Paris Agreement, greenhouse gas emissions have to be reduced in order to maintain the global warming well below 2 °C. Moreover, the European Union committed to become carbon neutral by 2050. This will require shifting industrial production currently based on fossil energies towards the use of renewable energies. The present article considers two conceptual industrial processes that may operate in Europe with low carbon emissions through the use of green hydrogen. The studied processes are projections of the production of ammonia and steel in the 2030s. Hydrogen is assumed to be produced by water electrolysis with Proton Exchange Membrane electrolyzers. The purpose of this paper being to evaluate the feasibility of such processes, it is assumed that the electricity required by the processes is entirely provided by renewable energies, in order to focus only on the challenges directly related to the ammonia and steelmaking plants. For the same reason, the prices are estimated in 2030 and not later, to avoid too uncertain costs assumptions, even if a complete supply by renewable energies may be unrealistic at that moment. Based on current industrial sectors of both ammonia and steel productions, a detailed modelling of the two decarbonised processes in *Aspen Plus* software is carried out and an economic analysis is also presented to prove the feasibility of these processes.

Introduction

This article details two hydrogen consuming processes that are adapted to use a feed of pure H₂ produced by electrolysis with renewable energy. Those processes should be examples of what the industrial processes will become in the next decades if environmental policies are followed. The two cases that are studied in this article are the production of ammonia and the steelmaking process for Europe. Currently, those processes exist but emit important amounts of greenhouse gases due to their consumption of fossil fuels. The goal of this work is to study the feasibility of a transition to very low-CO₂ emission processes and to see what assumptions have to be made to reach that objective.

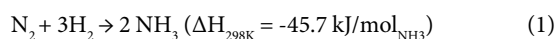
The present work includes a short literature review of the current processes and available technologies, describes in details the models of the two processes using pure hydrogen and ends with the cost analysis of the two systems. All the developments are coupled with discussions on the viability of the processes.

Literature review

The current processes emit large amounts of CO₂. Indeed, the H₂ required for the ammonia synthesis is produced by natural gas reforming or coal gasification and coal, or natural gas for some technologies, is an essential feedstock for reducing the iron ore in the steelmaking process. It is estimated that the production of ammonia and the production of iron and steel represented respectively 0.59 % and 2.24 % of the total greenhouse gases emissions of the EU-28 in 2017¹.

AMMONIA PRODUCTION

Currently, ammonia is mainly produced with the Haber-Bosch process, using the exothermic main reaction²:



Air is used as source of N_2 while H_2 is usually produced by natural gas reforming in Europe. The reforming of natural gas also produces CO and water which are converted into H_2 and CO_2 in a water gas shift reactor. A decarbonisation step is required to capture the CO_2 emitted during this reaction. The two reactants are then mixed in a catalytic reactor to form ammonia that is further separated by successive liquid-vapour separators. Liquid ammonia is obtained and the vapour containing the H_2 and N_2 that have not reacted is recycled to the inlet of the reactor. The reaction is usually conducted at high temperature and pressure, in ranges of 350–600 °C and 150–400 bar^{3,4}.

In current ammonia production plants, the synthesis step only represents 20 % of the CAPEX while more than 35 % of the CAPEX is due to the reforming and decarbonisation parts⁵. Moreover, the natural gas reforming required to produce the H_2 is the most emitting part of the ammonia process as for 1 ton of ammonia produced, 1.8 tons of CO_2 are emitted by a standard plant⁶. It is thus clear that using pure green hydrogen as raw material would be a very interesting alternative to the current gas reforming step of the process. It would allow to hugely decrease the CO_2 emissions if H_2 is produced with low-carbon electricity and the high investment of the reforming part could be avoided.

STEELMAKING

The purpose of the steelmaking process is to reduce iron ore. It contains around 95 % of Fe_2O_3 and 5 % of gangue, which is mainly composed of SiO_2 and Al_2O_3 ⁷. The industrial path studied in this work is the production of direct reduced iron (DRI) followed by electric arc furnace (EAF). This type of process only produces about 5 % of the world's steel, but it is the best available technology concerning greenhouse gas emission. Indeed, DRI processes emit about 0.5 ton of CO_2 per ton of steel, while common plants release about 2 tons of CO_2 per ton of steel⁸.

The principle of the DRI process is to directly reduce the iron ore with H_2 and CO while the ore is still solid. The reducing agent is a mixture of CO and H_2 in 80 % of the DRI production processes⁹. This mixture is produced by natural gas reforming. Other technologies are based on coke and use only CO as reductant. The reduction produces water and CO_2 as by-products. Those components leave the reactor with the remaining H_2 by the top of the shaft while the reduced iron exits at its bottom.

The EAF allows the production of steel from hot briquetted iron (HBI), hot direct reduced iron (HDRI) or scrap. The reduced iron is melted with carbon, scrap and limestone, which is used as a slag former. The slag removes most of the impurities present in the melt. There are two other outlets of the EAF: fumes and steel. Fumes are mainly composed of CO and can be burnt in order to produce heat.

Even if CO has been historically used as the main reductant in steel production, the H_2 -based process has advantages¹⁰. For instance, the kinetic rate is faster, which could lead to smaller reactors or higher production rates. However, processes based

on H_2 require more energy as the reaction is globally endothermic while it is exothermic with CO.

ELECTROLYSIS

In the present work, pure H_2 substitutes conventional fossil fuels in both processes. This allows to avoid most of the CO_2 emissions as natural gas, coal and coke are almost not used anymore. Pure H_2 and pure O_2 are produced from water electrolysis and it is assumed that the electricity required is provided by low-carbon energies.

