INITIATE
A STEPWISE PROJECT

PUBLIC

DELIVERABLE 5.3:

DEFINITION OF THE BASE AND REFERENCE CASES FOR THE KPIs ASSESSMENT

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Executive Summary

The iron and steel industry, along with the fertilizer industry, are one of the most carbon and energy intensive industrial sectors. The carbon dioxide emissions directly related to these two manufacturing processes are 30% of the emissions of all the industrial sectors. The INITIATE project aims to drastically decrease the CO_2 emissions of these industrial processes, creating an industrial symbiosis in which the process gases of the steel industry are exploited to produce ammonia and urea.

In this deliverable, the base and reference cases for steel, ammonia and urea production are defined and explained in detail. These cases will be used later in the project to assess the potentialities of the INITIATE process.

The base cases are defined as state-of-the-art commercially available plants, while the reference cases are defined as state-of-the-art commercially available plants with CO_2 capture technologies (see TABLE 1 and TABLE 2).

C4U project is taken as reference for the definition of the base and reference steel plants. Regarding the ammonia and urea plants, two different plant sizes are considered in this study, and, in this deliverable, they are referred as “small-scale” and “large-scale”. Ammonia is synthesized from natural gas through a steam reforming process for both plant scales while urea plants differ on technology. Small-scale urea plant employs a conventional total recycling process while the large-scale one is based on CO_2 stripping process.

Ammonia plants are considered as stand-alone or coupled with urea plants.

TABLE 1. Base cases

Plant	Product	Size	Technology	Application
Steel plant	Hot rolled coil	3.16 Mt/y		
Ammonia plant	Ammonia	86 t/day	Natural gas steam reforming	Stand alone or with urea plant
	Ammonia	848 t/day	Natural gas steam reforming	Stand alone or with urea plant
Urea plant	Liquid urea	150 t/day	Conventional process	AdBlue
	Liquid urea	1500 t/day	CO_2 stripping process	Liquid fertilizer

TABLE 2. Reference cases

Plant	Product	Size	Technology	Application	CO_2 capture
Steel plant	Hot rolled coil	3.16 Mt/y			WGS + MDEA pre-comb. on BFG
Ammonia plant	Ammonia	86 t/day	Natural gas steam reforming	Stand alone or with urea plant	MEA post combustion
	Ammonia	848 t/day	Natural gas steam reforming	Stand alone or with urea plant	MEA post combustion
Urea plant	Liquid urea	150 t/day	Conventional process	AdBlue	None
	Liquid urea	1500 t/day	CO_2 stripping process	Liquid fertilizer	None

Ammonia and urea plants have been simulated in Aspen Plus V11 while the power section of the steel plant in Aspen Plus V8.8. Main results are shown in the tables and figures below. KPIs such as primary energy consumption (PEC), SPECCA, CO_2 avoidance (CA) and cost of CO_2 avoided (CCA) are defined later in this document. The primary energy consumption and the process carbon intensity of the base cases agree with the values found in literature. In the reference cases, the addition of the carbon capture section implies a reduction of the CO_2 emissions bur also an increase of PEC. Consequently, also the levelized cost of the final product (hot rolled coil, ammonia, or urea) increases.
When considering the stand-alone ammonia plants, the large-scale plants are more cost-effective than the small ones since LCOA and CCA are lower. A similar argument can be done for the case in which the ammonia plants are coupled with the urea plants.

TABLE 3. KPIs – Steel plant

		Steel plant	
		Base case	Reference case
Key Performance Indicators			
Primary energy consumption	[GJ/t_{HRC}]	21.3	23.0
Process carbon intensity	[kg_{CO2}/t_{HRC}]	1823.9	1280.5
CO_2 avoidance (CA)	[%]	-	29.8
SPECCA	[GJ_{LHV}/t_{CO2}]	-	3.08
Levelized cost of hot rolled coil	[€/t_{HRC}]	468	491.65
Cost of CO_2 avoided	[€/t_{CO2}]	-	43.5

TABLE 4. KPIs – Stand-alone ammonia plant

		Stand-alone ammonia plant			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Key Performance Indicators					
Primary energy consumption	[GJ/t_{NH3}]	38.26	41.75	30.82	34.27
Process carbon intensity	[t_{CO2}/t_{NH3}]	2.28	0.45	1.87	0.11
CO_2 avoidance (CA)	[%]	-	80.06	-	94.22
SPECCA	[GJ/t_{CO2}]	-	1.91	-	1.96
Levelized cost of ammonia	[€/t_{NH3}]	733	799	295	337
Cost of CO_2 avoided	[€/t_{CO2}]	-	36.24	-	24.23

TABLE 5. KPIs –Ammonia plants coupled with urea plants

		Ammonia + urea plants			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Key Performance Indicators					
Primary energy consumption	[GJ/t_{urea}]	26.47	27.87	19.80	21.14
Process carbon intensity	[t_{CO2}/t_{urea}]	0.53	0.31	0.33	0.11
CO_2 avoidance (CA)	[%]	-	41.72	-	66.58
SPECCA	[GJ/t_{CO2}]	-	6.26	-	6.10
Levelized cost of ammonia	[€/t_{urea}]	624	657	205	224
Cost of CO_2 avoided	[€/t_{CO2}]	-	148.34	-	88.87

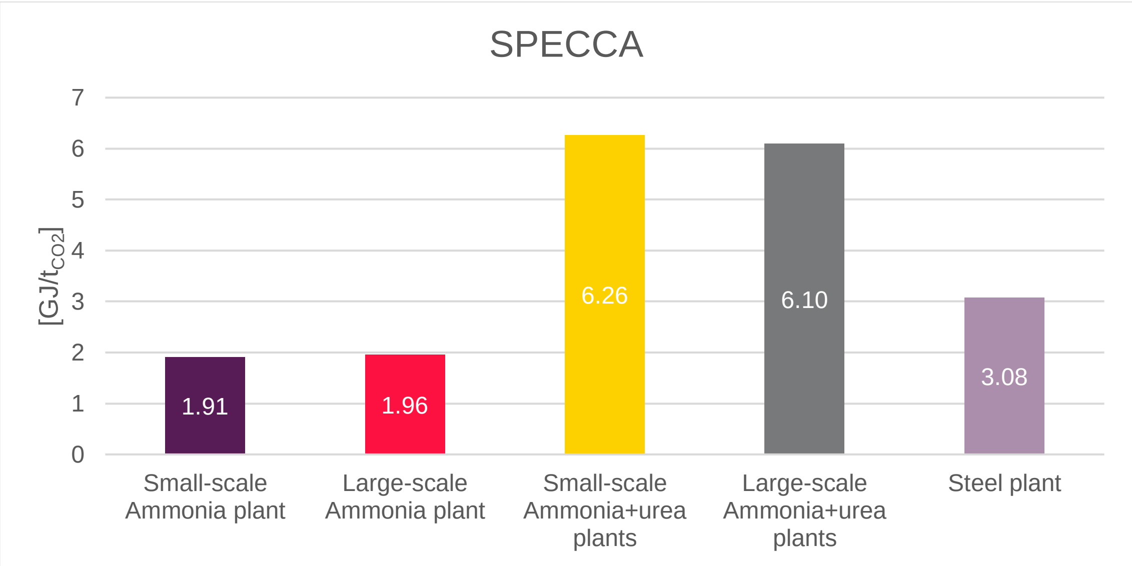

FIGURE 1. SPECCA of reference cases considered in this work

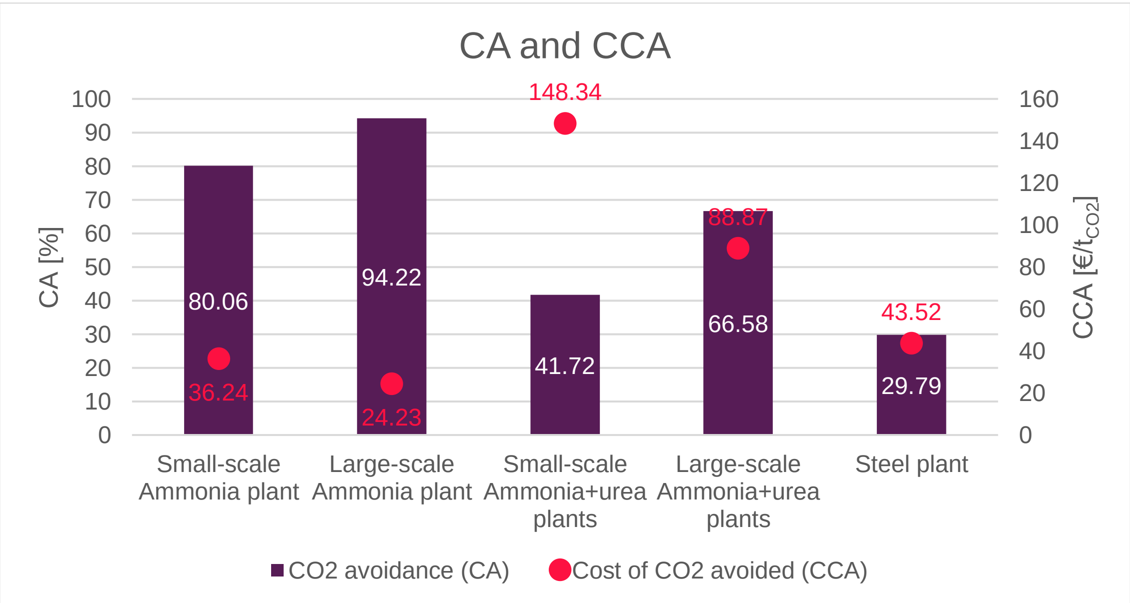

FIGURE 2. CA and CCA of reference cases considered in this work

Contents

List of abbreviations

ATR	Auto-thermal reforming
BFG	Blast furnace gas
BOFG	Basic oxygen furnace gas
CA	CO_2 avoidance
CCA	Cost of CO_2 avoided
CCR	CO_2 capture rate
CCS	Carbon capture and storage
CO_2	Carbon dioxide
COG	Coke oven gas
CGE	Cold gas efficiency
FCF	Fixed charge factor
HTS	High temperature shift
IRR	Internal rate of return
LCA	Life cycle assessment
LCOA	Levelized cost of ammonia
LCODF	Levelized cost of decarbonised fuel
LCOE	Levelized cost of electricity
LCOHRC	Levelized cost of hot rolled coil
LCOU	Levelized cost of urea
LHV	Lower heating value
LTS	Low temperature shift
NG	Natural gas
OEE	Overall energy efficiency
SEWGS	Sorption enhanced water gas shift
SMR	Steam methane reforming
SPECCA	Specific energy consumption for CO_2 avoided
TAC	Total annualised cost
TCR	Total capital requirement
TDPC	Total direct plant cost

TDIC	Total direct installation cost
TEC	Total equipment cost
TIC	Total installation cost
TIIC	Total indirect installation cost
TPC	Total plant cost

1. Introduction

The climate crisis that the world is facing imposes the adoption of urgent actions to mitigate the emissions of greenhouse gases. The European Union aims to be carbon neutral by 2050. The transition to an economy with net zero GHG emissions is challenging and will pass through the decarbonisation of the industrial sector that is one of the most emission-intensive sectors.

Among all the industrial sectors, the steel and the fertilizer industries are two of the most energy and carbon intensive. The annual emission of the steel industry is equal to 2.5-3.0 Gt_{CO2}/y representing the 9% of total global CO_2 emissions (equal to 33.1 Gt_{CO2}/y [1]) and 16% of total industrial CO_2 emissions [2]. Similarly, the fertilizer sector is responsible of a significant share of CO_2 emissions, indeed the emissions directly related to these two manufacturing processes are 30% of emissions of all industrial sectors [3].

In a steel plant around 50% of the total CO_2 emissions come from the power section where residual BOFG, and BFG are used as fuel in order to cover the electricity demand of the plant. The rest of the CO_2 emissions are attributed to several sections in the steel plant [2].

CO_2 direct emissions from urea sector are mainly related to the synthesis of ammonia that is combined with carbon dioxide to produce urea. In fact, in the ammonia plants, fossil fuels are burnt to supply the necessary heat in the primary reformer [4]. In addition, the CO_2 embedded in the urea molecule should not be considered as stored since it is emitted during urea final use.

The H2020 INITIATE project aims to demonstrate the feasibility of the industrial symbiosis between the steel and fertilizer industries by re-using residual steel gases (i.e., BOFG) as a resource for the production of urea. BOFG consists of CO, CO_2, N_2, H_2, with varying compositions and, as described before, is burnt in the steel power section, or used for other internal uses. The SEWGS technology, at the centre of the symbiosis between the steel and urea sectors, can be used to capture CO_2 from BOFG creating a highly concentrated CO_2 stream and another stream with a hydrogen to nitrogen concentration ratio of approximately 3:1 that can be exploited for the ammonia synthesis. The ammonia can then be combined with part of the captured CO_2 to produce urea, while the rest of CO_2 can be sent to storage.
The produced urea has a large market since it can be used as fertilizer, due to its large content of nitrogen, to reduce the NO_x emissions in the diesel engines or, for example, to produce chemicals and plastics.

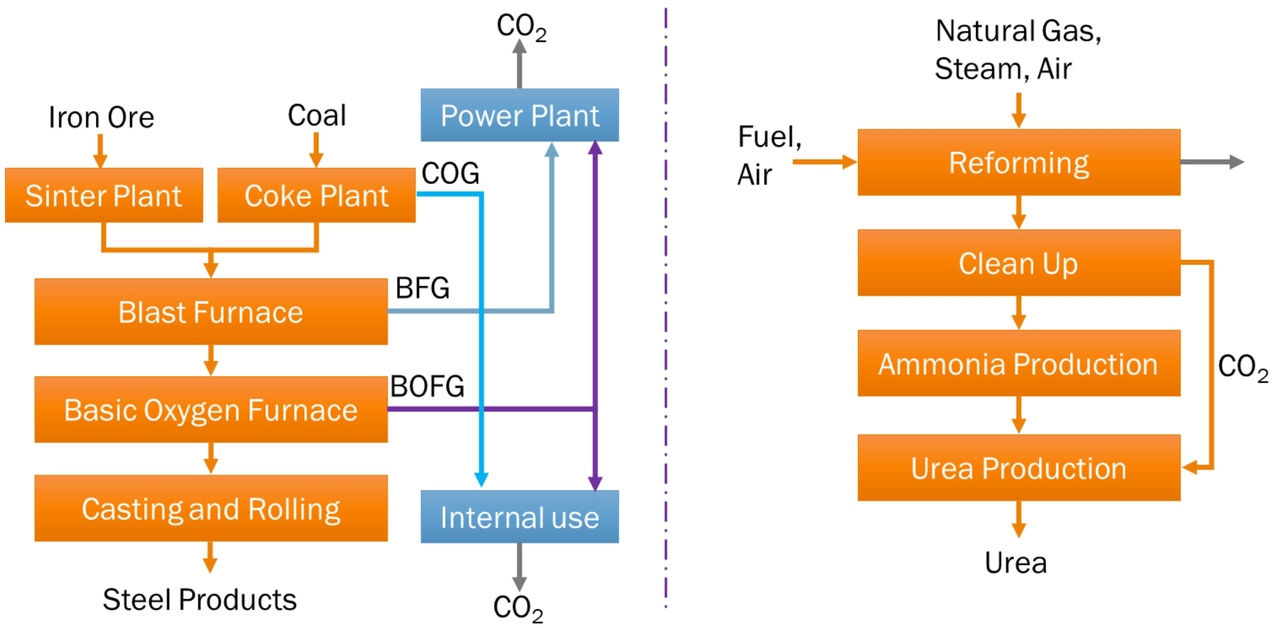

FIGURE 3. Conventional way to produce steel and urea

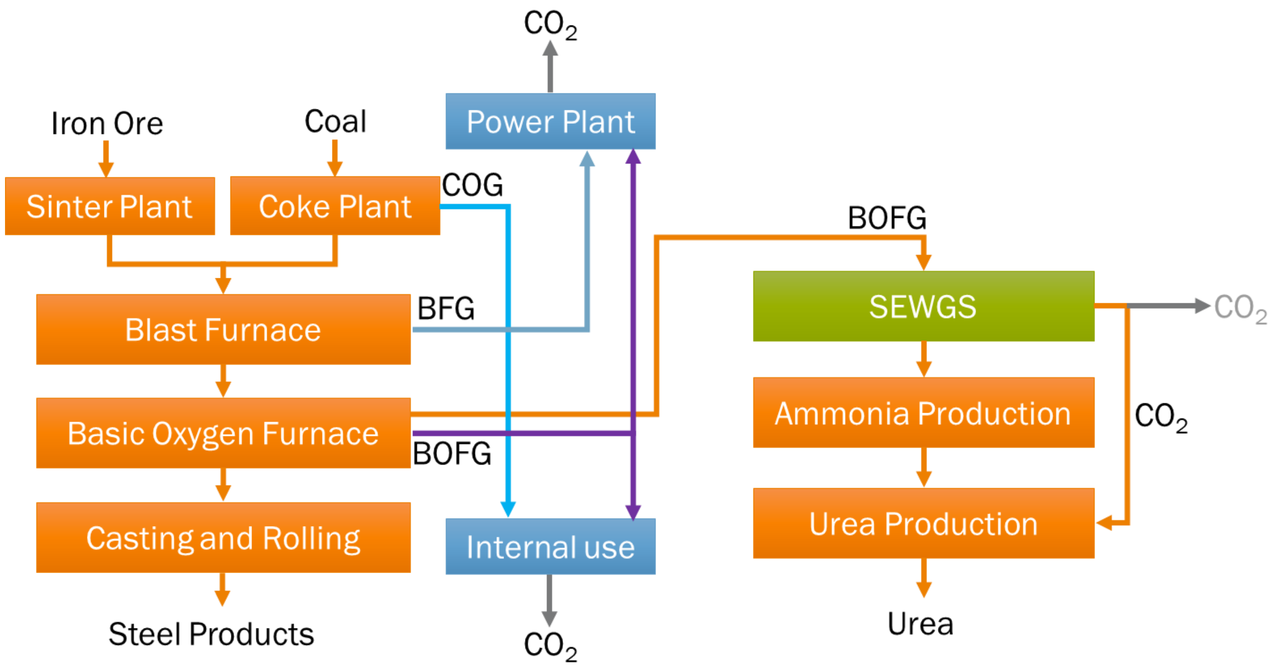

FIGURE 4. INITIATE concept

The activity of WP5: system modelling and techno-economic assessment of the entire INITIATE concept together with detailed modelling of the ammonia loop. In this Deliverable 5.3 (Definition of the base and reference cases for the KPIs assessment), the base and reference cases have been defined along with the main key performance indicators (KPIs) to compare the performance with the INITIATE technologies.

2. Base cases

The base cases are defined as state-of-the-art commercially available plants.
The following base cases have been selected.

TABLE 6. Base cases

Plant	Product	Size	Technology	Application
Steel plant	Hot rolled coil	3.16 Mt/y		
Ammonia plant	Ammonia	86 t/day	Natural gas steam reforming	Stand alone or with urea plant
	Ammonia	848 t/day	Natural gas steam reforming	Stand alone or with urea plant
Urea plant	Liquid urea	150 t/day	Conventional process	AdBlue
	Liquid urea	1500 t/day	CO_2 stripping process	Liquid fertilizer

2.1. Steel plant

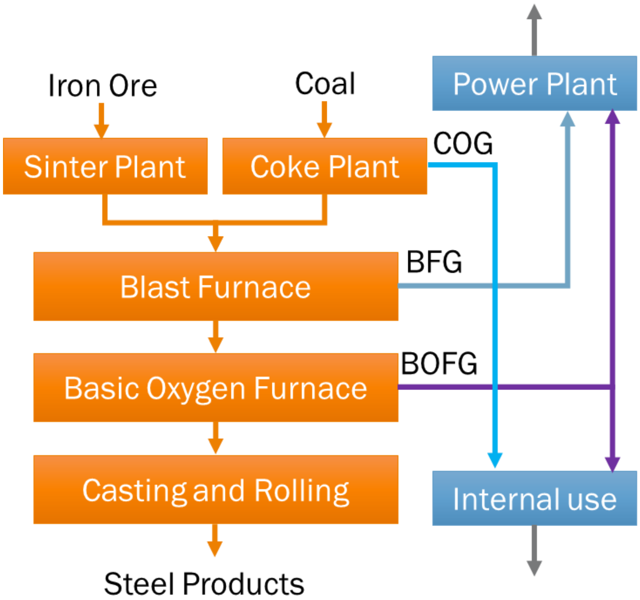

FIGURE 5. Schematic of steel production

Steel products are principally produced from reduction of iron ore or melting of recycled scrap. In the typical integrated steel plant several processes are involved in the production of hot rolled coil (HRC):

- raw materials preparation (sinter, coke and lime production);
- iron making process (hot metal production and desulphurization);
- steelmaking process (basic oxygen steelmaking process, ladle metallurgical refining);
- casting (continuous slab casting);
- reheating and rolling (finishing mill) [5].

Typically, off-gases from the steel mill, i.e. Blast Furnace Gas (BFG), Coke Oven Gas (COG) and Basic Oxygen Furnace Gas (BOFG), are used in the integrated power plant as fuel to cover part of the electricity demand. The electricity in excess is usually sold to the grid. Emissions related to the power plant section are around 50% of the overall CO_2 emissions while the remaining emissions are associated with several locations of the steel mill [2].

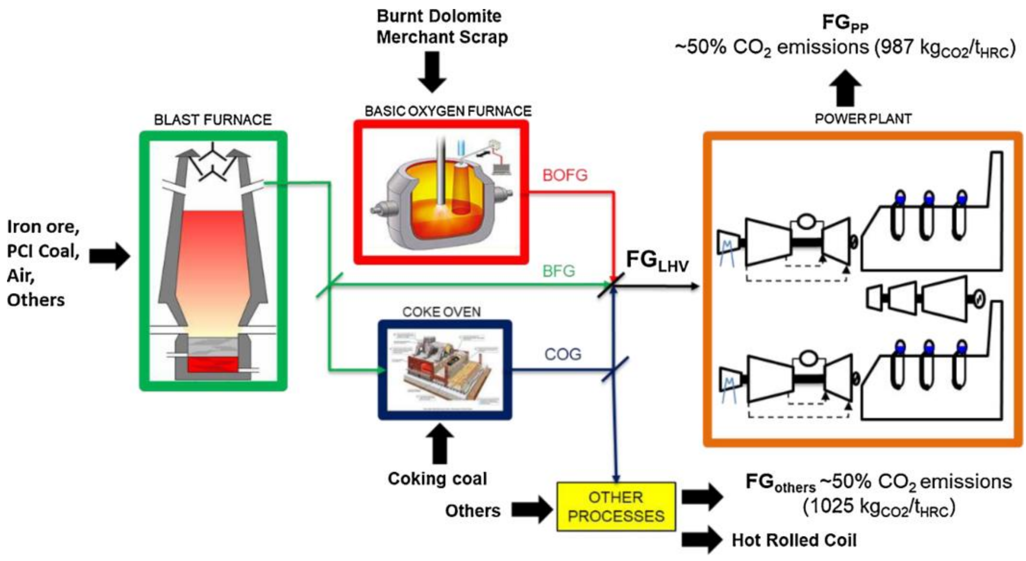

FIGURE 6. Integrated steel plant layout [2]

2.2. Ammonia plant

Ammonia is synthesised from nitrogen and hydrogen according to the following reaction:

$$N_2 + 3H_2 \leftrightarrow NH_3$$

Nitrogen is obtained from air while hydrogen is produced mainly from fossil fuels. Two different methods are used to produce hydrogen: steam reforming and partial oxidation.
Since that 77% of the ammonia globally produced is synthetised from natural gas through steam reforming, this case has been selected as base case [4].

Main output from ammonia production are: (i) anhydrous ammonia, (ii) CO_2, from clean-up section, that can be used for the urea synthesis and (iii) steam (modern steam reforming processes can be designed with no steam export or with some export if this is favourable for the site energy balance) [4].

Around 80% of ammonia worldwide produced is used in the fertilizer industry while the rest is used in several sectors [4].

2.2.1. Steam reforming

Using the steam reforming method ammonia is manufactured in six steps: (1) natural gas desulfurization, removing sulphur species, (2) catalytic steam reforming, in which hydrogen is produced and nitrogen is introduced in the synthesis process, (3) carbon monoxide shift, converting CO into CO_2 and producing additional hydrogen, (4) carbon dioxide removal, (5) methanation, to remove residual races of CO and CO_2, and (6) ammonia synthesis, to produce anhydrous ammonia. All ammonia plants use this basic process, but details such as operating pressures, temperatures, and quantities of feedstock are site specific.

2.2.1.1. Desulphurization

Sulphur compounds present in the natural gas feedstock must be removed since these compounds, even in small quantities, poison the catalyst used in the steam reforming process. The desulphurization is achieved by preheating the gas feed at around 350 – 400°C, (i) hydrogenating the sulphur compounds to H_2S and (ii) removing H_2S on a ZnO adsorber.

Final concentration of H_2S in gas feedstock should be less than 0.05 ppm (v/v) [6].

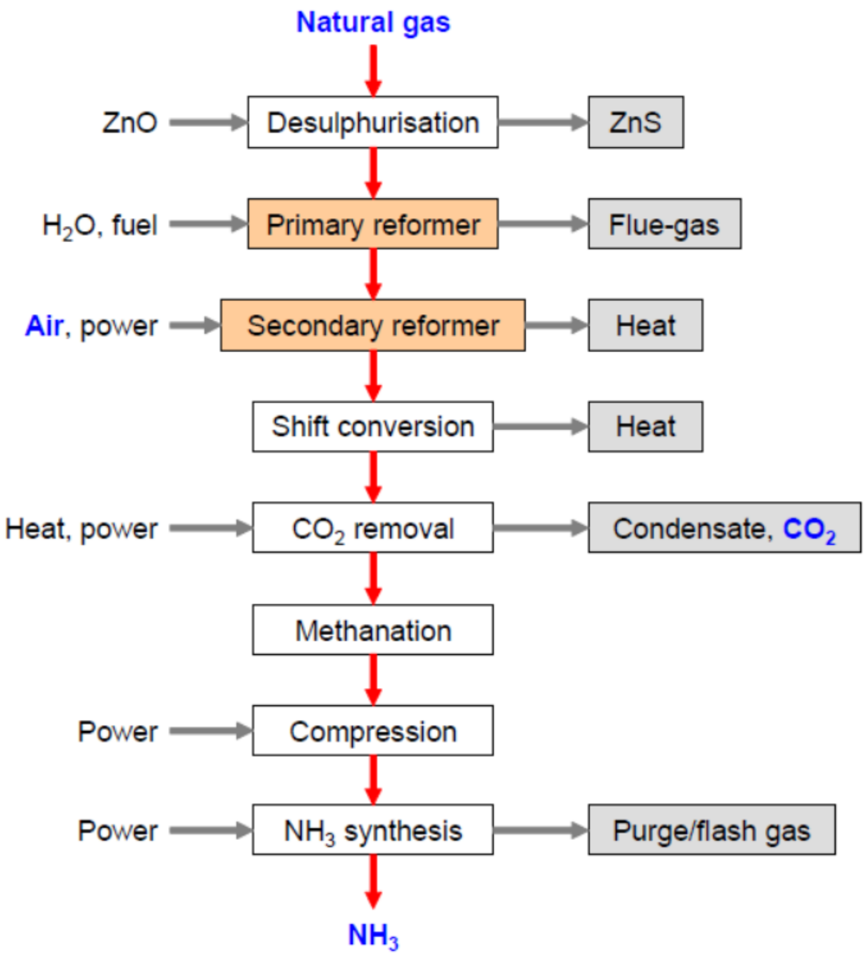

FIGURE 7. Schematic of NH3 synthesis through steam reforming

2.2.1.2. Primary reformer

The primary reformer is based on the principle of steam methane reforming (SMR).
Gas from desulphuriser is mixed with process steam; this mixture is preheated up to 400 – 600°C and enters the primary reformer, where natural gas (composed principally by methane) is reformed producing a syngas that mainly consist of H_2, CO_2, CO, CH_4 and steam.
The overall reaction is highly endothermic:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H_0 = 206 \text{ kJ/mol}$$

The primary reformer consists of a large number of tubes filled by catalyst. The heat necessary to the reaction is supplied by burning natural gas or another fuel; the residual heat in the flue gas is exploited to preheat several streams, such as the process air or the natural gas feedstock, in the convection section of the reformer. The steam to carbon molar ratio is usually around 3.0 [4], [6].

2.2.1.3. Secondary reformer

The secondary reformer is an air blown auto-thermal reforming (ATR).
In the secondary reformer, process air is added and the conversion of hydrocarbon is completed. The reaction heat is supplied by natural gas combustion in sub stoichiometric condition, taking place in the upper section of the ATR. In the lower section of the ATR, a catalyst bed containing nickel reforms the gas mixture producing the right amount of hydrogen and reducing the concentration of methane to less than 0.8%v.

Process air is compressed and then heated to around 500 – 600°C. The temperature of the gas mixture at the outlet of the ATR is approximately 1000°C and it is cooled to 330 – 380°C before being fed to shift conversion section, producing high pressure steam [4], [6].

2.2.1.4. Shift conversion

The gas leaving the ATR contains a significant amount of CO (12 – 15% on dry gas base) that is converted to CO_2 and H_2 in the shift section:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H_0 = -41 \text{ kJ/mol}$$

The reaction takes place in two stages. In the first reactor, the high temperature shift (HTS), the process gas passes through an iron-based catalyst promoted by chromium/copper oxides.

Before the low temperature shift reactor (LTS), that uses a copper oxide/zinc oxide catalyst, the gas leaving the HTS is cooled to around 180 – 220°C. The final concentration of CO is reduced to 0.1 – 0.3% (dry basis) [4], [6].

2.2.1.5. CO_2 removal

In this section the CO_2 in the syngas is removed. The final CO_2 content is approximately equal to 50 – 3000 ppmv. CO_2 can be removed using chemical or physical absorption process. In chemical absorption amine solutions, such as mono-ethanolamine (MEA) and methyl-diethanolamine (MDEA) or hot potassium carbonate solutions are mainly used. Glycol dimethylethers (Selexol) and propylene carbonate are the solvents typically used in physical absorption.
Pressure swing adsorption process (PSA) could also be used [4].

2.2.1.6. Methanation

In this section the residual amounts of CO and CO_2 are converted to CH_4 because oxygen compounds poison the ammonia synthesis catalyst. Two reactions take place:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad \Delta H_0 = -206 \text{ kJ/mol}$$
$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad \Delta H_0 = -165 \text{ kJ/mol}$$

Temperature in methanator is around 300°C and a rise of approximately 20°C takes place. Water formed is removed before entering the ammonia synthesis loop [4], [6].

2.2.1.7. Compression

Operating pressure of ammonia synthesis vary between 100 bar to over 300 bar [4], [7]. Centrifugal compressors typically driven by steam turbines are used to achieve these pressure levels. Typical operating temperatures range from 350 – 550°C [4].

2.2.1.8. NH_3 synthesis

The ammonia synthesis takes place on an iron catalyst in the ammonia synthesis converter:

$$N_2 + 3H_2 \leftrightarrow 2NH_3 \qquad \Delta H_0 = -46 \text{ kJ/mol}$$

In the ammonia reactor only 20 – 30% of the nitrogen and hydrogen are converted into ammonia. The unreacted gas is recycled after liquid ammonia separation.

Being an exothermic reaction, the temperature in the catalyst needs to be controlled by the injection of cooled synthesis gas or generating high pressure steam. The effluent gas from the ammonia reactor is then cooled in the ammonia chillers in order to condense ammonia which is separated from effluent gas in the ammonia separator. The effluent gas from the ammonia separator is then recycled back to the ammonia reactor.

The syngas from methanation section contains small quantities of inert gases, (i.e. Ar and CH_4), that accumulate in the synthesis loop and inhibit the formation of ammonia. To avoid the accumulation, a continuous purge is required. Purge gas, containing ammonia, nitrogen, hydrogen, inerts and unreacted gases, is sent to the recovery units to recover the ammonia (which is mainly recycled back to ammonia synthesis loop) and the hydrogen, while the tail gas is used as fuel in the SMR.
Liquid ammonia can be stored at -33°C and 1 atm or sent as warm product to a urea plant (10 – 20°C, 10 – 20 bar(g)) [4], [6].

2.2.1.9. Steam and energy system

The high amount of heat available in the different sections of the plant, e.g. reformer section, shift section and ammonia synthesis section, is usually exploited to generate high pressure steam exploited in steam turbines used to drive the synthesis gas compressor. At a medium pressure level part of the steam is extracted and used as process steam in the reforming reaction or used to drive other equipment. Usually, in modern ammonia plant there is an export of steam to other consumers [4].

2.3. Urea plant

Urea is synthetised from ammonia and carbon dioxide, both produced in the ammonia plant. Ammonia and carbon dioxide react at high pressure forming ammonium carbamate, which dehydrates forming urea and water:

$$2NH_3 + CO_2 \leftrightarrow NH_2COONH_4 \qquad \Delta H_0 = -151 \text{ kJ/mol}$$
$$NH_2COONH_4 \leftrightarrow NH_2CONH_2 + H_2O \qquad \Delta H_0 = 32 \text{ kJ/mol}$$

The two reactions take place in the same reactor: the first one, fast and exothermic, goes to completion rapidly while the second one, slower and endothermic, does not go to completion [8]. The conversion is favoured increasing temperature and NH_3/CO_2 ratio and decreasing the H_2O/CO_2 ratio.

Other reactions may take place in urea synthesis, for example the formation of biuret that must be avoided since it causes crop damage.

Typical urea production parameters are:
- pressure: 140 – 250 bar
- temperature: 180 – 210°C
- NH_3/CO_2 ratio: 2.8:1 – 4:1
- retention time: 20 – 30 minutes

Modern urea plants are based on the “total recycling process”. Different processes have been developed:
- conventional process without stripping
- CO_2 stripping process, e.g. by Stamicarbon or Toyo’s ACES process
- NH_3 stripping process, e.g. by Snamprogetti
- Isobaric Double Recycling process (IDR), applying stripping with NH_3 and CO_2, by Montedison [4]

As base cases, a conventional process without stripping has been selected for the small-scale urea plant while a CO_2 stripping process has been selected for the large-scale urea plant.

In addition, the final product, for both plants, is in liquid form, so the prilling or granulation section is not considered in this study.

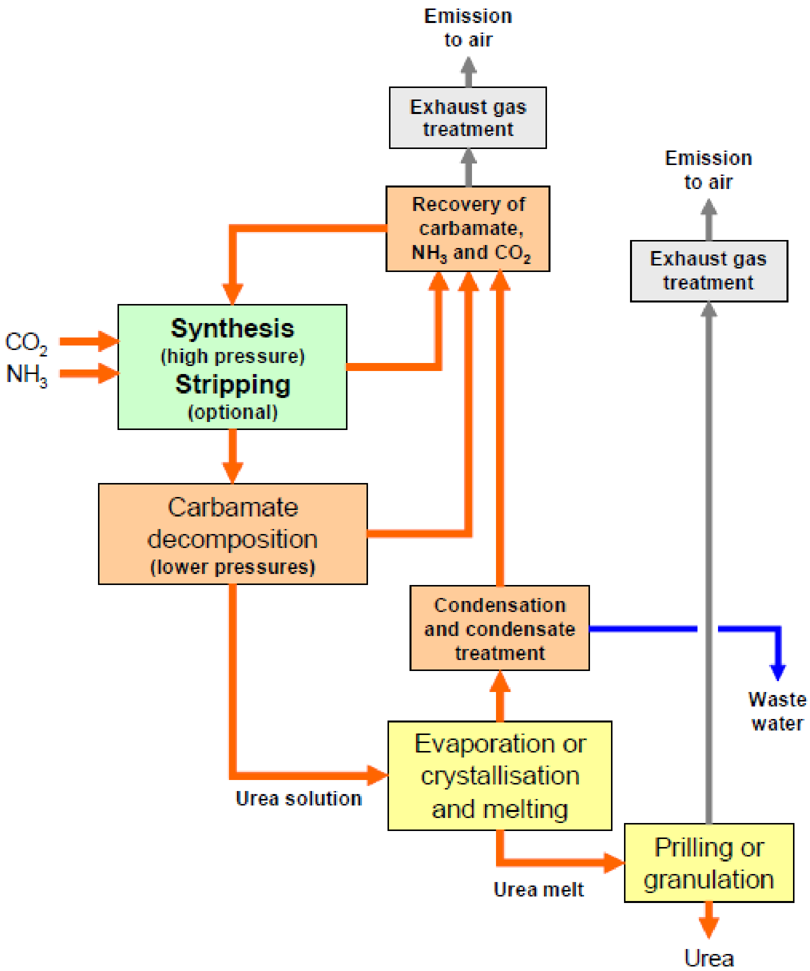

FIGURE 8. Urea synthesis through total recycling processes [4]

2.3.1. Conventional total recycling process

In conventional total recycling processes, the stripping section is not present. Carbamate is decomposed into NH_3 and CO_2 in three steps decreasing the pressure. NH_3 and CO_2 are then recycled back to the reactor with the residual carbamate.

Typical conditions of a conventional total recycling process are resumed in the following table.

TABLE 7. Typical conditions of a conventional total recycling process

Process sequence	Conditions	
Reactor	NH_3/CO_2 ratio	4:1
	Conversion	65 – 67% of CO_2 input
	Pressure	200 bar
Carbamate decomposition	Decomposer 1 pressure	16 – 20 bar
	Decomposer 2 pressure	3 bar
	Decomposer 3 pressure	1 bar

2.3.2. CO_2 stripping process

In CO_2 stripping process, NH_3 and CO_2 are converted to urea at a pressure of approximately 140 bar and a temperature of 180 – 185°C. About 60% of CO_2 and 41% of NH_3 are converted into urea. The reactor effluents are sent to the high-pressure CO_2 stripper that operates at the same pressure of the reactor. In the CO_2 stripper, the unconverted NH_3 and CO_2 are stripped off using carbon dioxide as stripping agent. Then the recovered NH_3 and CO_2 are partially condensed and recycled back to the reactor, producing steam at 4.5 bar. The NH_3 and CO_2 present in the stripper effluent are vaporized and then condensed to form a carbamate solution which is recycled back to the urea reactor [9].

TABLE 8. Typical conditions of a CO_2 stripping process

Process sequence	Conditions	
Reactor	NH_3/CO_2 ratio	2.8:1 (CO_2 via CO_2 stripper)
	Temperature	180°C
	Pressure	140 bar
Carbamate decomposition	Pressure	3 bar

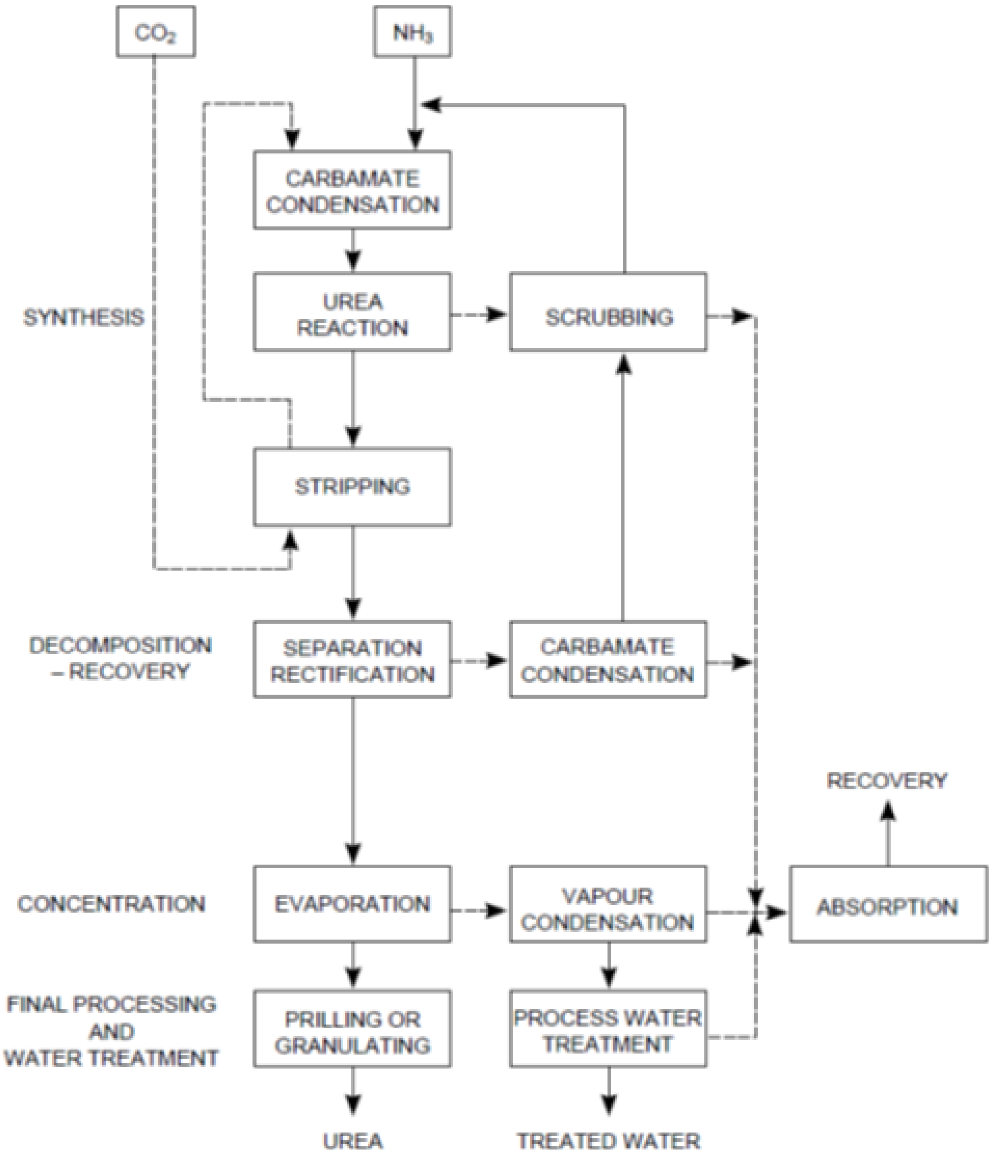

FIGURE 9. Block diagram of a CO_2 stripping process [9]

3. Reference cases

The reference cases are defined as state-of-the-art commercially available plants with CO_2 capture technologies.
The following reference cases have been selected.