To perform the electrolysis, proton exchange membrane electrolysis cells (PEMEC) are assumed here. This type of electrolyser is not mature currently but it is assumed that in 2030, PEM electrolysers will be available at the industrial scale and will reach an efficiency of 85 %^{11,12}, value that is used in the present work for both processes. The operating conditions of the PEMEC are around 70 to 90 °C and they can work under high pressures as they can be submitted to a few hundred bar¹³. This type of electrolyser can cope with flexible electricity inputs without a decrease of its performances¹⁴, which is important as the electricity is assumed to be provided by renewable energies so the supply may fluctuate along the day. As a consequence, hydrogen storage is also accounted for in the study, as it allows to ensure a constant feedstock supply. The PEM electrolysers efficiency is set at 85 %, as for the design of the ammonia process.

Processes modelling

In this section, the models used for each process are detailed. The processes are modelled with *Aspen Plus V8.8*. The NRTL model is used to represent the behaviour of liquid phases while gas phases are modelled with the ideal gas assumption.

PROTON EXCHANGE MEMBRANE ELECTROLYSER

As explained in the cost analysis section below, both processes are designed to produce H_2 by electrolysis during 18 hours per day only, to benefit from lower electricity prices. Therefore, H_2 storage is needed to feed the steady state processes. It means that more H_2 is produced than directly consumed and part of this production is stored in large vessels at high pressure. This storage is not modelled in *Aspen Plus* as only a storage vessel is required. Nevertheless, its cost is considered in the cost analysis.

To avoid a costly gas compression step and as PEMEC can operate under a maximum pressure of 200 bar¹³, the entering water is first compressed via a pump at 180 bar before electrolysis. This early compression allows to decrease the size of the storage vessel for the surplus of H_2 and to produce easily condensed and stored oxygen that can be sold afterwards.

AMMONIA PRODUCTION

The plant is sized to produce 540,000 tons of ammonia per year, i.e. 1,500 t/day, according to the average size of an ammonia production site¹⁵.

The modelling of the ammonia production process is presented in Figure 1. It comprises first the modelling of the PEMEC. The electrolysis is modelled in *Aspen Plus* for a flow rate of pure water of 2,688 t/day. The amount of electricity required for the electrolysis is 12,500 kWh per ton of ammonia produced³. The corresponding power required is

700 MW. High-purity liquid N_2 sold in the market at $-98\text{ }^\circ\text{C}$ and 180 bar¹⁶ enters the process at a flow rate of 1,415 t/day. It is then vaporised until it reaches at least $-20\text{ }^\circ\text{C}$. Contrary to the processes that use gas reforming, N_2 has to be pure so air cannot be directly used.

N_2 and H_2 are then mixed together along with the flow of recycled unreacted gases and the mixture is heated before entering the reactor. The reaction (1) is reversible. The kinetics of formation is described in the literature¹⁷. The reaction can be conveyed in a catalytic multi-bed plug flow reactor¹⁸ modelled as an isothermal reactor to reduce the number of degrees of freedom. The operating conditions are a pressure of 180 bar, a temperature of $450\text{ }^\circ\text{C}$ and a 3:1 H_2/N_2 ratio. The reactor is sized to reach a conversion of 20 %. Those conditions are based on a sensitivity study and on the conditions actually used in the industry¹⁴.

The reactor outlet is then cooled down from $450\text{ }^\circ\text{C}$ to $0\text{ }^\circ\text{C}$. First, a heat exchanger HTX-1 reduces the temperature of the stream to $120\text{ }^\circ\text{C}$, then an air-cooler cools down the hot stream to $40\text{ }^\circ\text{C}$ and the last cooling step is a heat exchanger with a refrigerant agent. Five flash tanks in series are then required to obtain the desired purity of NH_3 and the vapour phases leaving the first three ones are recycled to the entrance of the reactor as they contain most of the H_2 and N_2 that have not reacted.

The separation of ammonia at the outlet of the reactor is achieved using several flash tanks and valves in series, allowing impurities to be removed from the liquid phase. Between each tank, the pressure is reduced via a discharge valve. Four liquid-vapour separations are required, respectively at 180, 50, 10 and 1 bar. This leads to very pure NH_3 in the liquid phase. Vapour phases of the first three flash tanks are recycled to the reactor inlet.

The last flash tank allows to reach a very high purity in NH_3 in the liquid flux NH_3LIQ as less than 200 ppm of impurities are reached. This is the main product as it is pure ammonia that is sold on the market and can be transported easily as it is in the liquid phase. However, most of the ammonia produced is contained in the vapour phase at 1 atm in the flux of purified gaseous ammonia, named G-4 as it is the gaseous flux leaving

the fourth flash tank used in series. This vapour stream is very pure in ammonia but its storage would be costly as a compression chain of 12 MW is needed to store it in a tank of a reasonable size for 24 hours of production. Another possibility would be to use the pure NH_3 directly on site to produce urea, nitrate and other derivatives that could be sold and increase the revenues of the plant¹⁹. The last valuable flux is the gaseous flux G-3 leaving the third flash tank with a 93 % purity in NH_3 . This flux being less pure, it can be used elsewhere in the plant or be sold at a cheaper price, but the same storage problem would be encountered.

STEELMAKING

The model of the steelmaking plant is based on a fixed conversion as there is little information on reaction kinetics in the literature. This allows to establish the material and enthalpy balances required to evaluate the feasibility of a steelmaking plant operating with pure H_2 . The process modelled in *Aspen Plus* and presented in Figure 2 produces 1 million tons of steel per year with a carbon content of 0.2 %_{mass}.