TABLE 9. Reference cases

Plant	Product	Size	Technology	Application	CO_2 capture
Steel plant	Hot rolled coil	3.16 Mt/y			WGS + MDEA pre-comb. on BFG
Ammonia plant	Ammonia	86 t/day	Natural gas steam reforming	Stand alone or with urea plant	MEA post combustion
	Ammonia	848 t/day	Natural gas steam reforming	Stand alone or with urea plant	MEA post combustion
Urea plant	Liquid urea	150 t/day	Conventional process	AdBlue	None
	Liquid urea	1500 t/day	CO_2 stripping process	Liquid fertilizer	None

Basically, the plants considered as reference case are the base case plants with an additional section where CO_2 is removed from BFG (steel plant) or from primary reformer flue gases (ammonia plant). In the following section a simplified block diagram of the plants integrating a carbon capture section is shown.

3.1. Steel plant

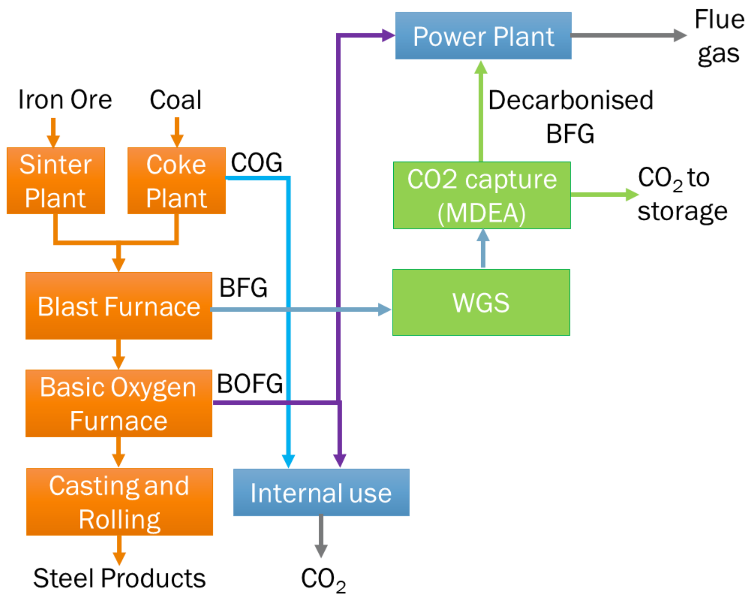

FIGURE 10. Reference case – steel plant

C4U project is taken as reference for the definition of the steel reference plant.

BFG, COG and BOFG all contain CH_4, CO, CO_2, H_2 and N_2 but BFG has the highest CO/CO_2 ratio and the lowest LHV due to higher N_2 and CO_2 concentration. Therefore, CO_2 removal from BFG is more cost-effective than from COG and BOFG (due to the higher CO_2 content in BFG) and it will increase BFG LHV which can be used as a fuel [10].

For this reason, in the reference steel plant only BFG is treated and decarbonised. First BFG is converted into H_2+CO_2-rich gas in the WGS stage, reacting with steam. Then the shifted gas is cooled and sent to the MDEA precombustion CO_2 removal section. A schematic of the reference steel plant is shown in FIGURE 10. In this work the power plant taken into account is a combined cycle.

3.1.1. WGS + MDEA pre combustion carbon capture section

This section describes the decarbonization process of BFG in the reference steel plant.
BFG is firstly converted into H_2+CO_2-rich gas in the WGS stage, reacting with steam. H_2O, available at 3 bar and 145°C is heated up to 330°C and then added to the WGS reactor. The shifted gas is cooled to 355°C pre-heating the WGS feed mixture. Before entering the absorber column, the shifted gas is further cooled to 40°C and the condensed water is removed. In the absorber column, the syngas is in contact with the lean solvent (MDEA) that absorbs the carbon dioxide. A decarbonised clean fuel (DCF) exits at the top of the column while the CO_2 rich solvent exits from the bottom. The rich solvent is pumped to 6 bar and heated to 80°C before entering the stripping column. The lean solvent leaves the bottom of the stripper, it is expanded to 2 bar and cooled to 40°C, then it is fed to the top of the absorber. The high-purity CO_2 exits the stripper column at the top and the evaporated water is removed in a condenser. The CO_2-rich stream is then compressed up to 78 bar in a multistage compressor, liquefied being cooled to 25°C and pumped to 110 bar [10].

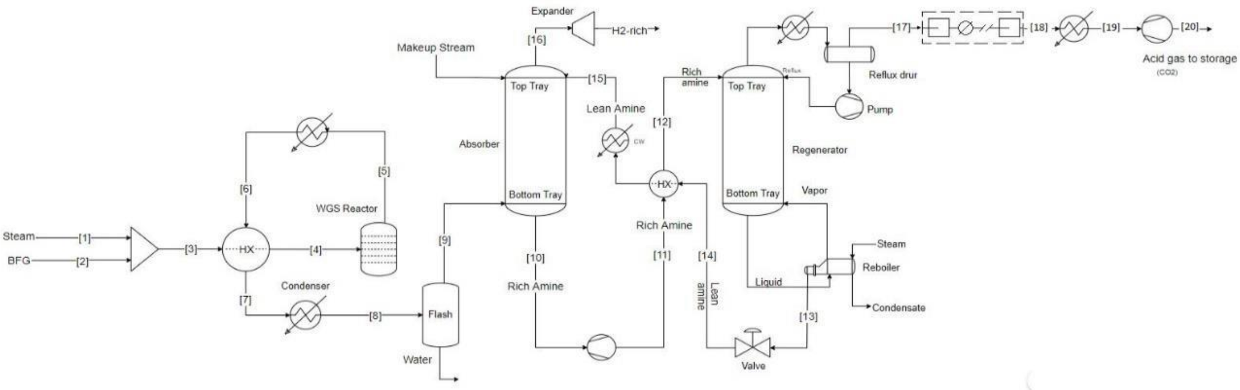

FIGURE 11. **Layout of the BFG decarbonisation section in the steel plant [10]**

3.2. Stand-alone ammonia plant

The simplified block flow diagram for the stand-alone reference ammonia plant is shown below. Flue gas from the primary reformer is treated in a post-combustion carbon capture section where CO_2 is removed using MEA and sent to storage. Similarly, the CO_2 stream, from the CO_2 removal section of the ammonia plant is sent to storage.

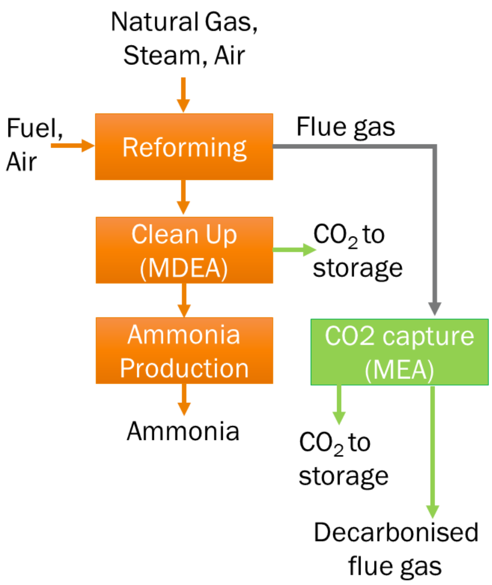

FIGURE 12. **Reference case – stand-alone ammonia plant**

3.2.1. MEA post combustion carbon capture section

This section describes the MEA post combustion carbon capture section for the decarbonisation of flue gas from the primary reformer of the ammonia plants.
Before the absorber column, the flue gas is cooled to 40°C and the condensed water is removed. In the absorber column, the flue gas is contacted with lean MEA and CO_2 in the flue gas is absorbed by the solvent. The CO_2 lean flue gas leaves the absorber top while rich solvent is pumped to 2.1 bar, heated to 115°C and then sent to the stripper. A CO_2-rich stream leaves the top of the stripper while the regenerated solvent exit from the bottom. The high-purity CO_2 is compressed to 80 bar in a multistage compressor, liquefied being cooled to 25°C and pumped to 110 bar.

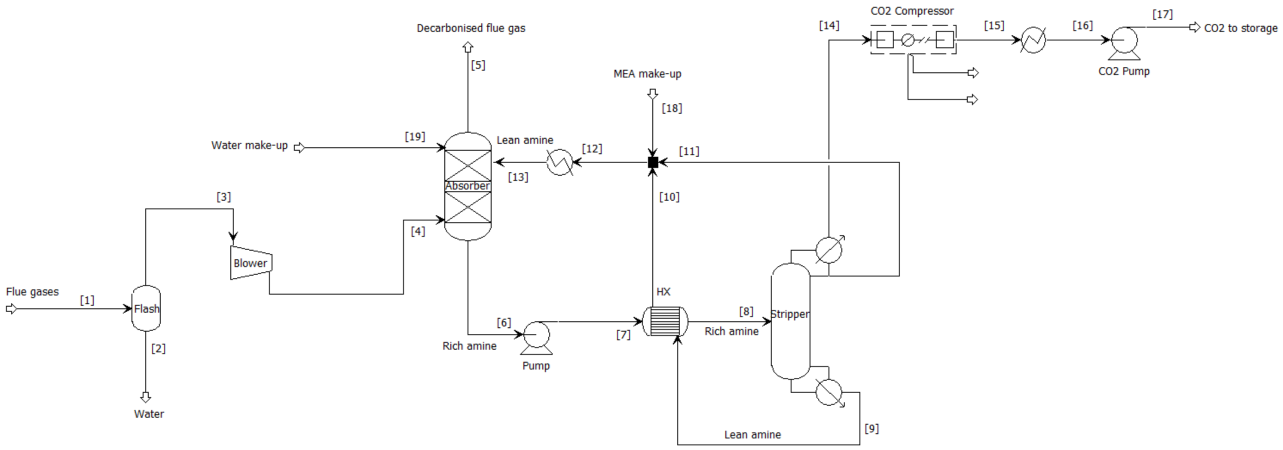

FIGURE 13. Layout of the flue gases decarbonisation section in the ammonia plant

3.3. Ammonia plant coupled with urea plant

The simplified block flow diagram for the reference ammonia plant coupled with a urea plant is shown below. Flue gas from the primary reformer is treated in a post-combustion carbon capture section where CO_2 is removed using MEA and sent to storage. The CO_2 stream, from the CO_2 removal section of the ammonia plant is sent to urea plant.

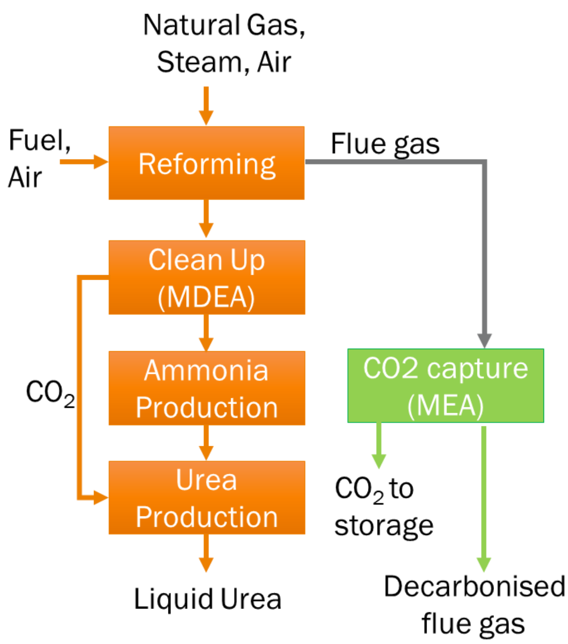

FIGURE 14. Reference case – ammonia plant coupled with urea plant

4. Methodology

Main assumptions used for the techno-economic analysis are shown in the following sections.

It is assumed that in ammonia plant the additional heat required in the CO_2 capture section is supplied generating steam in a boiler with 95% efficiency in which natural gas having the composition of TABLE 15 is burnt. This happens only if not enough steam is generated internally in the ammonia plant and additional steam has to be imported.

TABLE 10. General assumptions used in techno-economic analysis of ammonia and urea plants

Parameter		Value
Specific CO_2 emission from electricity production	[kg_{CO2}/MWh]	255 [11]
Gas boiler efficiency (for additional steam production)	[%]	0.95 [12]
Electricity production efficiency	[%]	0.45 [13]
CO_2 emission from natural gas combustion	[kg_{CO2}/kg_{NG}]	2.78

4.1. Steel plant

C4U project is taken as reference for the definition of the steel plant.
The steel plant considered in this study is representative of a steel mill located in Europe with an annual production of 3.16 Mt of hot rolled coil and it is based on a 125.1 kg/s (thermal input of 294.67 MW) of BFG gas which composition is shown in TABLE 12.
BFG LHV is 2.35 MJ/kg and its molecular weight is 30.8 kg/kmol [10].
BFG, along with a part of BOFG, are used as fuel for the power section (a combined cycle) of the integrated steel mill.

TABLE 11. Steel plant assumptions [2]

Parameter		Value
Primary energy consumption	[GJ/t_{HRC}]	21.3
Steel plant specific CO_2 emissions	[t_{CO2}/t_{HRC}]	1112
Cost of hot rolled coil	[€/t_{HRC}]	468

TABLE 12. BFG composition (dry basis)

Species	Mole fraction [%]
CO_2	21.2
CO	22.7
CH_4	0.2
H_2	2.4
N_2	53.5
S compounds	Not considered

4.1.1. Combined cycle

The simulation of the power plant has been carried out in Aspen Plus V8.8 and PENG-ROB equation of state has been used [10].

The combined cycle consists of a Brayton cycle (gas cycle) coupled with a Rankine cycle (steam cycle) that exploit the heat available in the gas turbine exhaust gas to produce steam in a 3 pressure levels heat recovery steam generator (HRSG).

Main parameters of the combined cycle are resumed in TABLE 13 while the combined cycle layout is shown in FIGURE 15.

TABLE 13. Combined cycle parameters [10]

Parameter		Value
BFG compressor		
- Isentropic efficiency	[%]	80
- Mechanical efficiency	[%]	95
- Delivery pressure	[bar]	28
- Number of stages	[-]	3
Gas turbine		
- Pressure ratio	[-]	17
- Turbine inlet temperature	[°C]	1180
- Generator efficiency	[%]	98.5
- Mechanical efficiency	[%]	99.6
- Isentropic/polytropic efficiency compressor	[%]	88
- Isentropic/polytropic efficiency expander	[%]	99.6
Heat Recovery Steam Generator		
- Pressure levels	[bar]	130 - 28 - 4
- Maximum temperature	[°C]	540
- Condensing pressure	[bar]	0.048
- Turbine isentropic efficiencies (HP - IP - LP)	[%]	92 - 94 - 88
- Pump efficiency (HP - MP)	[%]	83 - 75
- HRSG pressure losses	[kPa]	3
- ΔT pinch point	[°C]	10
- ΔT approach point	[°C]	25
Heat exchangers		
- Minimum ΔT gas-gas heat exchanger	[°C]	25
- Minimum ΔT gas-liquid heat exchanger	[°C]	10
- Minimum ΔT liquid-liquid heat exchanger	[°C]	10

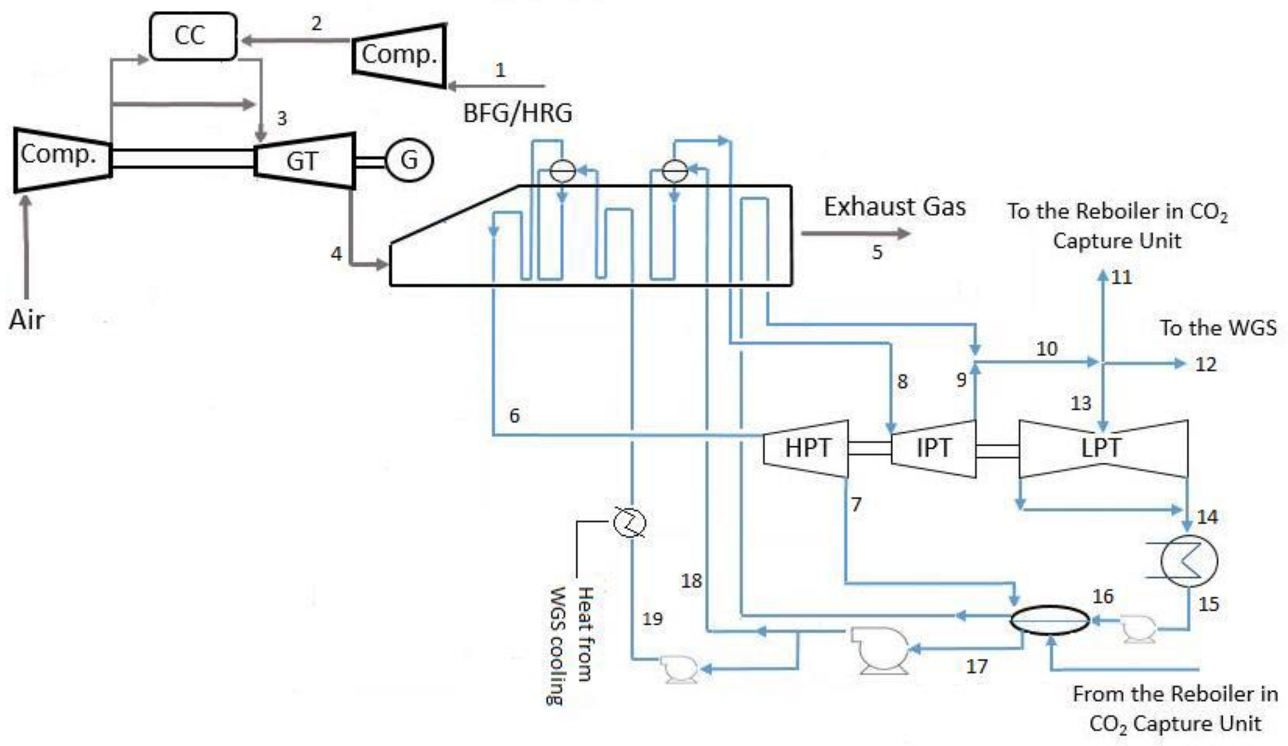

FIGURE 15. Combined cycle layout [10]

4.1.2. WGS + MDEA pre-combustion carbon capture section

In the reference steel plants decarbonisation of BFG is performed implementing a WGS and a MDEA pre-combustion section, as described in section 3.1.1. The simulation of the decarbonisation plant has been carried out in Aspen Plus V8.8 and the ELECNRTL method has been used [10].
The assumptions for the simulation of the capture plant are reported in the following table.

TABLE 14. Assumptions of the WGS + MDEA pre-combustion carbon capture section [10]

Parameter		Value
MDEA CO_2 absorption process		
- MDEA/water content in the lean solvent	[%wt]	25/72
- Absorber stage number	[-]	20
- Solvent/CO_2 ratio	[%wt basis]	3/25
- Stripper stage number	[-]	20
- Steam condition at the reboiler	[bar]	6.0
- Pinch point ΔT in regenerative heat exchanger	[°C]	10.0
- Pump hydraulic/mech efficiency	[%]	75/95
Heat exchangers		
- Minimum ΔT gas-gas heat exchanger	[°C]	25
- Minimum ΔT gas-liquid heat exchanger	[°C]	10
- Minimum ΔT liquid-liquid heat exchanger	[°C]	10
Turbomachines		
- Expander isentropic efficiency	[%]	93
- Expander delivery pressure	[bar]	1.015

Parameter		Value
CO_2 compression train		
- Number of stages	[-]	2
- Intercoolers temperature	[°C]	40
- Intercoolers pressure drops	[% of p_{inlet}]	5
- Isentropic efficiency	[%]	80
- Mechanical efficiency	[%]	95
- CO_2 delivery pressure	[bar]	110
- CO_2 delivery temperature	[°C]	31

4.2. Ammonia plant

The simulation of the ammonia plants has been carried out in Aspen Plus V11. The ammonia plant was simulated with the RKS-BM method, except for the clean-up section where the ELECNRTL method was used. The composition of the natural gas used as fuel and as feedstock is shown in the following table. Its LHV is equal to 48.45 MJ/kg.

TABLE 15. Composition of the natural gas

Species	Mole fraction [%]
CH_4	80.049
C_2H_6	17.715
C_3H_8	0.939
N-BUTANE	0.059
N-PENTAN	0.187
N-HEXANE	0.059
N_2	0.790
SULFUR	1.00E-04

Main operational conditions selected for the ammonia plants are summarized in TABLE 16, TABLE 17 and TABLE 18.

TABLE 16. Operational conditions of natural gas, process steam and process air in ammonia plant

Stream	Operational condition	
Natural gas feedstock	Pressure	38 bar
	Temperature	45°C
Natural gas fuel	Pressure	1.3 bar
	Temperature	47°C
Process steam	Pressure	35 bar
	Temperature	360°C
Process air	Pressure at ATR inlet	32.4 bar
	Temperature at ATR inlet	410°C

TABLE 17. Ammonia plant operational conditions

Section	Operational condition	
Desulphurization	Inlet pressure	35 bar
	Inlet temperature	345°C
	Outlet temperature	325°C
Primary reformer	Inlet pressure	35 bar
	Inlet temperature	495°C
Secondary reformer	Secondary reformer inlet pressure	31 bar
	Secondary reformer outlet temperature	900°C
Shift conversion	HTS inlet temperature	380°C
	HTS outlet temperature	440°C
	LTS inlet temperature	210°C
	LTS outlet temperature	230°C
CO_2 removal	MDEA (50% MDEA on weight basis)	
Methanation	Inlet temperature	280°C
NH_3 synthesis	NH_3 reactor inlet temperature	450°C
	NH_3 reactor outlet temperature	440°C
	NH_3 reactor inlet pressure	292 bar
NH_3 refrigeration (only for stand-alone ammonia plant)	Pressure	1 atm
	Temperature	-33°C

TABLE 18. Efficiencies of the main equipment in ammonia plants

Parameter		Small-scale	Large-scale
Process air compressor polytropic efficiency	[-]	0.75	0.85
Process air compressor mechanical efficiency	[-]	0.95	0.95
Syngas compressor polytropic efficiency	[-]	0.75	0.85
Syngas compressor mechanical efficiency	[-]	0.95	0.95
NH_3 synthesis compressor polytropic efficiency	[-]	0.75	0.85
NH_3 synthesis compressor mechanical efficiency	[-]	0.95	0.95
CO_2 compressor in clean up section polytropic efficiency	[-]	0.75	0.85
CO_2 compressor in clean up section mechanical efficiency	[-]	0.95	0.95
Pumps hydraulic efficiency	[-]	0.75	0.75
Pumps mechanical efficiency	[-]	0.95	0.95

It is assumed that the efficiency of the equipment in small-scale scale ammonia plant is lower with respect to the corresponding equipment in the large-scale ammonia plant.