Hydrogen is produced from PEM electrolyzers at $80\text{ }^\circ\text{C}$ and 180 bar. 1,400 t/day of pure water enter in the PEMEC and, their efficiency being of 85 %, the power consumed by the electrolyzers is around 400 MW.

DRI process

A plant based on a reduction with only H_2 should be avoided as the reduced iron without any carbon content is very reactive and can lead to explosions⁷. Therefore, a minimum amount of carbon has to be added in the direct reduction process. It seems thus logical to keep a small injection of CO in the reactor as it can react with FeO to produce Fe_3C . CO can also produce carbon soot according to Boudouard's equilibrium, which decreases the reactivity of the reduced iron produced. The designed process consumes about $5\text{ Nm}^3_{CO}/t_{ore}$.

Most DRI technologies use a shaft reactor where the iron ore is reduced by a counter-current reducing gas mixture. This equipment is modelled in three steps: the iron ore is heated to increase the kinetics of the reactions in the upper part of the

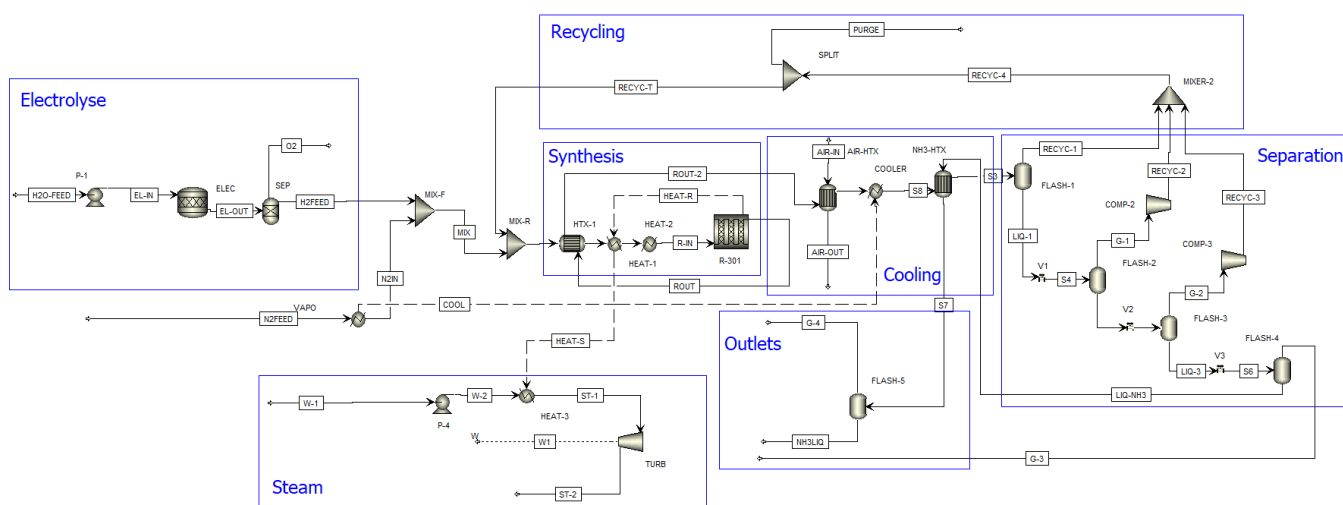


Figure 1. Aspen Plus flowsheet of the ammonia production process.

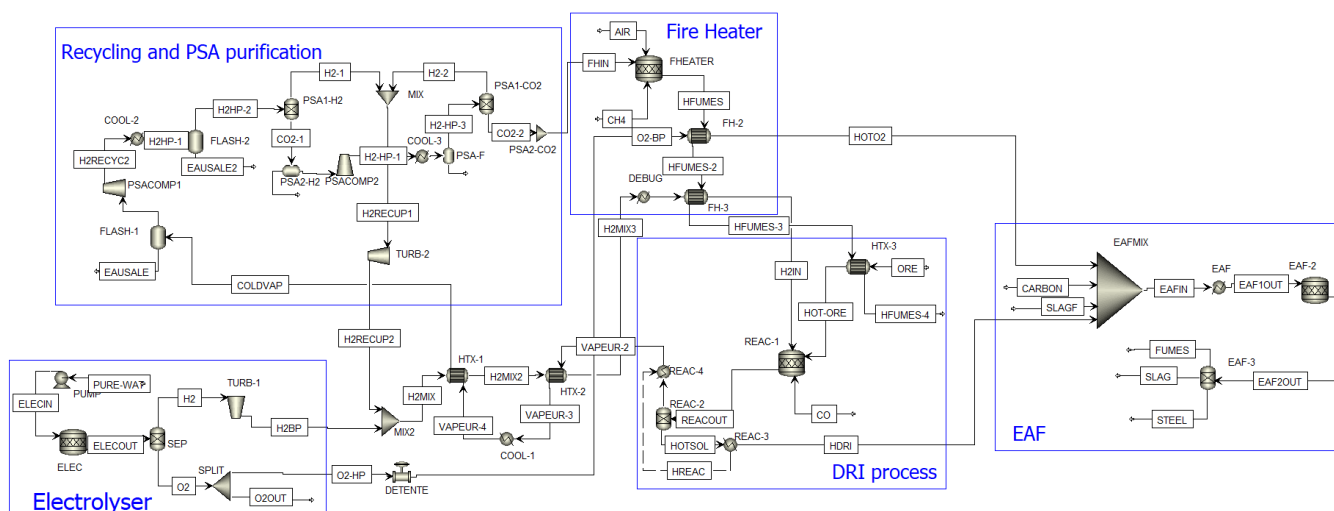


Figure 2. Aspen Plus flowsheet of the steelmaking process.

shaft, the reduction of the ore occurs in the middle part and the bottom of the equipment is used as a reformer and allows the cooling of the DRI. Nevertheless, when the reduction is mainly conducted with H_2 , there is no need to cool down the DRI as the reduction is already an endothermic process, so the bottom part of the shaft reactor is not needed. However, it is possible to keep the same type of reactor than common DRI processes by adapting its design. Only the feeds of the shaft have to be changed. The upper part of the shaft is still used to pre-heat the iron ore, its reduction occurs in the middle part and a deeper reduction with CO occurs in the bottom part. With this design, the heat generated by the carbon addition is used to keep the upper part at a good temperature.

The optimal temperature of the hydrogen feed is around 850 °C. At lower temperatures, the kinetics is slower, which results in an increase of the reactor size. At a higher temperature, a sticking phenomenon can be observed^{7,20}. This issue leads to the increase of the size of each particle of iron which slows down the reaction kinetics due to a longer diffusion time⁶. The CO is fed to the shaft at a temperature of 800 °C as its reactions are exothermic and as the sticking phenomenon has to be avoided.

The stoichiometric ratio of hydrogen required for the complete reduction of iron is $3 \text{ mol}_{H_2}/\text{mol}_{Fe_2O_3}$. Nevertheless, a higher ratio allows to increase the reaction kinetics and to keep a sufficiently high temperature in the shaft. For those reasons, the ratio could be up to five times the stoichiometric ratio⁶. A ratio of $10 \text{ mol}_{H_2}/\text{mol}_{Fe_2O_3}$ in the ore is chosen. As most of the H_2 is recycled, the hydrogen feed of the plant is $400 \text{ Nm}^3_{H_2}/\text{t}_{\text{ore}}$ with an iron ore consumption of $4,350 \text{ t}_{\text{ore}}/\text{day}$.

There are two outlets of the shaft reactor: the DRI and the exhaust gas. The gas can be cleaned and recycled while the DRI, which is at a temperature higher than 600 °C, can be transformed into HBI for transport or can be directly fed into an EAF as HDRI.

Recycling loop

The exhaust gas of the shaft contains a non-negligible amount of hydrogen, which has to be recycled. As the outlet stream is also contaminated with water, CO_2 and CO, a purification process is included inside the recycling loop. The first step is the

removal of water from the gas. It is performed by cooling the stream to a temperature around 5 °C. At this temperature, water condenses in a flash tank while other components are still in the vapour phase. As there is still a small amount of water in the vapour phase leaving the flash tank, additional flash tanks are added after each cooling step in the purification process.

CO can be recycled as it can reduce iron ore, but CO_2 has to be removed or it would never leave the system. This issue can be solved with the use of a two-stage pressure swing adsorption (PSA). Both PSA stages operate at a pressure of 7 bar for the selective adsorption of impurities and the regeneration takes place at a pressure of 0.1 bar²¹. The outlet streams of the two-stage PSA containing mainly H_2 can be recycled to the shaft, while the remaining mixture of CO_2 , CO and H_2 is purged. As this purge stream still contains H_2 , it can be valued by burning it in a fire heater. This fire heater is also fed with CH_4 and O_2 in order to produce enough heat to pre-heat the inlet of the shaft reactor and other small fluxes. Natural gas needs thus to be burnt in this decarbonised process too, but its amount is nearly negligible in comparison to the consumption in conventional steelmaking processes.

Electric arc furnace

The EAF is fed with HDRI, carbon and slag former. Scrap could also be charged instead of a part of the DRI. The carbon source should contain as few volatile compounds as possible in order to avoid excessive energy consumption due to their combustion.

The temperature of the melt is set around 1,650 °C^{22,23}. The energy required is provided by chemical reactions and by the electric arc generated by the EAF. Chemical energy is either provided by slag formation or slag foaming. The slag is composed of CaO , Al_2O_3 , SiO_2 and FeO . Oxygen is fed to the EAF to provide energy and to allow slag foaming. The slag also allows to refine the iron phase by absorbing most of the impurities.

Energy requirements

The main energy requirements of the process are presented in Table 1. These values represent the energy consumed, after heat integration and taking into account the efficiencies of the different devices. For instance, the use of HDRI rather than cold

recycled steel allows to decrease the EAF energy consumption. It can be seen in Table 1 that the electrolysis is by far the most energy consuming part of the process, so improving the efficiency of the PEM electrolyzers would have a huge impact on the total energy consumption of the plant. In the designed process, the use of fossil fuels is limited compared to that of conventional plants as they account for less than 15 % of the energy consumption.

Cost analysis

Formulas extracted from Turton et al.²⁴ and from Nilsson et al.²⁵ are used to calculate CAPEX, OPEX and cash flows. All the costs in this section are estimated for the year 2030, using an interpolation of the values of the Chemical Engineering's Plant Cost Index (CEPCI) from previous years. The CEPCI value for 2030 is estimated at 750²⁶.

For the cost analysis part, several assumptions have been made for both processes and are therefore valid for the whole section. The number of operating hours for both plants is fixed at 8,200 hours per year. In the evaluation of the cash-flow diagrams, the inflation rate considered for the study is 1.5 %. The discount rate is approximated at 10 % and the depreciation period is fixed at 10 years. Concerning the labour cost, a salary of €25/h is considered with six working positions. Finally, O₂ is valorised as a by-product with an estimated price of €27/t. All the costs are rounded to be presented in a more visual way.