Further assumptions are reported in TABLE 19. It is assumed that for the small-scale ammonia plant all the equipment are electrically driven meaning that all the electric power necessary for the plant is imported from the grid. On the other hand, in the large-scale ammonia plant the main equipment (i.e. compressors) are driven by steam turbines, exploiting the steam generated in the plant. Consequently, the steam exported is higher for the small-scale ammonia plant with respect to the large-scale one. In any case, when the ammonia plant is coupled with a urea plant the overall import of steam is equal or nearly equal to 0 GJ.

TABLE 19. Ammonia plants electric and steam input

Parameter		Small-scale	Large-scale
Ammonia plant power consumption	[MWh/ton$_{NH3}$]	1.40	0.70
Ammonia plant power imported from the grid	[GJ/t$_{NH3}$]	11.2	0.3 [14]
Ammonia plant steam input	[GJ/t$_{NH3}$]	-7.7	-3.9 [14]

4.2.1. MEA post combustion carbon capture section

As described in section 3.2.1 decarbonisation of flue gases from primary reformer in ammonia plants is performed in a MEA post combustion carbon capture plant. The simulation of the MEA CO_2 capture section has been carried out in Aspen V11 and the ENRTL-RK method has been selected.

The assumptions for the simulation of the capture plant are reported in TABLE 20.
The CO_2 compression train has been modelled according to [15].

TABLE 20. Assumptions of the MEA post-combustion carbon capture section

Parameter		Value
MEA CO_2 absorption process		
- MEA/water content in the lean solvent	[%wt]	32/68
- Absorber stage number	[-]	15
- Liquid to gas ratio	[%wt basis]	1.5
- Stripper stage number	[-]	20
- Steam condition at the reboiler	[bar]	2.0
- Pinch point ΔT in regenerative heat exchanger	[°C]	10.0
- Pump hydraulic/mech efficiency	[%]	75/95
CO_2 compression train		
- CO_2 compressor number of stages	[-]	3
- Intercoolers temperature	[°C]	28
- Intercoolers pressure drops	[bar]	0.05/0.19
- Polytropic efficiency	[%]	80
- Mechanical efficiency	[%]	95
- CO_2 delivery pressure	[bar]	110
- CO_2 delivery temperature	[°C]	31

4.3. Urea plant

Steam input in the small-scale, being based on a conventional total recycled process, is assumed to be double the amount needed for the large-scale one. Urea plants electric and steam input are showed in the following table while the efficiencies of the main equipment present in the urea plants can be found in TABLE 22. Urea plants are simulated in in Aspen Plus V11 using SR-POLAR method.

TABLE 21. Urea plants electric and steam input

Parameter		Small-scale	Large-scale
Urea plant power imported from the grid	[kWh/t$_{urea}$]	20	20
Urea plant steam input	[GJ/t$_{urea}$]	4.4	2.2 [14]

TABLE 22. Efficiencies of the main equipment in urea plants

Parameter		Small-scale	Large-scale
CO_2 compressor polytropic efficiency	[-]	0.75	0.85
CO_2 compressor mechanical efficiency	[-]	0.95	0.95
Pumps hydraulic efficiency	[-]	0.75	0.75
Pumps mechanical efficiency	[-]	0.95	0.95

Also in this case it is supposed that in the small-scale plant the efficiency of the equipment is lower.

4.3.1. Small-scale urea plant

Main operational condition of the small-scale urea plant, based on a conventional full recycling process are resumed in TABLE 23.

TABLE 23. Small-scale urea plant operational conditions

Process sequence	Operational condition	
NH_3 feed	Pressure	20 bar
	Temperature	26°C
CO_2 feed	Pressure	1 bar
	Temperature	40°C
Reactor	NH_3/CO_2 ratio	4:1
	Conversion	68% of CO_2 input
	Pressure	195 bar
Carbamate decomposition	Decomposer 1 pressure	19.6 bar
	Decomposer 2 pressure	4.12 bar
	Decomposer 3 pressure	1.47 bar

4.3.2. Large-scale urea plant

Main operational condition of the large-scale urea plant, based on a CO_2 stripping process are resumed in the following table.

TABLE 24. Large-scale urea plant operational conditions

Process sequence	Operational condition	
NH_3 feed	Pressure	20 bar
	Temperature	26°C
CO_2 feed	Pressure	1 bar
	Temperature	40°C
Reactor	NH_3/CO_2 ratio	3, CO_2 via CO_2 stripper
	Temperature	180°C
	Pressure	138 bar

4.4. Economic assessment approach

In the following sections, the assumptions for the assessment of the economic model are described.

4.4.1. Steel plant

In the steel plant the purchase cost $\boldsymbol{C}$ of the equipment in CO_2 capture section and in the power plant section is calculated according to the following equation:

$$C = n \cdot C_0 \left(\frac{S}{n \cdot S_0} \right)^f \tag{4.1}$$

where $\boldsymbol{C_0}$ is the cost of the reference component with the capacity of $\mathbf{S_0}$ and $\boldsymbol{f}$ is the scaling factor.

Total equipment cost (TEC) is then computed as:

$$TEC = \sum_i C_i \tag{4.2}$$

The scaling parameters for the component purchase cost can be found in the following table.

TABLE 25. Scaling parameters for component purchase cost [10]

Component	Scaling factor	C_0 [M€]	S_0	f
CO_2 capture unit (MDEA)	CO_2 mass flow rate [t/h]	8.8	12.4	0.6
CO_2 compressor and condenser	Power [MW]	44	50.5	0.67
Boiler	Heat duty [MW]	0.25	1	0.67
Compressor	Power [kW]	0.44	413	0.68
Pump	Volumetric flow [m^3/h]	0.017	250	0.14
WGS	H_2 and CO flow rate [kmol/s]	18.34	2.45	0.65
Fuel Compressor	Power [MW]	8.1	15.3	0.67
Expander	Power [MW]	33.7	200	0.67
Steam turbine	Power [MW]	33	200	0.67
Gas turbine	Power [MW]	49.4	272.1	0.67
HRSG	U·S [MW/K]	32.6	12.9	0.67
Cooling tower, BOP	Heat rejected [MW]	49.6	470	0.67
Heat exchanger	Heat transfer [MW]	6.1	828	0.67

Total Direct Plant Cost (TDPC) is computed as:

$$TDPC = TEC + TIC \tag{4.3}$$

where TIC is the Total Installation Cost and it is computed as shown in TABLE 26.

TABLE 26. Assumptions for the economic model of the steel plant [10]

Parameter		Value
TIC of power generation units	[%TEC]	66
TIC of CO_2 capture section	[%TEC]	104
Contingencies and owner's costs	[%TPC]	15

Parameter		Value
Engineering, procurement and construction cost	[%TDPC]	15
Variable O&M costs	[%C_{fuel}]	5
Fixed O&M costs	[%TCR]	5
BFG price	[€/GJ]	5.2
Heat price	[€/MWh]	11
Electricity price	[€/MWh]	50
Project interest rate	[%]	11
Plants lifetime	[years]	25
Plant availability	[-]	0.9

4.4.2. Ammonia and urea plants

The assumptions made regarding the economic model of the ammonia and urea plants are shown in the following table.

TABLE 27. Assumptions for the economic model of the ammonia and urea plants

		Small-scale	Large-scale
Macro-economics			
Project interest rate	[%]	8	
Plants lifetime	[years]	25	
Fixed Charge Factor	[1/y]	9.37%	
Contingencies and owner’s costs	[% of TPC]	35	
Engineering, procurement and construction cost	[% of TDPC]	20	
Variable costs			
Plant availability	[-]	0.9	
Natural gas price	[€/GJ (LHV)]	6	
Electricity price	[€/MWh]	50	
Raw process water price	[€/$t_{product}$]	1.4	
Chemicals and catalyst price	[€/$t_{product}$]	2.95	
MEA price	[€/kg]	1.042	
MEA consumption	[kg/t_{CO2}]	1.5	
CO_2 transport and storage cost	[€/t_{CO2}]	10	
Fixed costs			
Number of employees (ammonia plant)	[-]	33	33
Number of employees (urea plant)	[-]	33	33
Number of employees (CO_2 capture section)	[-]	5	5
Labour cost	[€/year]	60'000	
Maintenance cost	[%TPC]	1.5	
Maintenance labour	[% Maintenance cost]	40	
Maintenance materials	[% Maintenance cost]	60	
Adm./gen. overheads	[% O&M. labour]	30	
Insurance and local taxes	[%TPC]	1	

4.4.3. MEA post combustion carbon capture section

The cost of the MEA post combustion section has been computed with the methodology explained in section 4.4.1.

The equipment purchase cost and the total equipment cost (TEC) are calculated according to equations (4.1) and (4.2).

The scaling parameters for the component purchase cost can be found in the following table.

TABLE 28. Scaling parameters for component purchase cost

Component	Scaling factor	C_0 [M€]	S_0	f	Ref.
MEA CO_2 separation system	CO_2 captured [kg/s]	28.95	38.4	0.8	[15]
CO_2 compressor and condenser	Compressor power [MW]	9.95	13	0.67	[15]

Installation cost has been computed as follows.

TABLE 29. Assumptions for TIC calculation of MEA post-combustion CO_2 capture section [16]

Parameter		Value
Direct Installation Costs		
- Erection costs	[%TEC]	50
- Instrumentation and controls	[%TEC]	9
- Piping	[%TEC]	20
- Electrical equipment and materials	[%TEC]	12
- Civil works	[%TEC]	11
- Solvent inventory	[%TEC]	8.5
Indirect Installation Costs		
- Yard improvements	[%(TEC+TDIC)]	1.5
- Service facilities	[%(TEC+TDIC)]	2
- Engineering and supervision	[%(TEC+TDIC)]	6.5
- Buildings	[%(TEC+TDIC)]	4

5. Key performance indicators (KPIs)

The key performance indicators (KPIs) used in this work are listed below. In the definition of KPI the final product (i.e. hot rolled coil, ammonia or urea) is identified with letter "x".

In order to evaluate the energy performance of a plant the Primary Energy Consumption indicator is defined:

$$PEC\left[\frac{GJ_{LHV}}{t_x}\right] = \frac{\dot{m}_{fuel}LHV_{fuel} + \dot{W}_{req}/\eta_{el} + \dot{Q}_{req}/\eta_{th}}{\dot{m}_x} \tag{5.1}$$

The specific CO_2 emissions associated to a process, also referred as "carbon intensity" are calculated in the following way:

$$e_{CO_2}\left[\frac{t_{CO_2}}{t_x}\right] = \frac{\dot{m}_{CO_2}}{\dot{m}_x} \tag{5.2}$$

The CO_2 capture rate (CCR), the Specific Primary Energy Consumption for CO_2 Avoided (SPECCA) and CO_2 Avoidance are defined as follow:

$$CCR[\%] = 1 - \frac{\left(\dot{m}_{CO_2}\right)_{out}}{\left(\dot{m}_{CO_2}\right)_{in}} \tag{5.3}$$

$$SPECCA\left[\frac{GJ_{LHV}}{t_{CO_2}}\right] = \frac{PEC_{capture} - PEC_{nocapture}}{e_{CO_2,nocapture} - e_{CO_2,capture}} \tag{5.4}$$

$$CA[\%] = \frac{e_{CO_2,nocapture} - e_{CO_2,capture}}{e_{CO_2,nocapture}} \tag{5.5}$$

The SPECCA indicator is defined as the additional primary energy required (in GJ) to avoid the emission of 1 ton of CO_2 producing the same amount of product.

The economic performance is assessed in terms of levelized cost of products, Levelized Cost of Hot Rolled Coil, Levelized Cost of Ammonia and Levelized Cost of Urea. To compute them, the Total Annualised Cost (TAC) must be calculated, considering the Total Capital Requirement (TRC), the variable (C_v) and the fixed costs (C_f).

$$TAC\left[\frac{M€}{y}\right] = TCR \cdot FCF + C_v + C_f \tag{5.6}$$

$$TCR[M€] = TPC + C_{Co} + C_{oc} \tag{5.7}$$

$$TPC[M€] = TDPC + C_{EPC} \tag{5.8}$$

$$FCF = \frac{r(1+r)^T}{(1+r)^T} \tag{5.9}$$

where:

- TPC = Total Plant Cost
- TDPC = Total Direct Plant Cost
- C_{EPC} = engineering, procurement and construction cost
- C_{co} = contingencies
- C_{oc} = owner's cost
- FCF = Fixed Charge Factor

- T = project lifetime
- r = interest rate

$$LCO_x\left[\frac{€}{t_x}\right] = \frac{TAC}{\dot{m}_x \cdot 8760 \cdot \tau} \cdot 10^6 \tag{5.10}$$

where τ is the plant availability and $\dot{m}_x$ is expressed in ton per hour.

In addition, in the case of the steel plant also the Levelized Cost of Decarbonised Fuel (LCODF) and Levelized Cost of Electricity (LCOE) are considered:

$$LCODF\left[\frac{€}{GJ}\right] = \frac{TAC}{\dot{m}_{DCF} \cdot LHV_{DCF} \cdot 8760 \cdot \tau} \cdot 10^6 \tag{5.11}$$

$$LCOE\left[\frac{€}{MWh}\right] = \frac{TAC}{W_{el} \cdot 8760 \cdot \tau} \cdot 10^6 \tag{5.12}$$

Another important indicator is the Cost of CO_2 Avoidance (CCA). It compares the reference plant with CCS with the base plant without CCS.

$$CCA\left[\frac{€}{t_{CO_2}}\right] = \frac{LCO_{x,capture} - LCO_{x,nocapture}}{e_{CO_2,nocapture} - e_{CO_2,capture}} \tag{5.13}$$

In the case of steel plant, when only the carbon capture section is considered, LCODF is used in eq. (5.13), while in case of fully integrated steel mill with power generation LCOE is used.

Furthermore, when considering only the steel plant capture unit, the Cold Gas Efficiency (CGE), and the Overall Energy Efficiency (OEE) are defined.
CGE evaluates the amount of chemical energy left in the decarbonised fuel with respect to the BFG.

$$CGE[-] = \frac{\dot{m}_{DCF} \cdot LHV_{DCF}}{\dot{m}_{BFG} \cdot LHV_{BFG}} \tag{5.14}$$

OEE takes into account the additional energy consumptions required by the carbon capture unit.

$$OEE[-] = \frac{\dot{m}_{DCF} \cdot LHV_{DCF}}{\dot{m}_{BFG} \cdot LHV_{BFG} + \dot{Q}_{req} + \dot{W}_{req}} \tag{5.15}$$

In this case the SPECCA is computed as follows:

$$SPECCA\left[\frac{GJ_{LHV}}{t_{CO_2}}\right] = \frac{\left(\frac{1}{OEE_{capture}} - \frac{1}{OEE_{nocapture}}\right)}{e_{CO_2,nocapture} - e_{CO_2,capture}} \tag{5.16}$$

In the case of the steel plant capture unit and the combined cycle power plant, in the computation of SPECCA, OEE is replaced by the net electric efficiency.

Another indicator used is the incremental cost per ton of hot rolled coil with decarbonized BFG respect to the base case where BFG is used as fuel for power generation. The total annualised cost, in the reference case, also consider the cost of electricity purchased to compensate the reduction in power generation due to the integration of the carbon capture plant [10].

$$\Delta C_{HRC}\left[\frac{€}{t_{HRC}}\right] = \frac{TAC_{capture} + \Delta C_{el,capture} - TAC_{nocapture}}{\dot{m}_{HRC} \cdot 8760 \cdot \tau} \tag{5.17}$$

$\dot{m}_{HRC}$ is expressed in ton per hour.

6. Results

6.1. Steel plant

In the following table results regarding the pre-combustion section and the combined cycle plant in the steel mill are shown.

TABLE 30. Results – Power section of steel plant [10]

		Combined cycle	
		Base case	Reference case
Thermal input	[MW]	294.70	294.70
Net electric output	[MW]	146.96	71.54
Net electric efficiency	[%]	49.9	24.3
CO_2 emissions	[t/d]	6848	1160
CO_2 flow rate for storage	[t/d]	-	5685
Economics			
CO_2 capture unit	[M€]	-	89.00
Fuel compressor	[M€]	19.45	18.40
Gas turbine	[M€]	36.52	52.23
Heat recovery steam cycle	[M€]	25.97	17.55
Cooling system	[M€]	17.51	11.14
Total Equipment Cost	[M€]	99.45	188.32
Total Direct Plant Cost	[M€]	165.08	346.43
Total Plant Cost	[M€]	189.84	398.39
Total Capital Requirement	[M€]	218.32	458.15
Annualised Plant Cost	[M€/y]	24.89	52.23
Fuel cost	[M€/y]	43.49	43.49
Variable O&M	[M€/y]	2.17	7.85
Fixed O&M	[M€/y]	10.92	22.91
Total annualised cost	[M€/y]	81.47	126.48
Electricity purchased	[M€/y]	-	29.73
Key Performance Indicators			
CO_2 specific emissions (electricity based)	[kg_{CO2}/MWh]	1941.60	675.11
CO_2 specific emissions (power section)	[kg_{CO2}/t_{HRC}]	711.90	120.50
Carbon capture rate	[%]	-	83
CO_2 avoidance (electricity based)	[%]	-	65.2
Δcost of HRC	[€/t_{HRC}]	-	23.65
SPECCA	[GJ_{LHV}/t_{CO2}]	-	6.01
LCOE	[€/MWh]	70.32	224.26
Cost of CO_2 avoided (electricity based)	[€/t_{CO2}]	-	121.55

The results shown in the previous table refers only to the power section of the steel mill and not to the entire plant.

The results regarding the entire steel plant are shown below.

TABLE 31. Results - Steel mill

		Steel plant	
		Base case	Reference case
Steel mill size	[Mt_{HRC}/y]	3.16	3.16
CO_2 flow rate for storage	[t/d]	-	236.9
Δcost of HRC	[€/t_{HRC}]	-	23.65
Electricity purchased	[GWh/y]	-	594.6
CO_2 emission steel plant	[t_{CO2}/d]	10697	10697
CO_2 emissions power plant	[t_{CO2}/d]	6848	1160
CO_2 emissions related to electricity import	[t_{CO2}/d]	0	462
Total CO_2 emissions	[t_{CO2}/d]	17545	12319
Specific CO_2 emission steel plant	[t_{CO2}/t_{HRC}]	1112	1112
Specific CO_2 emissions power plant	[t_{CO2}/t_{HRC}]	711.90	120.50
Specific CO_2 emissions related to electricity import	[t_{CO2}/t_{HRC}]	0	48
Total specific CO_2 emissions	[t_{CO2}/t_{HRC}]	1823.9	1280.5
Key Performance Indicators			
Primary energy consumption	[GJ/t_{HRC}]	21.3	24.9
Process carbon intensity	[kg_{CO2}/t_{HRC}]	1823.9	1280.5
CO_2 avoidance (CA)	[%]	-	29.8
SPECCA	[GJ_{LHV}/t_{CO2}]	-	3.08
Levelized cost of hot rolled coil	[€/t_{HRC}]	468.00	491.65
Cost of CO_2 avoided	[€/t_{CO2}]	-	43.5

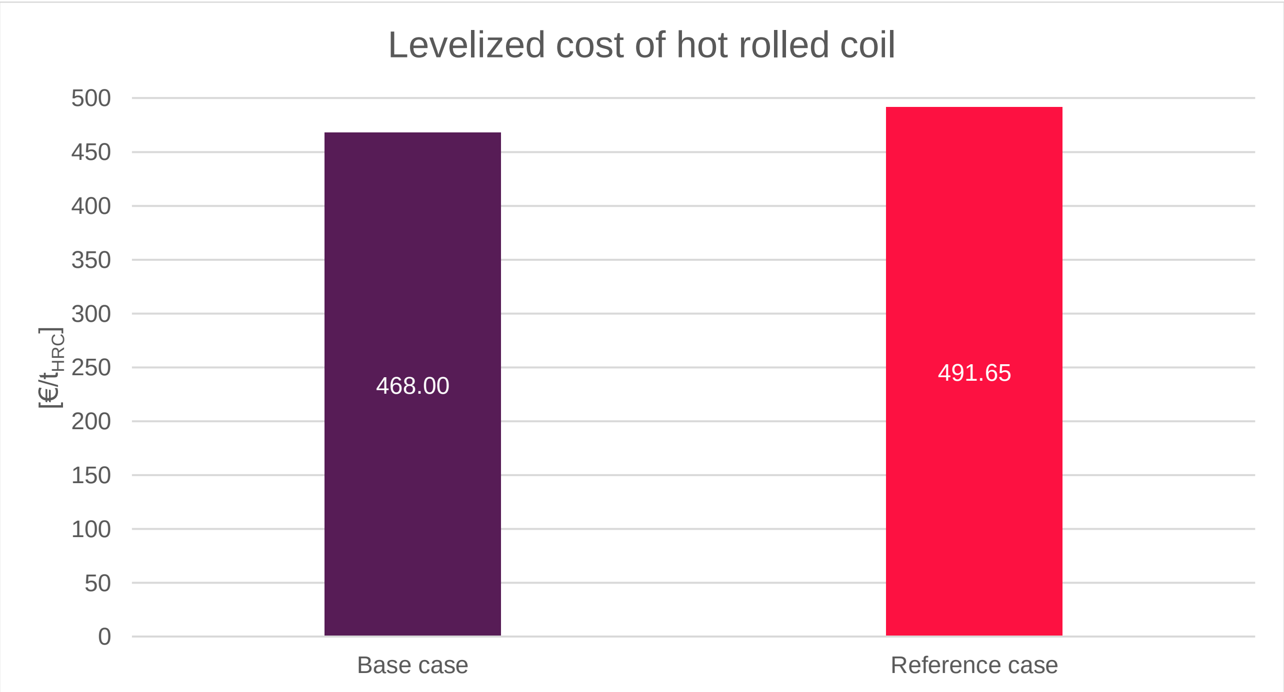

FIGURE 16. Levelized cost of hot rolled coil comparison

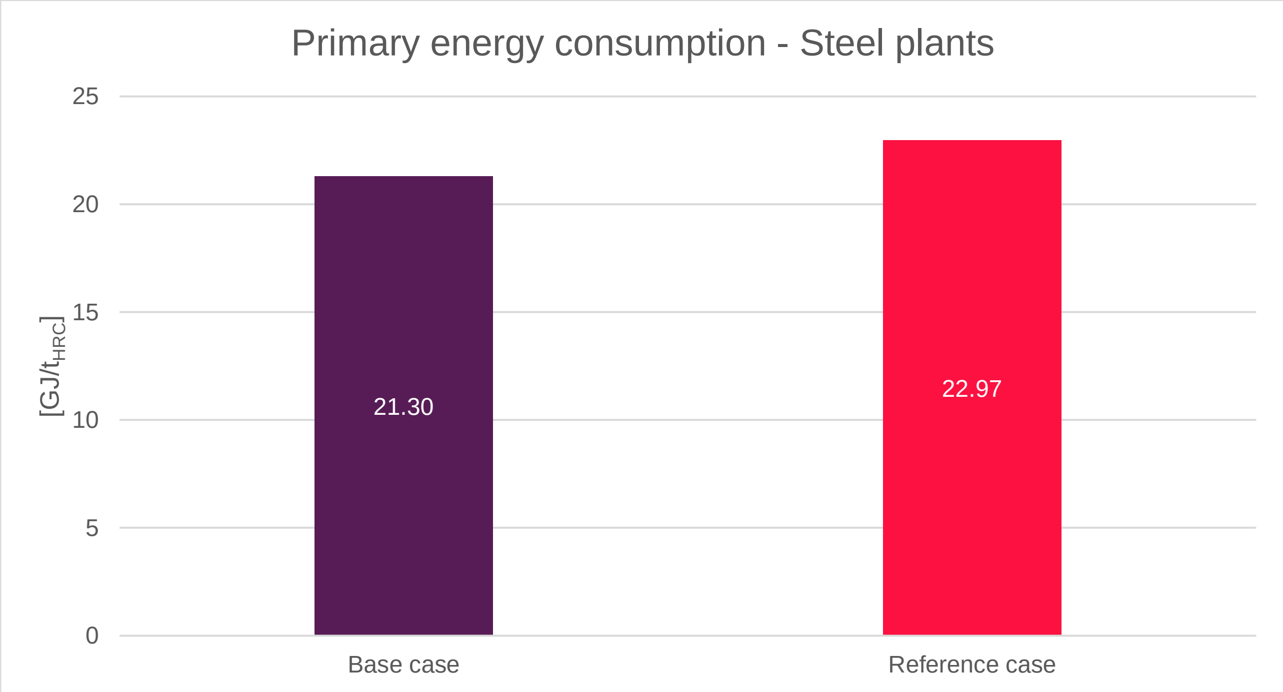

FIGURE 17. Primary energy consumption of steel plants

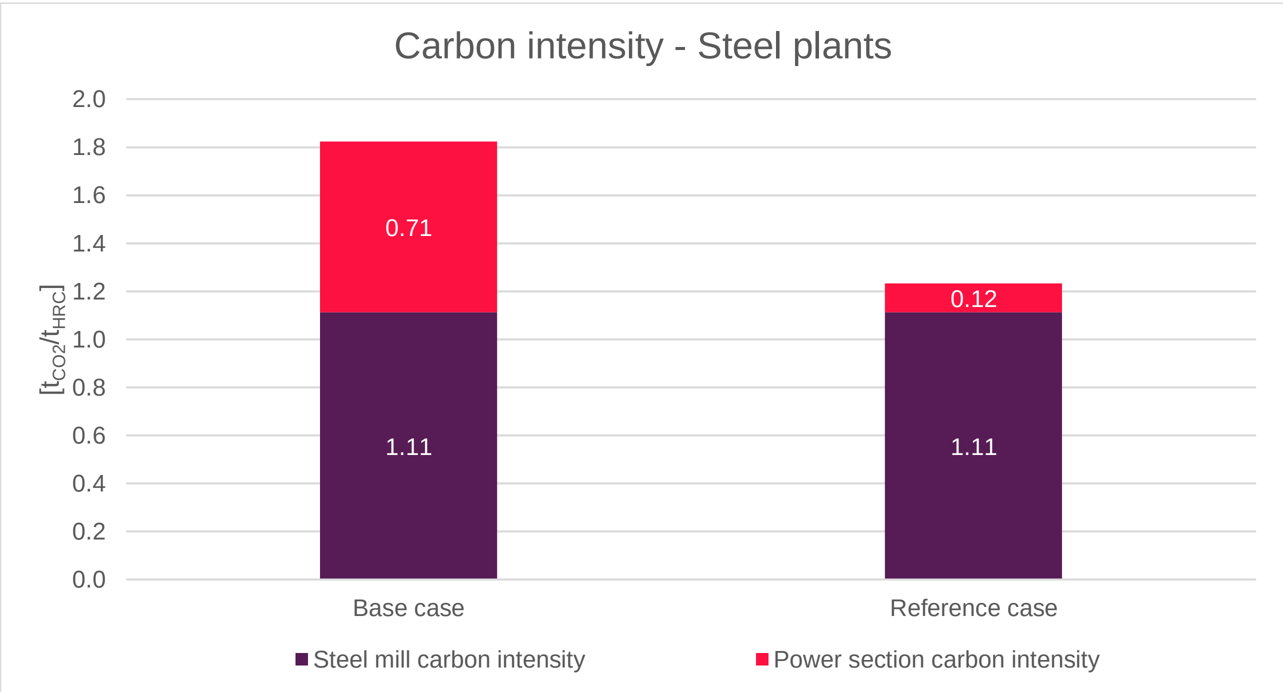

FIGURE 18. Carbon intensity of steel plants

Considering only the power section of the steel mill with the BFG treated in the pre-combustion section, the CO_2 avoidance is 65.2% but considering the entire steel plant, this value drops to 29.8%. The installation of the carbon capture section implies an increase of the cost of the hot rolled coil equal to 23.65 €/t_{HRC} so the LCOHRC is equal to 468 €/t_{HRC} for the base case and 491.65€/t_{HRC} for the reference case. The cost of CO_2 avoided is 43.5 €/t_{CO2} while the SPECCA is around 3.08 GJ_{LHV}/t_{CO2}.

6.2. Ammonia plant

Main results for the stand-alone ammonia plant are shown below.

TABLE 32. Results - stand-alone ammonia plants

		Stand-alone ammonia plant			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Capacity of NH_3 plant	[t_{NH3}/day]	85.8	85.8	847.5	847.5
Plant electrical consumption					
Total Plant Power consumption	[MW_e]	5.00	5.68	24.72	31.35
Power imported from the grid	[MW_e]	5.00	5.68	1.32	7.95
Steam input					
Steam input	[MW_{th}]	-7.26	-5.41	-36.34	-18.21
Plant emissions					
Total CO_2 emissions	[t_{CO2}/day]	195.4	39.0	1582.6	91.5
Total CO_2 emissions saved	[t_{CO2}/day]	-	156.5	-	1491.1
Total CO_2 to storage	[t_{CO2}/day]	-	160.6	-	1531.7
Economics					
Total Direct Plant Cost CC section	[M€]	0.00	3.55	0.00	19.61
Total Direct Plant Cost ammonia plant	[M€]	55.00	58.55	110.00	129.61
Total Plant Cost (TPC)	[M€]	66.00	70.26	132.00	155.53
Total Capital Requirement (TCR)	[M€]	89.10	94.85	178.20	209.97
Total variable costs	[M€/year]	7.97	8.79	59.23	67.10
Total fixed costs	[M€/year]	4.34	4.85	6.11	7.13
Key Performance Indicators					
Primary energy consumption	[GJ/t_{NH3}]	38.26	41.75	30.82	34.27
Process carbon intensity	[t_{CO2}/t_{NH3}]	2.28	0.45	1.87	0.11
CO_2 avoidance (CA)	[%]	-	80.06	-	94.22
SPECCA	[GJ/t_{CO2}]	-	1.91	-	1.96
Levelized cost of ammonia	[€/t_{NH3}]	733	799	295	337
Cost of CO_2 avoided	[€/t_{CO2}]	-	36.24	-	24.23

For sake of brevity, not all the results are reported in the table. For detailed results please see TABLE 38 in Appendix.

In the case of the stand-alone ammonia plants some differences arise between the small-scale plant and the large-scale one. The first one is the primary energy consumption that, considering the base cases, is equal to 38.26 GJ/t_{NH3} for the small-scale plant and 30.82 GJ/t_{NH3} for the large-scale one. This is due to the difference in the electric and steam input of the two plants. In the small-scale ammonia plant, it is supposed that all the electric energy is imported from the grid. On the other hand, in the large-scale plant, the electric energy import is much lower because the equipment is driven by steam turbines that use the high-pressure steam generated exploiting the various heat sources in the plant. Consequently, the steam export is higher in the small-scale ammonia plant respect to the large-scale one. In any case the two values are in accordance with the reference ones (FIGURE 19). In FIGURE 19 it is possible to observe the specific energy demand of 35 ammonia plants located in Europe. The values range from about 28 GJ/t_{NH3} to about 48 GJ/t_{NH3}.

The process carbon intensity of the base case stand-alone ammonia plants is in line with the reference values (FIGURE 20). The process carbon intensity is higher in the small-scale plant because, as underlined above, all the electric energy is imported from the grid. If this energy would be produced from renewable energy sources with emissions nearly equal to zero, the carbon intensity of the two plants would be very similar.
Typical values of the emissions related to the production of one ton of ammonia range from about 1.4 t_{CO2}/t_{NH3} to about 3 t_{CO2}/t_{NH3} (without including emissions related to electricity consumption) (FIGURE 20).

In the reference stand-alone ammonia plants, the primary energy consumption is increased, with respect to the base cases, by the presence of the CO_2 carbon capture section where specific heat requirement is equal to 3.6 GJ/t_{CO2} and the electricity requirement is 0.4 GJ/t_{CO2} (where 0.34 GJ/t_{CO2} are required for CO_2 compression). The carbon capture ratio is around 90% both for the small-scale and the large-scale ammonia plants but CO_2 avoidance is 80% for the small-scale plant and 94.2% for the large-scale plant. This difference is due to the emissions related to the electric energy input that are 0.41 t_{CO2}/t_{NH3} and 0.06 t_{CO2}/t_{NH3} for the small-scale and the large-scale plant respectively. The SPECCA of the two plants is similar, 1.91 GJ/t_{CO2} for the small-scale plant and 1.96 GJ/t_{CO2} for the large-scale one. The carbon intensity of the process from 2.28 t_{CO2}/t_{NH3} drops to 0.45 t_{CO2}/t_{NH3} for the small-scale plant and from 1.87 t_{CO2}/t_{NH3} to 0.11 t_{CO2}/t_{NH3} for the large one.

By an economic point of view, the cost of CO_2 avoided is 36.24 €/t_{CO2} for the small-scale plant and 24.23 €/t_{CO2} for the largest one. The levelized cost of ammonia is significantly higher in the case of the small-scale ammonia plant respect to the large-scale one. Indeed, LCOA is 733 €/t_{NH3} for the small-scale base ammonia plant and 295 €/t_{NH3} for the large-scale base ammonia plant. LCOA rises to 799 €/t_{NH3} and to 337 €/t_{NH3} for the reference ammonia plants.

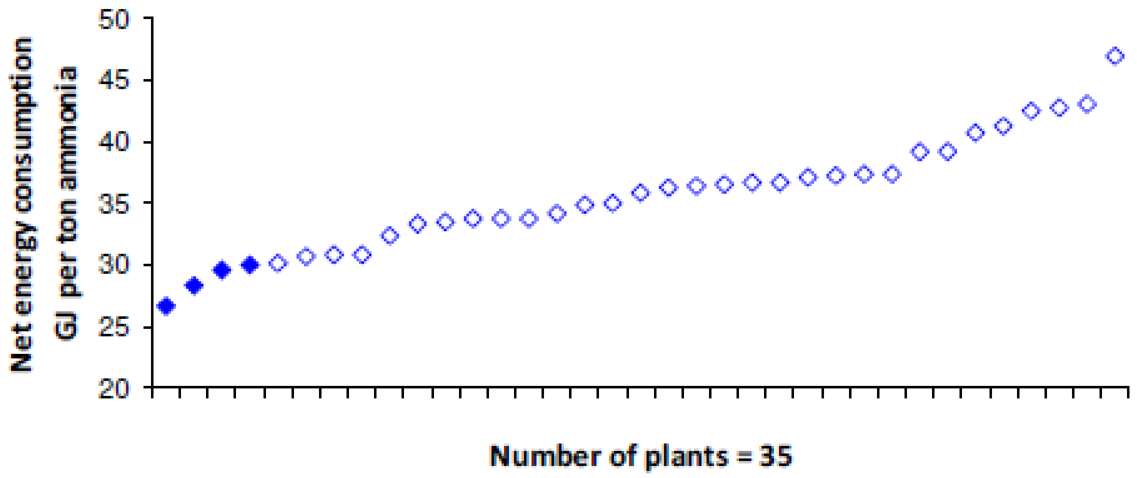

FIGURE 19. Energy benchmark curve including all 35 European EFMA plants and the input feed, fuel and steam (EFMA 2009a) [17]

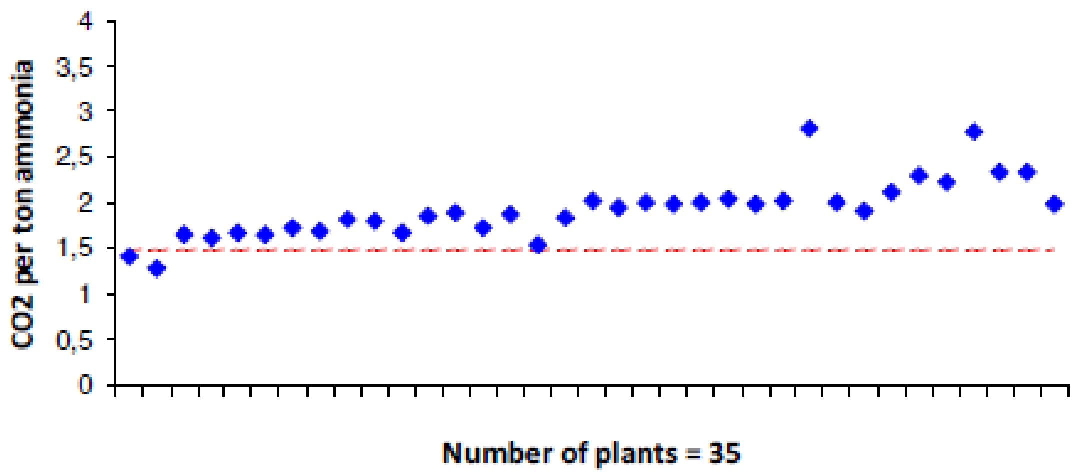

FIGURE 20. CO_2 benchmark curve including all 35 European EFMA plants (EFMA 2009a) [17]

The results previously discussed are summarized in the following figures.

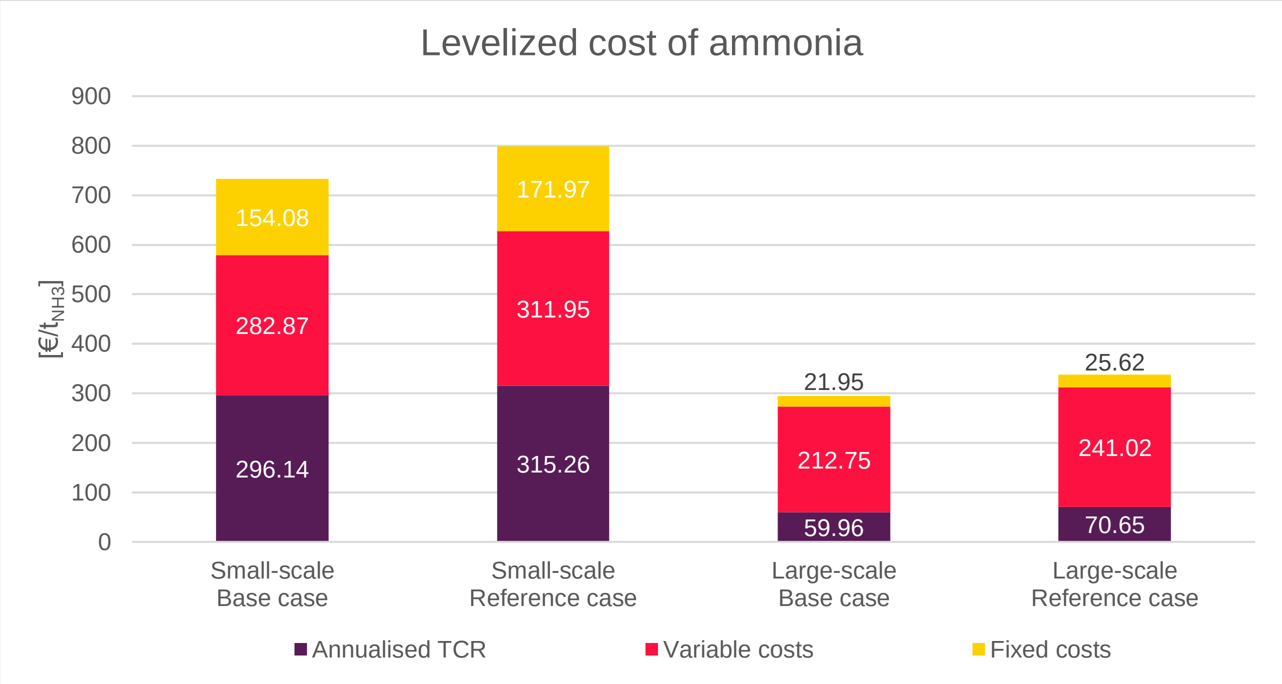

FIGURE 21. Levelized cost of ammonia

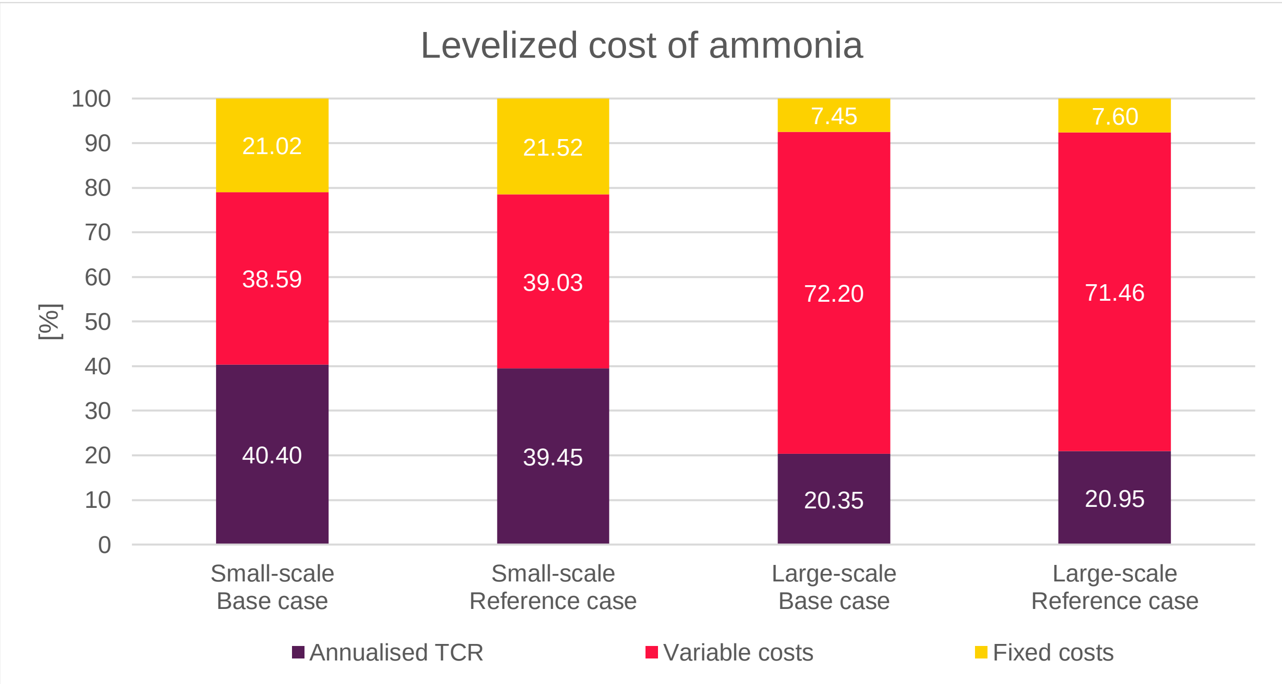

FIGURE 22. Percentage composition of levelized cost of ammonia

As can be observed in previous figure, considering small plants the “annualised TCR” and the “variable costs” represent, each one, roughly the 40% of $LCONH_3$ while the “fixed costs” the remaining 20%. On the other hand, in the case of large-scale
plants, the “variable costs” mainly contribute to $LCONH_3$, representing about the 72%.