HYDROGEN PRODUCTION AND STORAGE

The cost of PEMEC without its installation is currently of €700/kW and it is expected to decrease to €500/kW by 2030³. The electrolysis is the most electricity-consuming step of both ammonia and steel processes. Given the large required amounts of H₂, many PEMEC are needed. The cost of electricity is thus an important factor for the viability of the processes.

As explained previously, the price of electricity in Europe is estimated for 2030, based on the current situation. The assumption that the electricity required by the processes will be entirely provided by renewable energies is done even if it is unrealistic. The influence of the decarbonisation of the European electricity production on its price is not taken into account in the present work in order to focus only on the viability of the studied processes.

The cost of electricity in Europe is thus generalised and assumed to be €40/MWh for both processes. Indeed, it can be seen in Figure 3²⁷ that a classical ammonia plant consumes less than 100 GWh/yr at a price of about €70/MWh but, as a low-carbon emission plant of a classical size consumes around 5,000 GWh/yr, the price of electricity decreases because of the inverse proportionality between the electricity consumption and its price.

Even with this reduced price of electricity, the electricity consumption is one of the most important factors for the total

cost of the processes. For instance, the capacity required for the desired production of ammonia being 700 MW, it induces an operating cost of more than M€250/yr at an electricity cost of €40/Mwh.

In order to decrease these huge operating costs, a peak shaving approach can be considered. Peak shaving consists in stopping the electricity consumption of the plant during parts of the day when consumption peaks occur on the electrical grid, in order to help the electricity supplier to cope with peaks of demand from other consumers. If a process is able to operate without or at least with less electricity from the grid during some periods of the day, better prices can be negotiated with the electricity supplier. A decrease by 25 to 35 % can be expected²⁸, leading to a cost of maximum €30/MWh. The two studied processes are designed to consider a peak shaving of 6 hours per day, spread throughout the day, corresponding to electrolysis shut-off. H₂ needs to be stored during the 18-hour period when electricity is supplied in order to be continuously available. The electrolyzers capacity increases thus by about 33 % compared to continuous operation.

In the ammonia plant for instance, the capacity increases from 700 to 900 MW. 75 tons of H₂ have to be stored each day. H₂ is stored as a gas as it is already at 180 bar when it is produced by the electrolyser. A 7,000 m³ tank is sufficient to store enough H₂ for 6 hours. The same system is applied for the steel-making plant, where 40 tons of H₂ have to be stored each day. Therefore, a 3,750 m³ tank is required for storage.

AMMONIA PRODUCTION

The choice of a normal size plant producing 1,500 t_{NH₃}/day is made. Such a size allows to benefit from the economy of scale. Moreover, the plant is not too large as it would be difficult to supply it with green electricity and as the number of equipment would have to be doubled because their size cannot increase indefinitely. The total greenfield plant cost is estimated at M€800. This value also considers auxiliary facilities and the purchase of the land in case of a new plant²⁹.

In terms of OPEX, the costs of the raw materials are estimated from different sources based on the flow rates calculated in the Aspen model. The costs of the raw materials and products of the plant are listed in Table 2.

As mentioned in the previous section, the price of electricity has a huge influence on the income revenue of the plant. Indeed, approximately 6,400 GWh are needed every year. In the base case, with a peak shaving approach leading to a price of electricity of €30/Mwh, it represents a total cost of about M€192 per year.

Another factor for ammonia plants in Europe will be the cost of the CO₂ emissions in 2030. Currently, European companies that emit CO₂ have to buy emission allowances to be legally authorised to emit CO₂, otherwise heavy fines are imposed³⁰. At the end of 2019, the allowances cost was around €25/t_{CO₂}³¹.

Table 1. Energy consumption in the steelmaking process per ton of steel produced.

	Electricity for electrolysis	Natural gas for heating	Electricity for EAF	Electricity for compressor	Total
Energy consumption (kW)	2,500	400	260	100	3,260
Percentage (%)	77	13	8	3	100

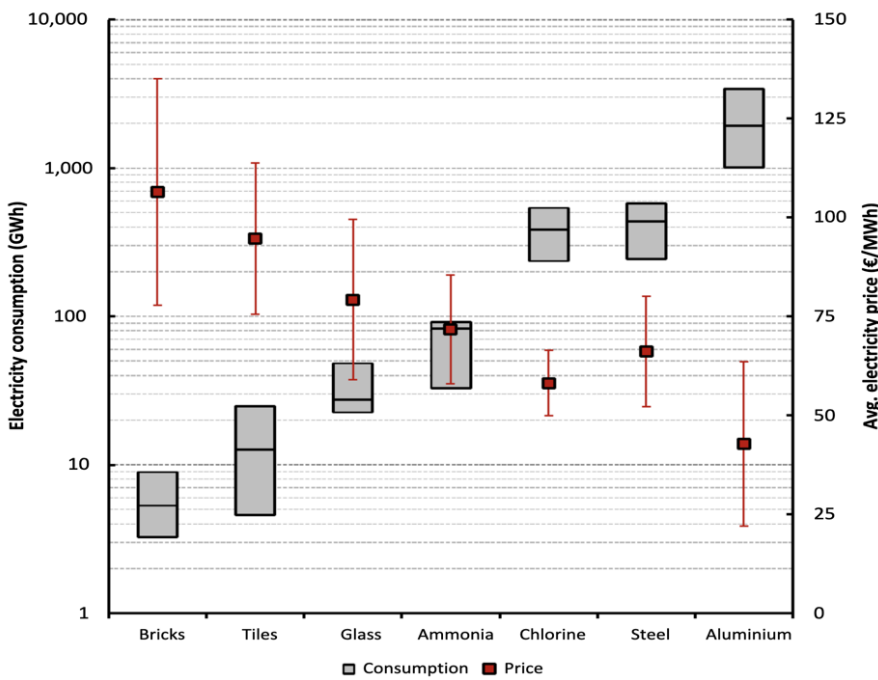


Figure 3. Correlation between electricity price and electricity consumption for plants of different sectors.