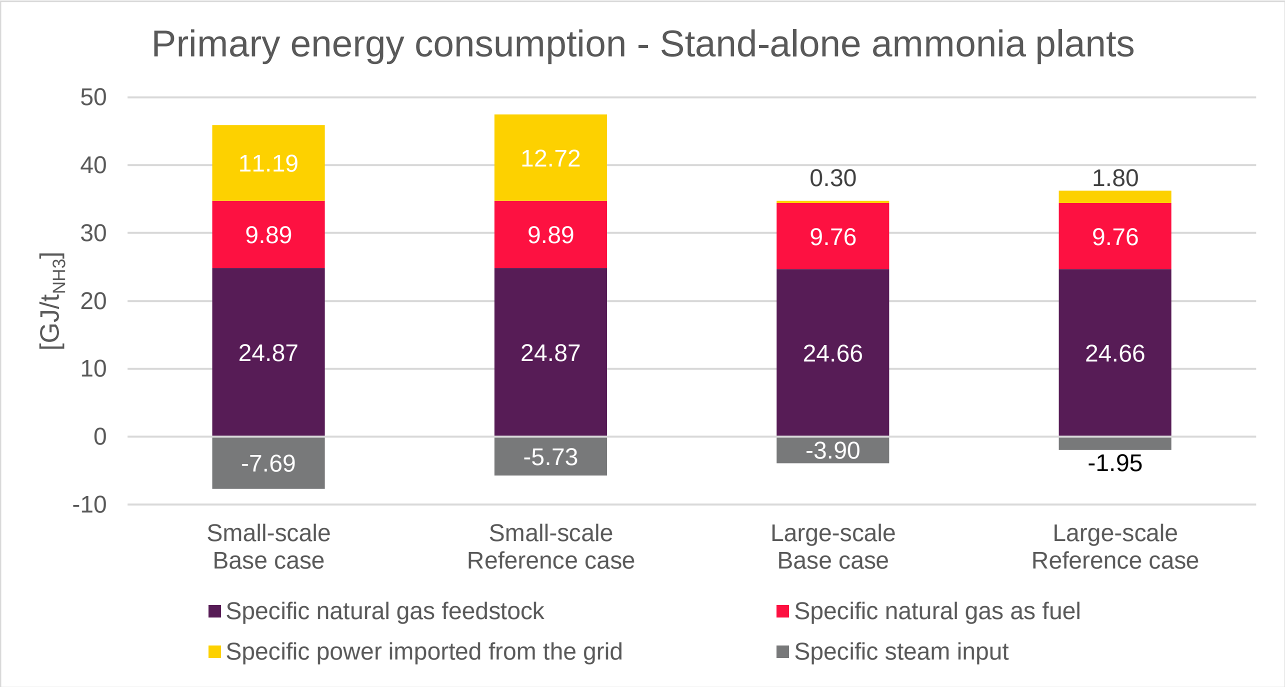

FIGURE 23. **Primary energy consumption of stand-alone ammonia plants**

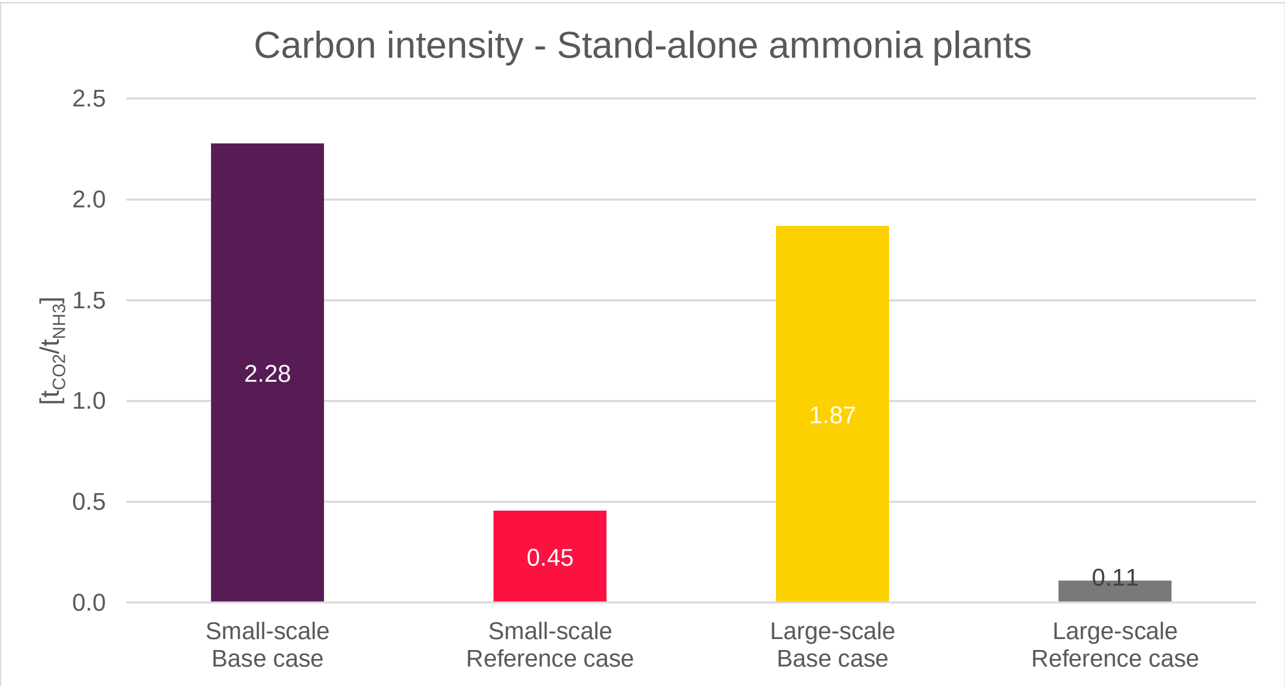

FIGURE 24. **Carbon intensity of stand-alone ammonia plants**

6.3. Ammonia plants coupled with urea plants

Principal results obtained for the ammonia plant coupled with the urea are shown below.

TABLE 33. Results - ammonia plants coupled with urea plants

		Ammonia + urea plants			
		Small-scale plant		Largescale plant	
		Base case	Reference case	Base case	Reference case
Capacity of urea plant	[t_{urea}/day]	150	150	1500	1500
Urea plant NH_3 input	[t_{NH3}/day]	85.8	85.8	847.5	847.5
Urea plant CO_2 input	[t_{CO2}/day]	116.3	116.3	1095.0	1095.0
Ammonia plant electrical consumption					
Total Plant Power consumption	[MW_e]	4.87	5.08	23.40	25.32
Power imported from the grid	[MW_e]	4.87	5.08	0.01	1.93
Electrical consumption in urea plant					
Plant Power consumption	[MW_e]	0.936	0.936	8.19	8.19
Power imported from the grid	[MW_e]	0.28	0.28	2.78	2.78
Ammonia + urea plants electrical consumption					
Power imported from the grid	[MW_e]	5.15	5.36	2.79	4.71
Steam input					
Steam input (ammonia plant)	[MW_{th}]	-7.26	-5.41	-36.34	-18.21
Steam input (urea plant)	[MW_{th}]	7.26	7.26	36.28	36.28
Steam net input (ammonia+urea plants)	[MW_{th}]	0.00	1.85	-0.06	18.07
Plant emissions					
Total CO_2 emissions	[t_{CO2}/day]	80.0	46.7	496.6	165.9
Total CO_2 emissions saved	[t_{CO2}/day]	-	33.4	-	330.6
Total CO_2 to storage	[t_{CO2}/day]	-	44.3	-	436.7
Economics					
Total Direct Plant Cost CC section	[M€]	0.00	3.55	0.00	19.61
Total Direct Plant Cost ammonia plant	[M€]	55.00	58.55	110.00	129.61
Total Direct Plant Cost urea plant	[M€]	40.00	40.00	80.00	80.00
Total Direct Plant Cost ammonia+urea plants	[M€]	95.00	98.55	190.00	209.61
Total Plant Cost (TPC) ammonia+urea plants	[M€]	114.00	118.26	228.00	251.53
Total Capital Requirement (TCR) ammonia+urea plants	[M€]	153.90	159.65	307.80	339.57
Total variable costs	[M€/year]	8.12	8.71	60.74	66.40
Total fixed costs	[M€/year]	8.20	8.71	11.26	12.28
Key Performance Indicators					
Primary energy consumption	[GJ/t_{urea}]	26.47	27.87	19.80	21.14
Process carbon intensity	[t_{CO2}/t_{urea}]	0.53	0.31	0.33	0.11
CO_2 avoidance (CA)	[%]	-	41.72	-	66.58
SPECCA	[GJ/t_{CO2}]	-	6.26	-	6.10
Levelized cost of urea	[€/t_{urea}]	624	657	205	224
Cost of CO_2 avoided	[€/t_{CO2}]	-	148.34	-	88.87

For sake of brevity, not all the results are reported in the table. For detailed results please see TABLE 39 in Appendix.

In the case of ammonia plants coupled with urea plants (base cases), the primary energy consumption is 26.47 GJ/t_{urea} and 19.80 GJ/t_{urea}. This difference is due to the higher energy intensity of the small-scale ammonia plant with respect to the large-scale one and the higher steam consumption in the small-scale urea plant. Considering only the urea plants (without the ammonia plants) the energy intensities are 4.56 GJ/t_{urea} and 2.36 GJ/t_{urea} for the small-scale urea plant and for the large-scale urea plant respectively. Values indicated in [4] ranges from 1.7 GJ/t_{urea} to 5.5 GJ/t_{urea}. The carbon intensity of the process is equal to 0.53 t_{CO2}/t_{urea} for the small-scale plant and 0.33 t_{CO2}/t_{urea} for the large-scale one. Again, this difference is due to the indirect emissions related to the electricity import in the small-scale ammonia plant.

The power consumption of the ammonia plants, when are coupled to the urea plants are slightly lower than the respective stand-alone ammonia plants. In the base cases, the only difference is given by the fact that NH_3 is sent to urea plant as warm product, so the consumption of the refrigeration circuit is accounted for. Considering the reference cases also the power consumption related to CO_2 compression for the storage is not considered since CO_2 is sent to urea plant.

CO_2 embedded in the urea molecule is 116.3 t/d for the small-scale plant and 1095.0 t/d for the large-scale one.

CO_2 avoidance is 41.72% for the small-scale reference case and 66.68% for the large-scale one. With respect to the stand-alone ammonia plants CA drops to these values because the CO_2 captured in the clean-up section of the ammonia plant is not sent to storage, but it is used for the manufacturing of urea. SPECCA is very similar, around 6 GJ/t_{CO2}. LCOU is above 600 €/t_{CO2} for the small-scale plants (624 €/t_{CO2} for the base case and 657 €/t_{CO2} for the reference case) and around 200 €/t_{CO2} for the large-scale plants (205 €/t_{CO2} for the base case and 224 €/t_{CO2} for the reference case). CCA is 148.34 €/t_{CO2} for the small-scale reference plant and 88.87 €/t_{CO2} for the large-scale reference plant.

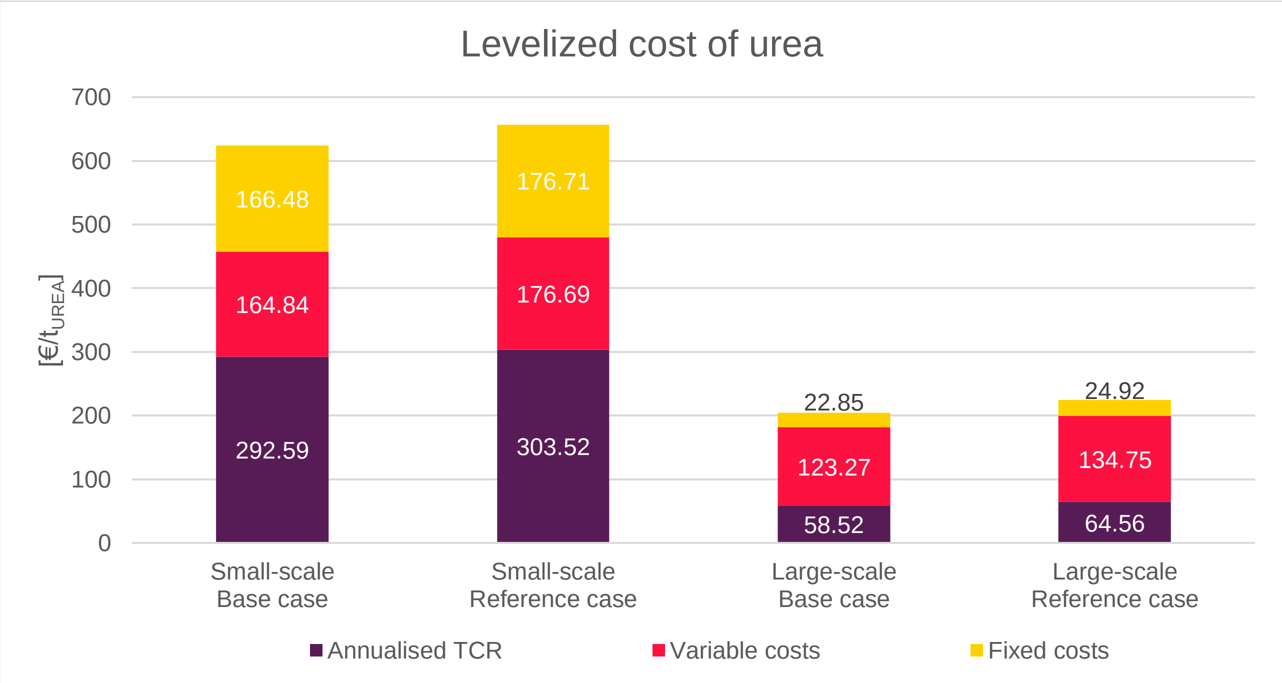

FIGURE 25. Levelized cost of urea

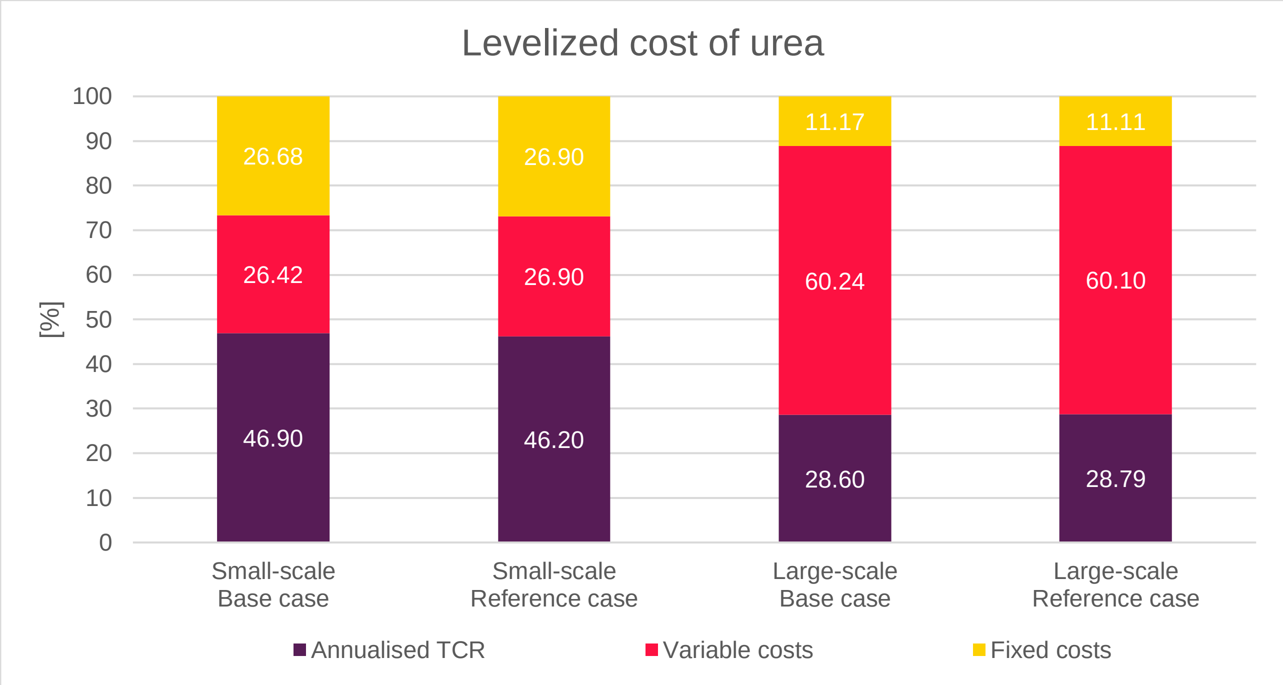

FIGURE 26. Percentage composition of levelized cost of urea

As shown in previous figure, considering small plants, the "annualised TCR" represents roughly the 46% of LCONH3 while the "variable costs" and the "fixed costs", each one, account for about 26/27%. On the other hand, in the case of large-scale plants, the "variable costs" mainly contribute to LCONH3, representing about the 60%.

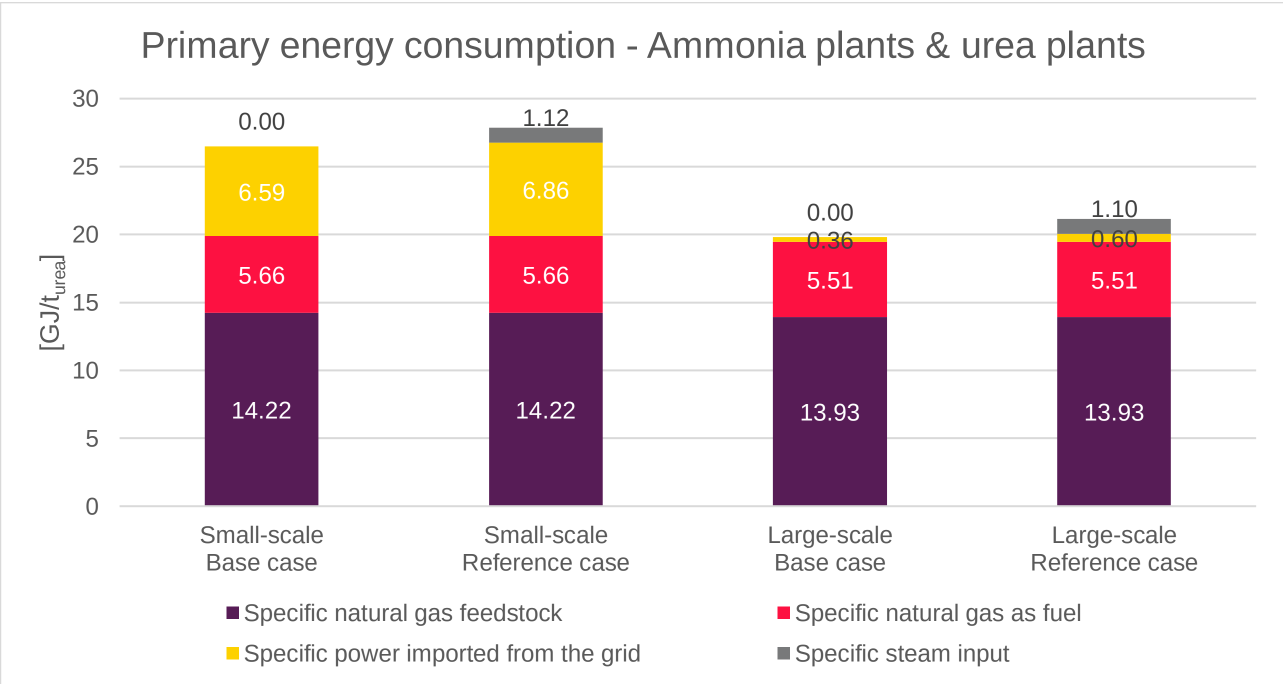

FIGURE 27. Primary energy consumption of ammonia plants coupled with urea plants

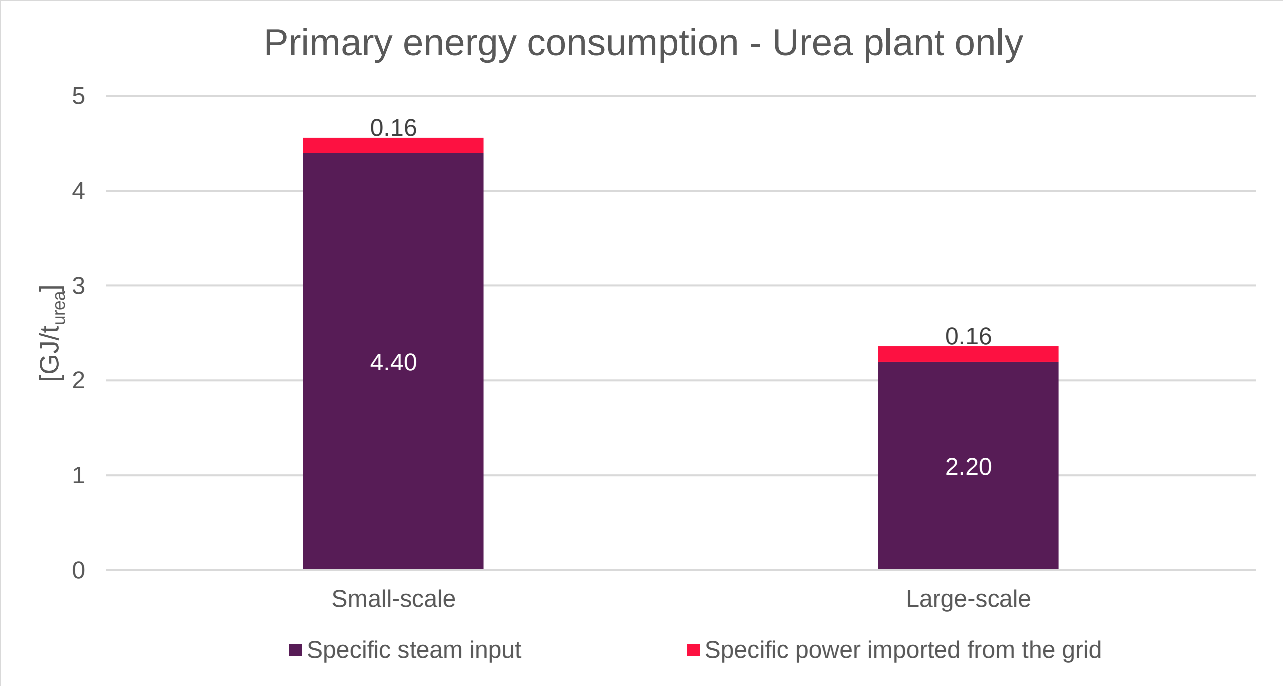

FIGURE 28. Primary energy consumption of urea plant only

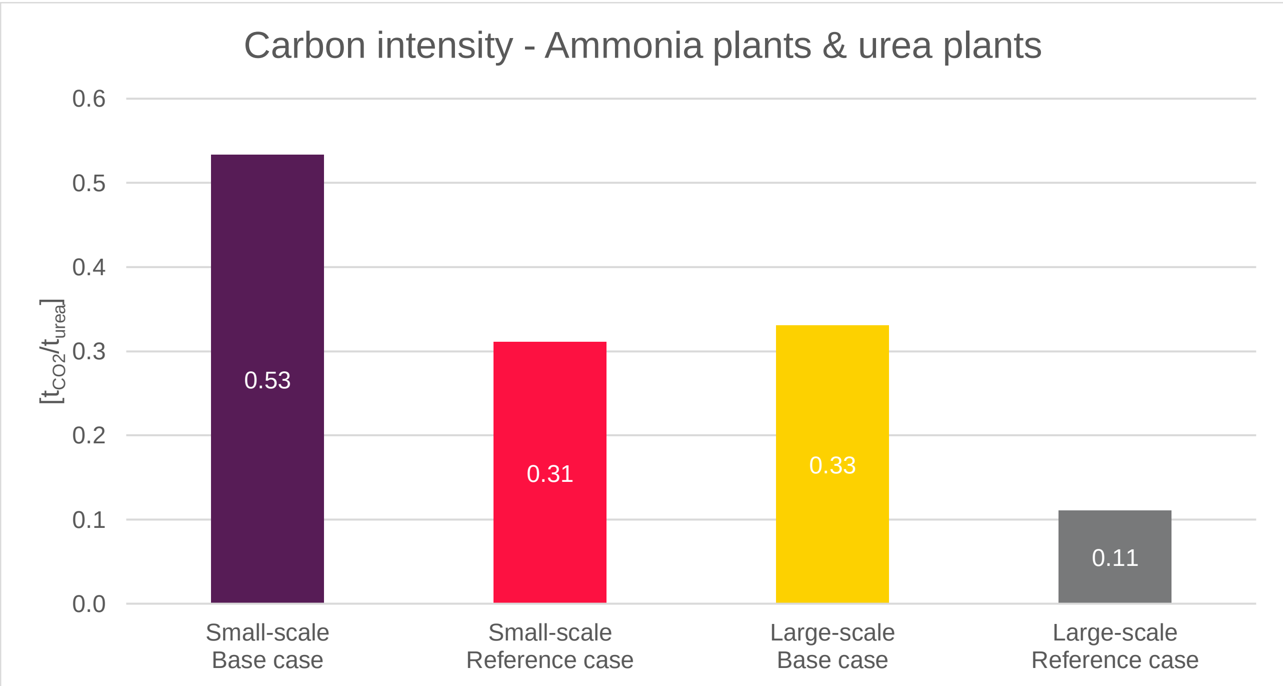

FIGURE 29. Carbon intensity of ammonia plants coupled with urea plants

6.4. Comparison of KPIs

In this section KPIs such as SPECCA, CO_2 avoidance and cost of CO_2 avoidance, described in the above sections separately, are compared through the following figures.

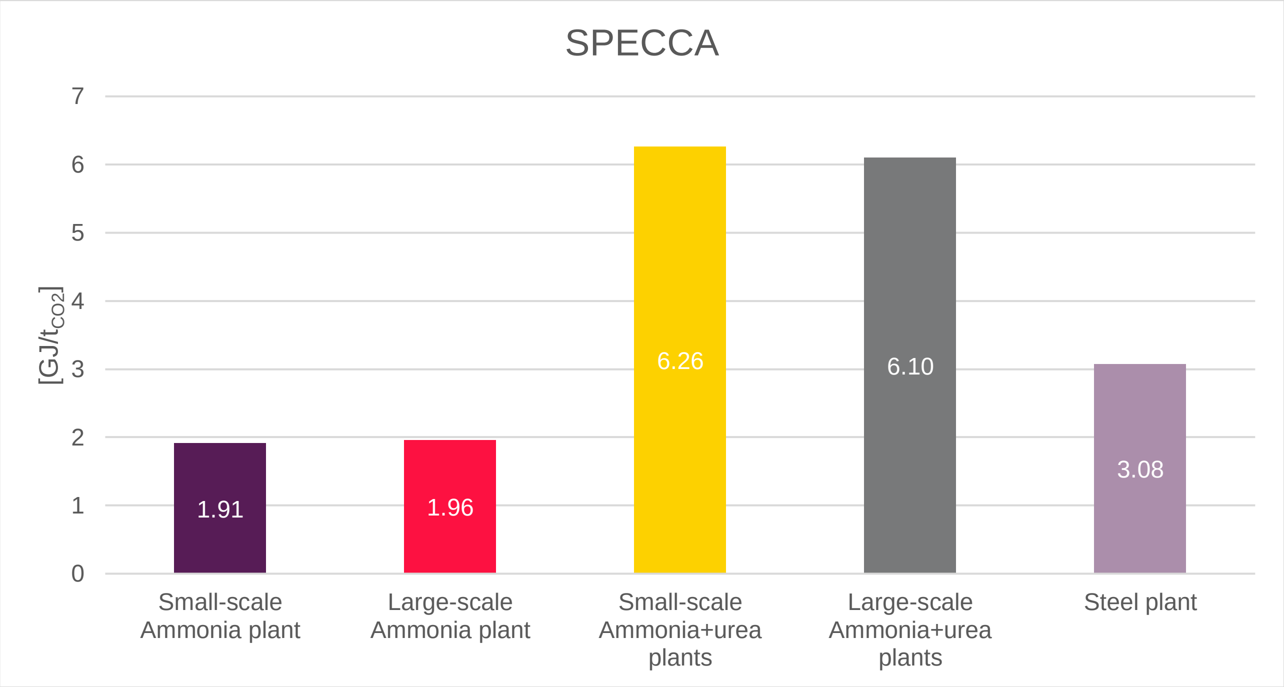

FIGURE 30. SPECCA of reference cases considered in this work

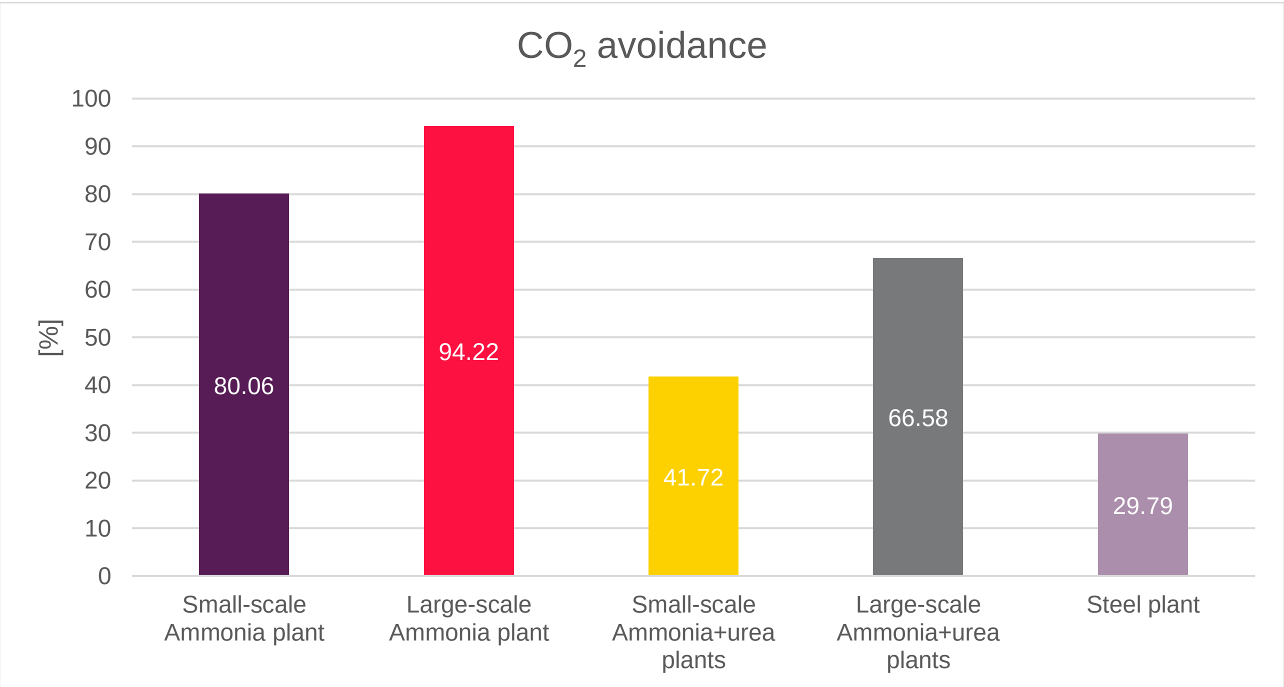

FIGURE 31. CO_2 avoidance of reference cases considered in this work

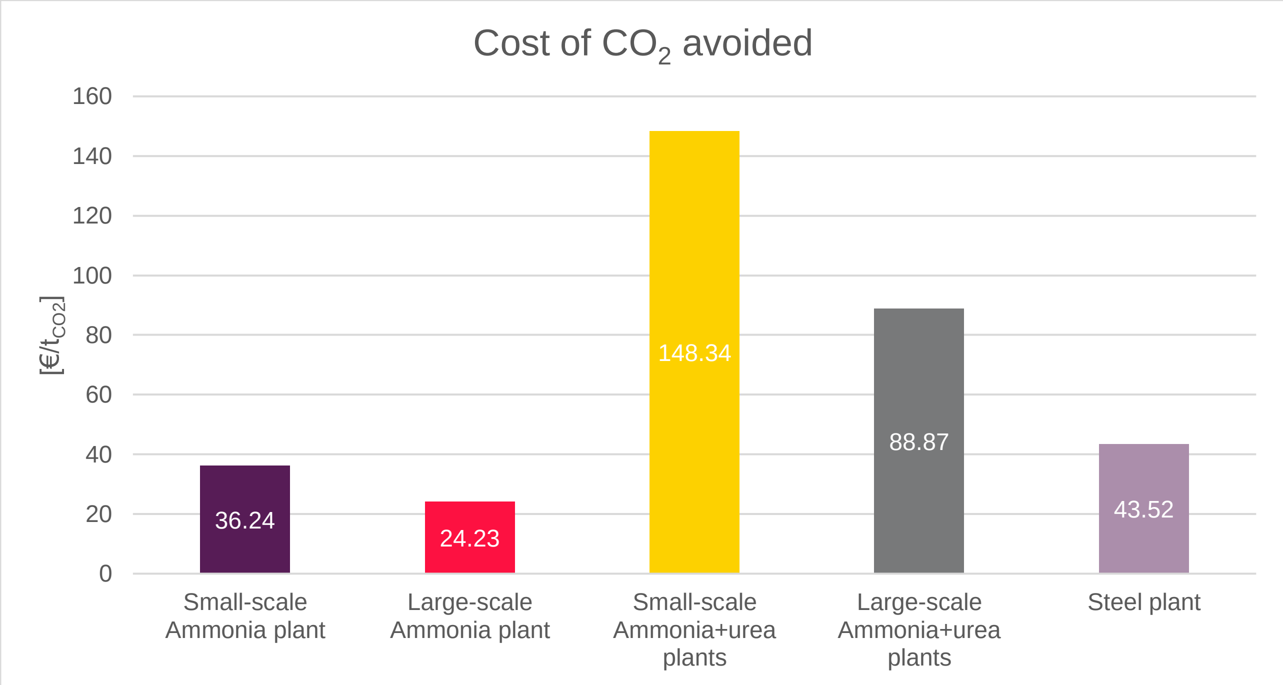

FIGURE 32. Cost of CO_2 avoided of reference cases considered in this work

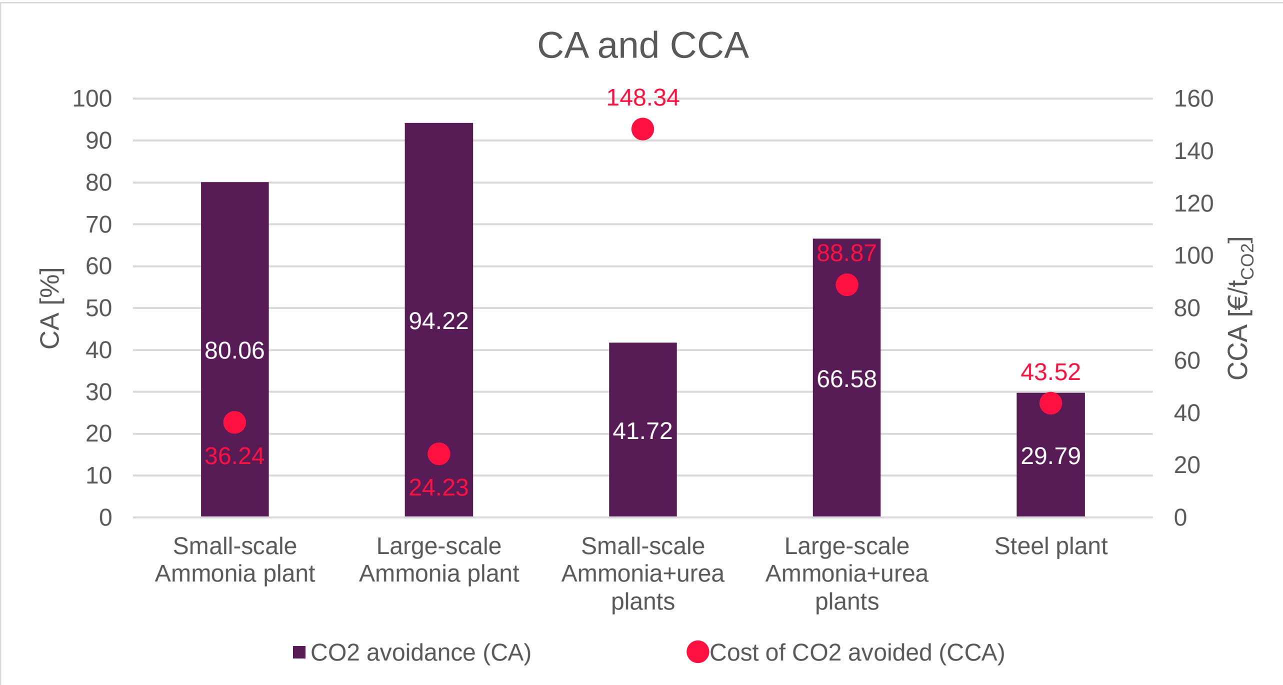

FIGURE 33. CA and CCA of reference cases considered in this work

7. Conclusions

The iron and steel industry, along with the fertilizer industry, is one of the most carbon and energy intensive industrial sectors. This deliverable defines the base and the reference cases of the INITIATE projects which aims to reduce the carbon footprint of these industrial sectors exploiting the steel mill residual gases to produce ammonia and urea.

Considering only the MDEA pre-combustion carbon capture section and power section of the steel plant, the CO_2 emissions from 711.90 kg_{CO2}/t_{HRC} (base case) drop to 120.5 kg_{CO2}/t_{HRC}. Therefore, carbon capture rate is 83% and the SPECCA of 6 GJ/t_{CO2}.
By an economic point of view, the incremental cost of HRC is 21.65 €/t_{HRC} and the CCA is 121.55 €/t_{CO2}.

When the whole steel plant is considered, the CO_2 emissions from 1824 kg_{CO2}/t_{HRC} (base case) drop to 1280.5 kg_{CO2}/t_{HRC} resulting in a CO_2 avoidance equal to 29.8%. The SPECCA is around 3 GJ/t_{CO2} and the CCA is 43.5 €/t_{CO2}. The levelized cost of HRC is 468 €/t_{HRC} for the base case and 491.65 €/t_{HRC} for the reference case.

When considering the ammonia plants, the large-scale plants are more cost-effective than the small ones since the LCOA is much higher in the case of the small-scale plants. Also, the CCA is lower in the reference large-scale plant respect to the reference small-scale one. A similar argument can be done for the case in which the ammonia plants are coupled with the urea plants.

TABLE 34. KPIs – Steel plant

		Steel plant	
		Base case	Reference case
Key Performance Indicators			
Primary energy consumption	[GJ/t_{HRC}]	21.3	23.0
Process carbon intensity	[kg_{CO2}/t_{HRC}]	1823.9	1280.5
CO_2 avoidance (CA)	[%]	-	29.8
SPECCA	[GJ_{LHV}/t_{CO2}]	-	3.08
Levelized cost of hot rolled coil	[€/t_{HRC}]	468	491.65
Cost of CO_2 avoided	[€/t_{CO2}]	-	43.5

TABLE 35. KPIs – Stand-alone ammonia plant

		Stand-alone ammonia plant			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Key Performance Indicators					
Primary energy consumption	[GJ/t_{NH3}]	38.26	41.75	30.82	34.27
Process carbon intensity	[t_{CO2}/t_{NH3}]	2.28	0.45	1.87	0.11
CO_2 avoidance (CA)	[%]	-	80.06	-	94.22
SPECCA	[GJ/t_{CO2}]	-	1.91	-	1.96
Levelized cost of ammonia	[€/t_{NH3}]	733	799	295	337
Cost of CO_2 avoided	[€/t_{CO2}]	-	36.24	-	24.23

TABLE 36. KPIs –Ammonia plants coupled with urea plants

		Ammonia + urea plants			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Key Performance Indicators					
Primary energy consumption	[GJ/t_{urea}]	26.47	27.87	19.80	21.14
Process carbon intensity	[t_{CO2}/t_{urea}]	0.53	0.31	0.33	0.11
CO_2 avoidance (CA)	[%]	-	41.72	-	66.58
SPECCA	[GJ/t_{CO2}]	-	6.26	-	6.10
Levelized cost of ammonia	[€/t_{urea}]	624	657	205	224
Cost of CO_2 avoided	[€/t_{CO2}]	-	148.34	-	88.87

8. References

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9. Appendix

In the Appendix, detailed results are shown.

9.1. Steel plant

The energy balance of the simulated plants is reported in the following table

TABLE 37. Energy balance of the combined cycle [10]

		Base case	Reference case
Thermal Energy input (BFG)	[MW]	294.67	294.67
Gas turbine power output	[MW]	139.05	128.75
BFG/DCF compressor	[MW]	40.39	37.35
HPT power output	[MW]	12.12	8.85
IPT power output	[MW]	14.98	10.38
LPT power output	[MW]	21.82	-
HP-Pump power consumption	[MW]	0.48	0.38
IP-Pump power consumption	[MW]	0.13	0.1
LP-Pump power consumption	[MW]	0.02	-
Capture plant power consumption	[MW]	-	38.59
Additional heat to reboiler	[MW]	-	65.48
Net power output	[MW]	146.96	71.54
Efficiency	[%]	50.00	24.27
Total CO_2 emissions[1]	[kg/s]	78.52	17.33

[1] It is assumed that the CO_2 emission from heat generation is 220 g/kWh [10]

9.2. Ammonia plant

Detailed results obtained for the stand-alone ammonia plants are shown below.