Table 2. Raw materials and products costs for the ammonia process in 2030.

	Cost/Value (€/t)	Flow rate (t/yr)	Cost/Revenue (M€/yr)
Raw materials			
Nitrogen	30 ³⁶	478,880	13.47
Pure water	1 ³⁷	911,020	0.91
Products			
Ammonia	350 ³⁸	512,500	179.38
Oxygen	27 ²⁹	809,102	21.85

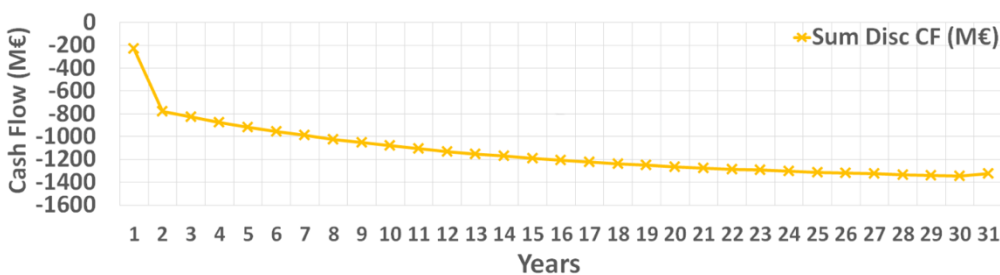


Figure 4. Discounted cash flow diagram of the ammonia production in the base case, with a discount rate of 10 %.

In the coming years, the cost of the CO₂ emissions is expected to increase and other forms of taxes could be imposed. Estimations show that this cost should reach between €50/t_{CO2} to €100/t_{CO2} by 2030³². The cost of the CO₂ in 2030 is thus assumed to be of €75/t_{CO2} in the present work. This will lead to an increased interest in low-carbon emission plants. Indeed, traditional ammonia producers will have to pay these taxes, which will increase their cost of production of ammonia, directly affecting the selling price of their ammonia. These CO₂ taxes are therefore an additional fictitious income for low-carbon emitting

plants. The discounted cash-flow diagram of the process for a lifetime of 30 years is presented in Figure 4.

Figure 4, in the form of a discounted cash flow diagram, shows that a green ammonia plant, in these conditions, is not economically viable. The method used of a discounted cash flow is a valuation approach used to estimate the value of an investment based on its future cash flows. As it is not viable, some parameters have to be varied to be able to design a profitable process.

The dependency of the break-even CO₂ emissions cost as function of electricity cost is presented in Figure 5. The profit-

ability of the plant after 30 years is positive above the curve. It shows for example that for an electricity price of €30/MWh, the plant only becomes profitable for a cost of CO₂ higher than €225/t_{CO₂}.

Figure 6 shows that the low-CO₂ emission ammonia process designed in the present article could be profitable in the case of an emission cost of €250/t_{CO₂} with a price of electricity of €30/MWh.

Subsidies would be needed to build a profitable low-carbon emission plant compared to a classical plant. Their amount can be calculated from the electricity required to make one ton of ammonia from green hydrogen and from the cost of the CO₂ emission related to one ton of ammonia produced by gas reforming (1.8 t_{CO₂}/t_{NH₃}) at a price of €350/t_{NH₃}. In any case, €396/t_{NH₃} of subsidies are required to be profitable. These €396/t_{NH₃} can result from CO₂ taxes or from a decrease of the price of electricity compared to the base case, considered €30/MWh. An increase in the CO₂ cost would directly impact the price of ammonia from gas reforming as 1.8 t_{CO₂} are produced for each ton of ammonia. Similarly, the electricity price influences the cost of the ammonia produced as 12.5 MWh of electricity are required to produce one ton of ammonia with H₂.

Conducting a sensitivity analysis on the cost of the CO₂ emission up to €250/t_{CO₂} is not that utopian. Indeed, the Dutch government is currently approving a climate law that intends to introduce a CO₂ flat tax from 2021 that will increase up to €150/t_{CO₂} by 2030³³, in addition to the European allowances. However, as ammonia is a commodity, there is a global ammonia market price. Therefore, such CO₂ prices have to be internationally accepted or Europe has to establish carbon import taxes in order to protect the industry from the risk of so-called carbon leakage, *i.e.* the shift of production outside of regions with carbon pricing.

STEELMAKING

To the total cost of equipment for CAPEX, the price of the casting stage that has not been modelled in *Aspen Plus* has to be added. This is estimated at a cost of M€273 in terms of green-field plant cost in 2030³⁶. The total grassroots plant cost can be estimated at M€1,560 from the costs of the equipment and the cost of the casting of steel.

For the OPEX, the costs of the raw materials are estimated from different sources and are listed in Table 3. The costs of casting are added to the raw materials costs and are estimated

at €100/t_{steel}³⁴. The total annual costs for this process step are therefore M€100. The costs of the products are also displayed in Table 3. As the steel price fluctuates significantly over time, a sensitivity analysis on this price is performed later in this work.