TABLE 38. Detailed results - stand-alone ammonia plants

		Stand-alone ammonia plant			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Capacity of NH_3 plant	[t_{NH3}/day]	85.8	85.8	847.5	847.5
Natural gas feedstock	[t/day]	44.04	44.04	431.4	431.4
Natural gas as fuel	[t/day]	17.52	17.52	170.7	170.7
Total natural gas	[t/day]	61.56	61.56	602.1	602.1
Natural gas LHV	[MJ/kg]	48.45	48.45	48.5	48.5
Process steam	[t/day]	168	168	1615.1	1615.1
Process air	[t/day]	104.3	104.3	1028.6	1028.6
Electrical consumption					
Process air compressor power consumption	[MW_e]	0.42	0.42	3.65	3.65
Syngas compressor power consumption	[MW_e]	1.45	1.45	12.70	12.70
Ammonia synthesis compressor power consumption	[MW_e]	0.10	0.10	0.85	0.85
Syngas recirculation compressor	[MW_e]	0.004	0.004	0.037	0.037
Boiler feed water pump	[MW_e]	0.09	0.09	0.73	0.73
Refrigeration circuit					
NH_3 refrigeration heat duty	[MW_{th}]	0.30	0.30	3.02	3.02
COP NH_3 refrigeration circuit	[-]	2.3	2.3	2.3	2.3
NH_3 refrigeration circuit power consumption	[MW_e]	0.13	0.13	1.31	1.31
Clean up section					
Pump in CO_2 removal section power consumption	[MW_e]	0.01	0.01	0.55	0.55
CO_2 compressor power consumption	[MW_e]	0.00	0.46	0.00	4.63
CO_2 pump power consumption	[MW_e]	0.00	0.008	0.00	0.08
Post combustion section					
CO_2 in	[t_{CO2}/day]	48.5	48.5	479.5	479.5
CO_2 out	[t_{CO2}/day]	48.5	4.2	479.5	42.8
CO_2 captured	[t_{CO2}/day]	0.00	44.3	0.00	436.7
Carbon Capture Ratio	[%]	0.00	91.3	0.00	91.1
Reboiler Heat Duty	[MW_{th}]	0.00	1.85	0.00	18.13
CO_2 compressor power consumption	[MW_e]	0.00	0.18	0.00	1.61
CO_2 pump power consumption	[MW_e]	0.00	0.003	0.00	0.03
Flue gases compressor power consumption	[MW_e]	0.00	0.03	0.00	0.27
Pump in CO_2 removal section power consumption	[MW_e]	0.00	0.001	0.00	0.008
Specific heat requirement	[GJ/t_{CO2}]	0.00	3.60	0.00	3.59
Specific electric consumption for CO_2 compression	[GJ/t_{CO2}]	0.00	0.35	0.00	0.33
Other specific electric consumptions	[GJ/t_{CO2}]	0.00	0.06	0.00	0.05
Total specific electric consumptions	[GJ/t_{CO2}]	0.00	0.42	0.00	0.38
Plant electrical consumption					
Miscellaneous	[MW_e]	2.80	2.80	4.90	4.90
Total Plant Power consumption	[MW_e]	5.00	5.68	24.72	31.35
Power imported from the grid	[MW_e]	5.00	5.68	1.41	8.04

		Stand-alone ammonia plant			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Steam input					
Steam input	[MW_{th}]	-7.26	-5.41	-36.34	-18.21
Plant emissions					
CO_2 emission (clean up section)	[t_{CO2}/day]	116.3	0	1095.0	0
CO_2 emission (combustion)	[t_{CO2}/day]	48.5	4.2	479.5	42.8
Direct CO_2 emissions	[t_{CO2}/day]	164.8	4.2	1574.5	42.8
Indirect CO_2 emissions	[t_{CO2}/day]	30.6	34.8	9.0	49.6
Total CO_2 emissions	[t_{CO2}/day]	195.4	39.0	1583.5	92.4
Total CO_2 emissions saved	[t_{CO2}/day]	0.0	156.5	0.0	1491.1
Total CO_2 to storage	[t_{CO2}/day]	0.0	160.6	0.0	1531.7
Specific results					
Specific natural gas feedstock	[GJ/t_{NH3}]	24.87	24.87	24.66	24.66
Specific natural gas as fuel	[GJ/t_{NH3}]	9.89	9.89	9.76	9.76
Specific total natural gas	[GJ/t_{NH3}]	34.76	34.76	34.42	34.42
Specific process steam consumption	[t/t_{NH3}]	1.96	1.96	1.91	1.91
Specific process air consumption	[t/t_{NH3}]	1.22	1.22	1.21	1.21
Specific CO_2 emission (high purity CO_2)	[t_{CO2}/t_{NH3}]	1.36	0.00	1.29	0.00
Specific CO_2 emission (combustion)	[t_{CO2}/t_{NH3}]	0.57	0.05	0.57	0.05
Total specific direct CO_2 emissions	[t_{CO2}/t_{NH3}]	1.92	0.05	1.86	0.05
Specific indirect CO_2 emissions	[t_{CO2}/t_{NH3}]	0.36	0.41	0.01	0.06
Total specific CO_2 emissions	[t_{CO2}/t_{NH3}]	2.28	0.45	1.87	0.11
Specific power imported from the grid	[GJ/t_{NH3}]	10.49	11.92	0.30	1.71
Specific steam input	[GJ/t_{NH3}]	-7.69	-5.73	-3.90	-1.95
Specific energy demand	[GJ/t_{NH3}]	37.56	40.95	30.82	34.17
Economics					
Total Direct Plant Cost CC section	[M€]	0.00	3.55	0.00	19.61
Total Direct Plant Cost ammonia plant	[M€]	55.00	58.55	110.00	129.61
Total Plant Cost (TPC)	[M€]	66.00	70.26	132.00	155.53
Total Capital Requirement (TCR)	[M€]	89.10	94.85	178.20	209.97
Variable costs					
Natural gas (feedstock + fuel)	[€/year]	5'878'669	5'878'669	57'493'216	57'493'216
Electricity (import from grid)	[€/year]	1'971'000	2'240'257	556'808	3'170'547
Raw water (make-up)	[€/year]	39'910	39'910	394'220	394'220
Chemicals and catalyst	[€/year]	83'147	83'147	821'291	821'291
MEA makeup	[€/year]	0	22'769	0	224'206
CO_2 transport and storage cost	[€/year]	0	527'721	0	5'031'532
Total variable costs	[€/year]	7'972'726	8'792'474	59'265'535	67'135'012
Specific variable costs	[€/t_{NH3}]	282.9	312.0	212.9	241.1
Fixed costs					
Direct labour	[€/year]	1'980'000	2'280'000	1'980'000	2'280'000
Adm./gen. overheads	[€/year]	712'800	810'471	831'600	963'962
Insurance and local taxes	[€/year]	660'000	702'616	1'320'000	1'555'345
Maintenance	[€/year]	990'000	1'053'924	1'980'000	2'333'018
Total fixed costs	[€/year]	4'342'800	4'847'011	6'111'600	7'132'326
Specific fixed costs	[€/t_{NH3}]	154.1	172.0	22.0	25.6

		Stand-alone ammonia plant			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Key Performance Indicators					
Primary energy consumption	[GJ/t_{NH3}]	37.56	40.95	30.82	34.17
Process carbon intensity	[t_{CO2}/t_{NH3}]	2.28	0.45	1.87	0.11
CO_2 avoidance (CA)	[%]	-	80.06	-	94.19
SPECCA	[GJ/t_{CO2}]	-	1.86	-	1.91
Levelized cost of ammonia	[€/t_{NH3}]	733	799	295	337
Cost of CO_2 avoided	[€/t_{CO2}]	-	36.24	-	24.23

9.3. Ammonia plant coupled with urea plant

Detailed results obtained for the ammonia plant coupled with the urea are shown below.

TABLE 39. Detailed results - ammonia plants coupled with urea plants

		Ammonia + urea plants			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Capacity of urea plant	[t_{urea}/day]	150	150	1500	1500
Urea plant NH_3 input	[t_{NH3}/day]	85.8	85.8	847.5	847.5
Urea plant CO_2 input	[t_{CO2}/day]	116.3	116.3	1095.0	1095.0
Natural gas feedstock in ammonia plant	[t/day]	44.04	44.04	431.4	431.4
Natural gas as fuel in ammonia plant	[t/day]	17.52	17.52	170.7	170.7
Total natural gas in ammonia plant	[t/day]	61.56	61.56	602.1	602.1
Natural gas LHV	[MJ/kg]	48.45	48.45	48.5	48.5
Process steam in ammonia plant	[t/day]	168	168	1615.1	1615.1
Process air in ammonia plant	[t/day]	104.3	104.3	1028.6	1028.6
Electrical consumption in ammonia plant					
Process air compressor power consumption	[MW_e]	0.42	0.42	3.65	3.65
Syngas compressor power consumption	[MW_e]	1.45	1.45	12.70	12.70
Ammonia synthesis compressor power consumption	[MW_e]	0.10	0.10	0.85	0.85
Syngas recirculation compressor	[MW_e]	0.004	0.004	0.037	0.037
Boiler feed water pump	[MW_e]	0.09	0.09	0.73	0.73
Clean up section in ammonia plant					
Pump in CO_2 removal section power consumption	[MW_e]	0.01	0.01	0.55	0.55
Post combustion section in ammonia plant					
CO_2 in	[t_{CO2}/day]	48.5	48.5	479.5	479.5
CO_2 out	[t_{CO2}/day]	48.5	4.2	479.5	42.8
CO_2 captured	[t_{CO2}/day]	0.00	44.3	0.00	436.7
Carbon Capture Ratio	[%]	0.00	91.3	0.00	91.1
Reboiler Heat Duty	[MW_{th}]	0.00	1.85	0.00	18.13
CO_2 compressor power consumption	[MW_e]	0.00	0.18	0.00	1.61
CO_2 pump power consumption	[MW_e]	0.00	0.00	0.00	0.03
Flue gases compressor power consumption	[MW_e]	0.00	0.03	0.00	0.27
Pump in CO_2 removal section power consumption	[MW_e]	0.00	0.001	0.00	0.008
Specific heat requirement	[GJ/t_{CO2}]	0.00	3.60	0.00	3.59
Specific electric consumption for CO_2 compression	[GJ/t_{CO2}]	0.00	0.35	0.00	0.33
Other specific electric consumptions	[GJ/t_{CO2}]	0.00	0.06	0.00	0.05
Total specific electric consumptions	[GJ/t_{CO2}]	0.00	0.416	0.00	0.379
Ammonia plant electrical consumption					
Miscellaneous	[MW_e]	2.80	2.80	4.90	4.90
Total Plant Power consumption	[MW_e]	4.87	5.08	23.40	25.32
Power imported from the grid	[MW_e]	4.87	5.08	0.10	2.02
Electrical consumption in urea plant					
CO_2 compressor power consumption	[MW_e]	0.66	0.66	5.74	5.74
NH_3 pump power consumption	[MW_e]	0.09	0.09	0.33	0.33
Miscellaneous	[MW_e]	0.19	0.19	2.13	2.13
Plant Power consumption	[MW_e]	0.936	0.936	8.19	8.19
Power imported from the grid	[MW_e]	0.26	0.26	2.60	2.60

		Ammonia + urea plants			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Ammonia + urea plants electrical consumption					
Power imported from the grid	[MW_e]	5.13	5.34	2.70	4.62
Steam input					
Steam input (ammonia plant)	[MW_{th}]	-7.26	-5.41	-36.34	-18.21
Steam input (urea plant)	[MW_{th}]	7.26	7.26	36.28	36.28
Steam net input (ammonia+urea plants)	[MW_{th}]	0.00	1.85	-0.06	18.07
NG mass flow rate to produce additional steam	[t/day]	0.00	3.47	0.00	33.93
Plant emissions					
Direct CO_2 emissions (combustion in ammonia plant)	[t_{CO2}/day]	48.5	4.2	479.5	42.8
Indirect CO_2 emissions from electricity input	[t_{CO2}/day]	31.4	32.7	16.5	28.3
CO_2 emissions for additional steam production	[t_{CO2}/day]	0.00	9.65	0.00	94.3
Total CO_2 emissions	[t_{CO2}/day]	79.9	46.5	496.0	165.4
Total CO_2 emissions saved	[t_{CO2}/day]	0.0	33.4	0.0	330.6
Total CO_2 to storage	[t_{CO2}/day]	0.0	44.3	0.0	436.7
Specific Results					
Specific NH_3 input	[t_{NH3}/t_{urea}]	0.57	0.57	0.57	0.57
Urea plant specific CO_2 input	[t_{CO2}/t_{urea}]	0.78	0.78	0.73	0.73
Specific natural gas feedstock	[GJ/t_{NH3}]	24.87	24.87	24.66	24.66
Specific natural gas as fuel	[GJ/t_{NH3}]	9.89	9.89	9.76	9.76
Specific total natural gas	[GJ/t_{NH3}]	34.76	34.76	34.42	34.42
Specific process steam consumption	[t/t_{NH3}]	1.96	1.96	1.91	1.91
Specific process air consumption	[t/t_{NH3}]	1.22	1.22	1.21	1.21
Specific natural gas feedstock	[GJ/t_{urea}]	14.22	14.22	13.93	13.93
Specific natural gas as fuel	[GJ/t_{urea}]	5.66	5.66	5.51	5.51
Specific NG consumption for additional steam	[GJ/t_{urea}]	0.00	1.12	0.00	1.10
Specific total natural gas consumption	[GJ/t_{urea}]	19.88	21.00	19.45	20.54
Specific direct CO_2 emission (combustion)	[t_{CO2}/t_{urea}]	0.32	0.03	0.32	0.03
Specific indirect CO_2 emissions	[t_{CO2}/t_{urea}]	0.21	0.22	0.01	0.02
Specific CO_2 emission for additional steam	[t_{CO2}/t_{urea}]	0.00	0.06	0.00	0.06
Total specific CO_2 emissions	[t_{CO2}/t_{urea}]	0.53	0.31	0.33	0.11
Specific power imported from the grid (ammonia plant)	[GJ/t_{NH3}]	10.21	10.66	0.02	0.43
Specific power imported from the grid (urea plant)	[GJ/t_{urea}]	0.15	0.15	0.15	0.15
Specific power imported from the grid (ammonia+urea)	[GJ/t_{urea}]	6.16	6.41	0.32	0.55
Specific steam input (ammonia plant)	[GJ/t_{NH3}]	-7.69	-5.73	-3.90	-1.95
Specific steam input (urea plant)	[GJ/t_{urea}]	4.40	4.40	2.20	2.20
Specific steam input (ammonia+urea)	[GJ/t_{urea}]	0.00	1.12	-0.003	1.10
Specific energy demand (urea plant)	[GJ/t_{urea}]	4.55	4.55	2.35	2.35
Specific energy demand (ammonia+urea)	[GJ/t_{urea}]	26.04	27.42	19.77	21.10
Economics					
Total Direct Plant Cost CC section	[M€]	0.00	3.55	0.00	19.61
Total Direct Plant Cost ammonia plant	[M€]	55.00	58.55	110.00	129.61
Total Direct Plant Cost urea plant	[M€]	40.00	40.00	80.00	80.00
Total Direct Plant Cost ammonia+urea plants	[M€]	95.00	98.55	190.00	209.61
Total Plant Cost (TPC) ammonia+urea plants	[M€]	114.00	118.26	228.00	251.53
Total Capital Requirement (TCR) ammonia+urea plants	[M€]	153.90	159.65	307.80	339.57

		Ammonia + urea plants			
		Small-scale plant		Large-scale plant	
		Base case	Reference case	Base case	Reference case
Variable Costs					
Natural gas (feedstock+fuel)	[€/year]	5'878'669	6'210'127	57'493'216	60'733'236
Electricity (import from grid)	[€/year]	2'021'998	2'106'087	1'065'188	1'821'206
Raw water (make-up)	[€/year]	69'773	69'773	697'734	697'734
Chemicals and catalyst	[€/year]	145'361	145'361	1'453'613	1'453'613
MEA makeup	[€/year]	0	22'769	0	224'206
CO_2 transport and storage cost	[€/year]	0	145'676	0	1'434'457
Total variable costs	[€/year]	8'115'802	8'699'793	60'709'751	66'364'450
Specific variable costs	[€/t_{urea}]	164.7	176.6	123.2	134.7
Fixed costs					
Direct labour	[€/year]	3'960'000	4'260'000	3'960'000	4'260'000
Adm./gen. overheads	[€/year]	1'393'200	1'490'871	1'598'400	1'730'762
Insurance and local taxes	[€/year]	1'140'000	1'182'616	2'280'000	2'515'345
Maintenance	[€/year]	1'710'000	1'773'924	3'420'000	3'773'018
Total fixed costs	[€/year]	8'203'200	8'707'411	11'258'400	12'279'126
Specific fixed costs	[€/t_{urea}]	166.5	176.7	22.8	24.9
Key Performance Indicators					
Primary energy consumption	[GJ/t_{NH3}]	26.04	27.42	19.77	21.10
Process carbon intensity	[t_{CO2}/t_{urea}]	0.53	0.31	0.33	0.11
CO_2 avoidance (CA)	[%]	-	41.77	-	66.65
SPECCA	[GJ/t_{CO2}]	-	6.19	-	6.03
Levelized cost of urea	[€/t_{urea}]	624	657	205	224
Cost of CO_2 avoided	[€/t_{CO2}]	-	148.34	-	88.87

9.4. WGS + MDEA pre-combustion carbon capture section

This section shows the detailed results of the techno-economic analysis on the WGS+MDEA pre-combustion CO_2 section.

TABLE 40. Thermodynamic performance [10]

Parameter		Value
Total Fuel Input	[MW]	294.67
Net power consumption	[MW]	33.7
CO_2 flow rate for storage	[kg/s]	65.8
Specific electricity demand	[kWh/kg$_{CO2}$]	0.142
Reboiler heat duty	[MW]	91.4
Reboiler heat duty/CO_2 flow rate for storage	[MJ/kg$_{CO2}$]	1.3
Required heat for WGS	[MW]	66.5
CO_2 capture efficiency	[%]	83.8
CO_2 purity for storage	[%]	98.1
Thermal energy output (DCF)	[MW]	266.8

TABLE 41. Techno-economic performance [10]

Parameter		Base case	Reference case
Steel mill size	[Mt$_{HRC}$/y]	3.16	3.16
Thermal input (BFG LHV)	[MW]	294.67	294.67
Thermal output (decarbonised fuel LHV)	[MW]	294.67	266.80
Heat requirements	[MW]	-	142.47
Electricity requirements	[MW]	-	33.62
Carbon Capture Rate	[%]	-	83%
Cold gas efficiency	[%]	100.0%	90.5%
Overall energy efficiency	[%]	100.0%	56.7%
CO_2 specific emissions	[kg$_{CO2}$/GJ$_{LHV}$]	267.1	51.19
CO_2 capture avoidance	[%]	-	80.8%
ΔCO_2 specific emissions (power section)	[kg$_{CO2}$/t$_{HRC}$]	711.9	120.28
SPECCA	[MJ$_{LHV}$/kg$_{CO2}$]	-	3.54
MDEA unit cost	[M€]	-	56.65
WGS reactors + heat exchangers cost	[M€]	-	12.36
Gas expander cost	[M€]	-	2.80
CO_2 compressor units cost	[M€]	-	19.98
Pumps cost	[M€]	-	0.02
Total Equipment Cost	[M€]	-	91.81
Total Direct Plant Cost	[M€]	-	187.29
Total Plant Cost	[M€]	-	247.69
Annualised Plant Cost	[M€/y]	-	28.24
Fuel Cost	[M€/y]	43.49	43.49
Variable, heat, and electricity costs	[M€/y]	-	27.78

Parameter		Base case	Reference case
Fixed O&M costs	[M€/y]		12.38
Total Annualised cost	[M€/y]	43.49	111.9
LCODF	[€/GJ]	5.20	14.78
Δcost of HRC	[€/t_{HRC}]		21.65
CO_2 avoidance cost	[€/t_{CO2}]		49.38

9.5. MEA post-combustion carbon capture section

Detailed results of the economic model of the MEA post-combustion carbon capture section are shown below.

TABLE 42. Detailed results of the economic model of MEA post-combustion CO_2 capture section

		Small-scale	Large-scale
CO_2 captured	[kg/s]	0.5133	5.054
Compressor power	[MW]	0.18	1.61
MEA CO_2 separation system cost	[M€]	0.92	5.72
CO_2 compressor and condenser cost	[M€]	0.56	2.46
Total Equipment Cost (TEC)	**[M€]**	**1.48**	**8.17**
Erection costs	[M€]	0.74	4.09
Instrumentation and controls	[M€]	0.13	0.74
Piping	[M€]	0.30	1.63
Electrical equipment and materials	[M€]	0.18	0.98
Civil works	[M€]	0.16	0.90
Solvent inventory	[M€]	0.13	0.69
Total Direct Installation Costs (TDIC)	**[M€]**	**1.64**	**9.03**
TEC+TDIC	**[M€]**	**3.12**	**17.20**
Yard improvements	[M€]	0.05	0.26
Service facilities	[M€]	0.06	0.34
Engineering and supervision	[M€]	0.20	1.12
Buildings	[M€]	0.12	0.69
Total Indirect Installation Cost (TIIC)	**[M€]**	**0.44**	**2.41**
Total Installation Cost (TIC = TDIC+TIIC)	**[M€]**	**2.07**	**11.44**
Total Direct Plant Cost (TDPC = TEC+TIC)	**[M€]**	**3.55**	**19.61**