Obviously, it can be added that the price of electricity has a huge influence on the income revenue of the plant. Indeed, approximately 2,663 GWh of electricity are needed every year, about 80 % of which is needed in the PEM. In the base case, with a price of electricity of €30/MWh, it leads to a total cost of about M€80 per year.

In Figure 7, the obtained discounted cash flow diagram for a lifetime of 30 years is displayed for an electricity price of €30/MWh. Figure 7 shows that a low-CO₂ emission steelmaking process is not economically viable for a price of electricity of €30/MWh. Indeed, the process becomes economically viable only for a price of electricity of €19/MWh. The evolution of the cost of the CO₂ emissions in the next years is not considered in this calculation. However, it is obvious that the more the cost of the CO₂ emissions will increase, the more beneficial it will be for the decarbonised plants. Indeed, common steelmaking plants emit around 2 tons of CO₂ per ton of steel⁷ while the process studied here only emits about 0.15 ton of CO₂ per ton of steel. Furthermore, nearly half of those emissions can be avoided by replacing the methane used in the process by low-carbon emission fuels such as biomass.

The steel price has varied widely during the previous years³⁹. Therefore, a sensitivity analysis of the plant's revenue based on this price is relevant. Figure 8 shows the conditions to obtain a

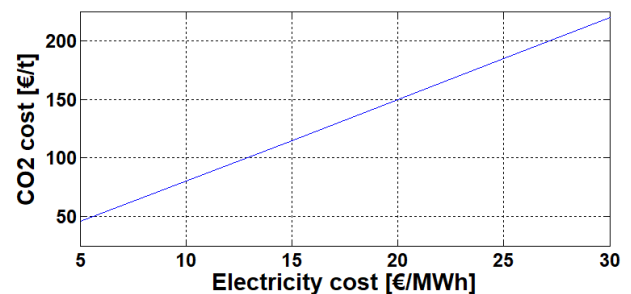


Figure 5. Break-even CO₂ emissions cost as function of electricity cost to design a viable process after 30 years.

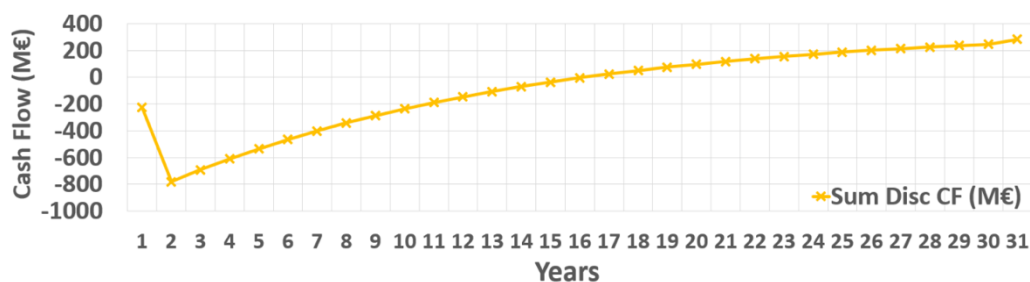


Figure 6. Discounted cash flow diagram of the ammonia production for an emission cost of €250/t_{CO₂} and an electricity price of €30/MWh, with a discount rate of 10 %.

Table 3. Raw materials and products costs for the steelmaking process.

	Cost/Value (€/t)	Flow rate (t/yr)	Cost/Revenue (M€/yr)
Raw materials			
Hematite	45 ³⁹	1,485,168	67
Pure water	1 ³⁰	480,151	0.5
Anthracite	400 ³⁷	18,409	7.4
Lime	63 ³⁷	66,493	4.2
Methane	220 ⁴⁰	27,855	6.1
Products			
Steel (August 2019)	540 ⁴¹	1,000,000	540
Oxygen	27 ²⁷	472,369	12.7
Slag	5 ⁴²	136,161	0.7

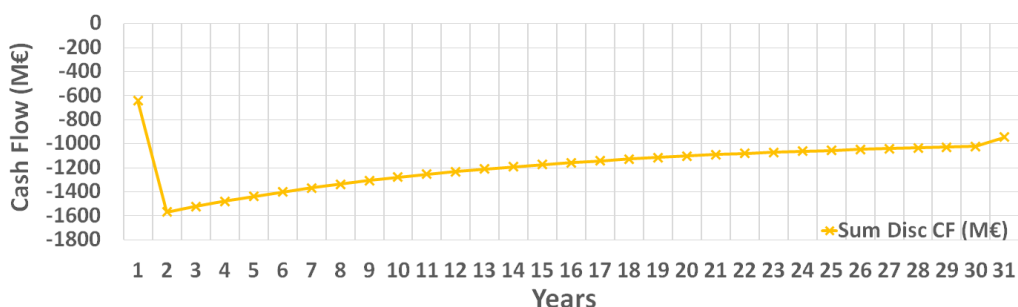
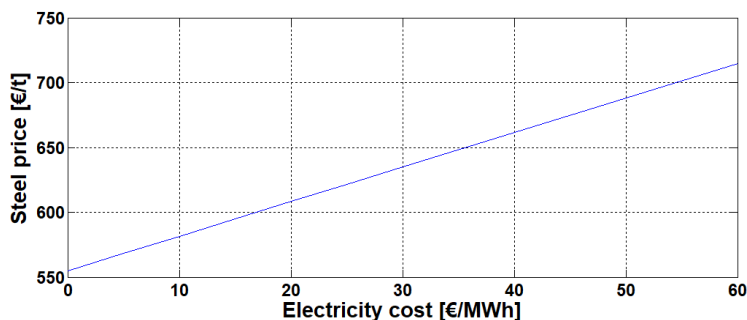
Figure 7. Discounted cash flow diagram of the steelmaking process with a steel price of €540/t_{steel} with a discount rate of 10%.

Figure 8. Limit of profitability of the steelmaking process after 30 years.

positive discounted cash flow diagram after 30 years and thus design a viable process: the plant is only economically viable above the curve. For instance, it can be seen that for a price of electricity of €30/MWh, the limit of profitability is reached for a steel price corresponding to approximately €635/t.

As the steel price in August 2019 that is considered in Table 3 was almost at its lowest value in more than 10 years, one could expect prices to increase in the future. In fact, the trend of the last months of 2019 showed an increase in the steel price³⁹. In addition, as explained before, negotiations on the price of electricity and reduction of CO₂ emissions can also lead to an important decrease of the OPEX. Figure 9 shows that the low-CO₂ emission steelmaking process designed in the present article could be profitable in the case of the high steel price as experienced in 2018 (€840/t_{steel}), even with a price of electricity of €30/MWh and without considering any CO₂ taxes.

The cost analysis of the steelmaking plant highlights the fact that the viability of the process is very dependent on the price of electricity and steel. However, the total investment cost is huge and it may be difficult to attract investors. Nevertheless, if it is possible to negotiate contracts with electricity suppliers to decrease as much as possible the electricity cost and if the steel price does not crash, this kind of low-carbon emission plants could be built in a near future.

Conclusions

This study showed that, to reach the objective of a viable decarbonised industry, many assumptions on the developments of technologies and on the political and economic decisions have to be made, such as the development of the PEMEC to the industrial scale for instance. The transition to the use of

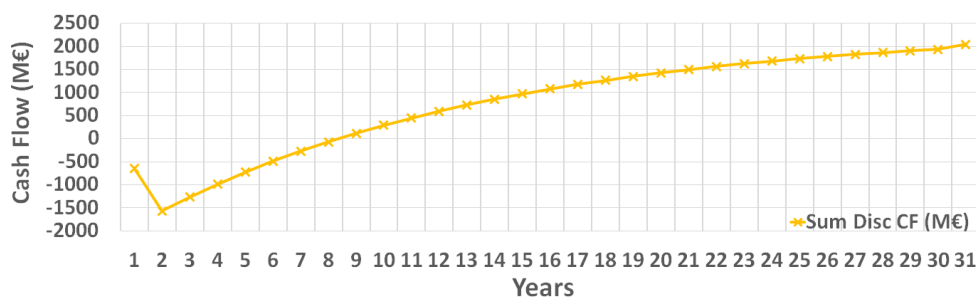


Figure 9. Discounted cash flow diagram of the steelmaking process for a high steel price of €840/t_{steel} with a discount rate of 10 %.

pure H₂ produced by electrolysis as raw material should be easier to implement for the ammonia production as pure H₂ is already used, thus only the gas reforming step should be replaced by the production of H₂ with electrolyzers. The modification of the steelmaking process would require deeper studies to modify the operating conditions as most of the production sites are designed to operate with a CO-H₂ mixture as reducing agent.

One of the most important factors is the cost of electricity. Indeed, for both processes, the electricity consumption is the major cost. Depending on the negotiations with the electricity suppliers and the possibility to cope with peak shaving, reduction of the prices can lead to important modifications of the income revenues.

To be economically viable, the studied low-carbon processes also rely on other economic factors to balance their high operating costs. The steelmaking process can expect rises of the steel prices due to its high fluctuation; the competitiveness of the process depends importantly on both electricity and steel prices. On the contrary, the price of ammonia is nearly constant over time, so the ammonia production plant needs to focus on another factor to cope with its significant operating costs: the cost of CO₂ emissions. This cost can increase drastically in the future and depends mostly on political decisions. It is a determining variable for the viability of low-carbon processes as it is an additional cost for conventional plants, and the economic feasibility of the ammonia production process designed in the present work is mostly influenced by both electricity price and CO₂ emission costs.

An important subvention channel that is not considered in this work is the new investment program from the European Commission. Indeed, the Commission announced an investment programme worth over €10 billion for low-carbon technologies in several sectors to boost their global competitiveness and the first call for application will be launched in 2020^{27,35}. These funds intend to promote the transition to decarbonised industries by subsidising part of the investments made to reach that goal. The European Union intends to allocate 60 % of the difference between the CAPEX of a classical plant and the CAPEX of the low-carbon emitting one to encourage the companies to decrease their CO₂ emissions. 60 % of the difference between the OPEX of the two plants will also be subsidised during the first 10 years of functioning.

As explained previously, the situation considered in this paper is that the processes designed for the 2030's are entirely supplied by electricity from renewable energies. This assump-

tion is unrealistic but is due to the focus of the present work, which is to evaluate the feasibility of two industrial processes based on low-carbon emitting electricity, thus assuming that issues on the supply of renewable electricity are solved by 2030. Many technological improvements and political decisions will be required to reach an electricity production with such low carbon emissions. However, the goal of the present paper is to discuss the possibility of adapting industrial processes to low-carbon designs.

Work of many different parties will thus be needed to reach the objective of decarbonised industries, and studies as the present one should help in the process, being a first step that intends to prove the feasibility of such decarbonised processes.

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