Ammonia, Carbon Capture and Gas Turbine ensure United States Energy Independence

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1 Introduction

The contribution of renewable energy sources to the production of green electricity is well known.

However, the difficulty in storing the electricity produced handicaps those faced with fossil fuels that may be stored in solid or liquid form, but with CO_2 emissions.

On the other hand the United States has large coal reserves.

The question then arises: can coal be transformed into a CO_2 free liquid fuel as a new feedstock for power plants?

Coal *gasification* electricity power plants are now operating commercially in the United States and other countries with well known environmental and efficiency benefits.

A gasifier differs from a combustor in a classical power plant. In a combustor, the coal is completely burnt by air. In a gasifier, the oxidizer supplied is insufficient for complete combustion of the coal. In a modern gasifier, coal is exposed to air or oxygen and steam under high temperature and pressure. Under these conditions, a mixture of carbon monoxide, hydrogen and other gaseous compounds is produced. This gas mixture is further converted into synthesis gas, or 'syngas', for the production of electrical power, steam and basic chemicals such as hydrogen.

These *Integrated Gasification Combined Cycle* power plants can operate with subsequent carbon capture and storage.

Green electricity in this case is delivered to the grid and the CO_2 problem seems to be satisfactorily solved.

Except that in some cases there is no grid or the grid is saturated.

There is obviously no grid available from coal gasification plants in remote or overseas countries.

Coal gasification with subsequent carbon capture and storage could in, those cases, be transformed into *green ammonia fuel* to serve as *feedstock* for power plants.

Our study focuses on the production of hydrogen from coal for its conversion to ammonia and, after storage and transport, its use into a Gas Turbine for electricity production. This is visualized under Figure 1.

2 Report objectives

This report intends to demonstrate that green ammonia produced from coal gasification with carbon capture and storage is, in various circumstances, a competitive fuel for Combined Cycle Gas Turbine power plants.

Implemented on a large scale it can contribute to the reduction of fossil fuel imports.

The processes for coal transformation into green ammonia and then into green electricity are explained in the section chapter 3.

In chapter 4, the study reports the economic interest of green ammonia:

- supplied as feed stock for Combined Cycle Gas Turbines in the United States
- exported in Europe to supplement renewable energies sources
- as a storable power vector complementing wind and solar power.

3 Green ammonia production from coal

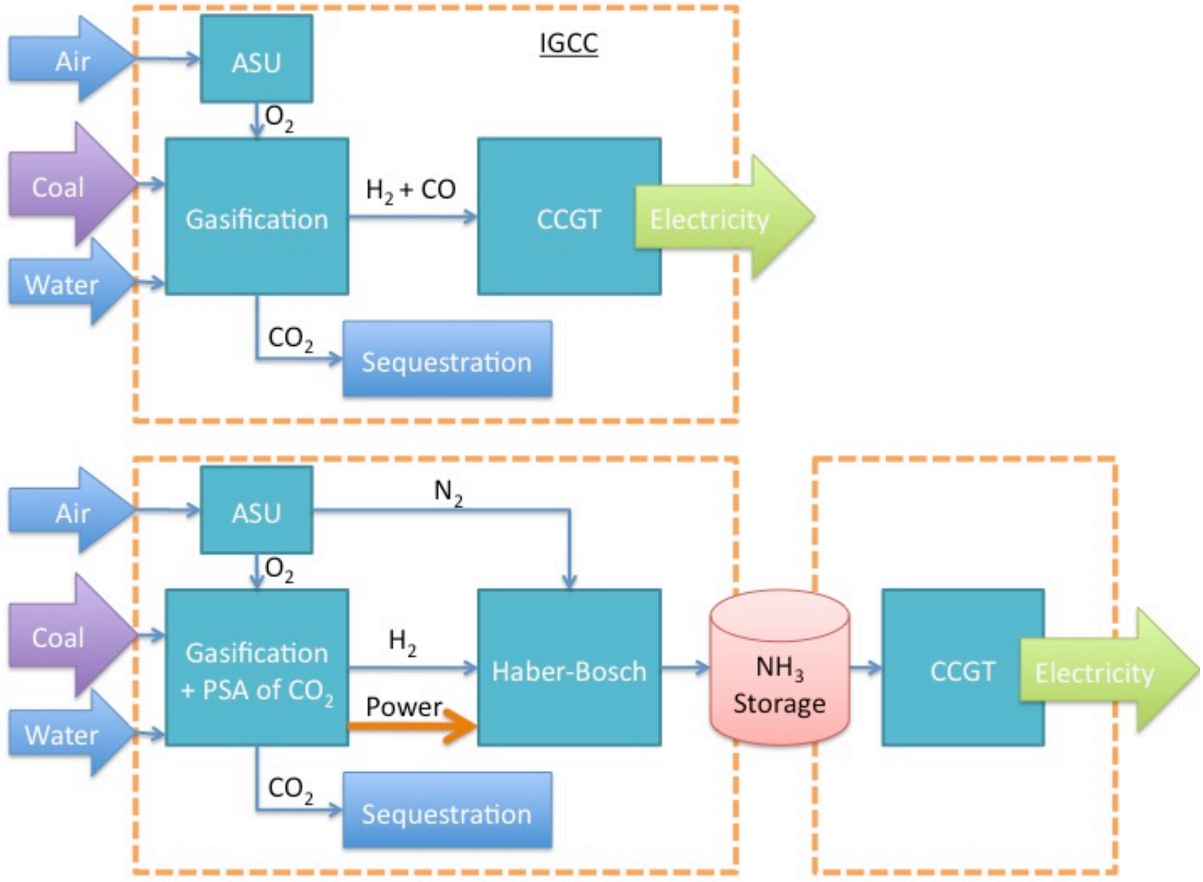
3.1 Description of the ammonia production process

The goal of the process is, in a first step, to convert coal to NH_3 fuel and, in a second step, to burn this fuel in a Combined Cycle Gas Turbine to produce green electricity. The two steps can be separated in time and space.

CO_2 capture and sequestration are foreseen at the level of the gasification where CO_2 outputs alone in a pure stream. This will avoid the need of a CO_2 segregation process that is needed in a classical post combustion CO_2 capture process to separate CO_2 from nitrogen (N_2).

This process is somehow comparable to the IGCC power plants with the noticeable difference that the power generation is replaced by an Haber-Bosch Synloop to produce ammonia. The electricity generation can be located away or even abroad. Figure 1 illustrates both IGCC process and the process proposed in this study.

Figure 1 : Process overview and comparison with the IGCC with sequestration process



The process feedstock are Coal, Water and Air.

The intermediate outputs are green ammonia fuel for CCGT power plants, sequestrated CO_2, slag and sulfur.

The final output of the process is green electricity.

The process is made of four major steps:

1. Coal gasification;
2. CO_2 capture and sequestration;
3. Ammonia production (Haber-Bosch);
4. Efficient and carbon-free electricity production in a CCGT.

It is important to note that the Step 1, 2 and 3 are preferably associated in one factory located in an area with sequestration potential.

There is no need of proximity of this plant with the coal mine and or the CCGT power plant.

This process has two major advantages.

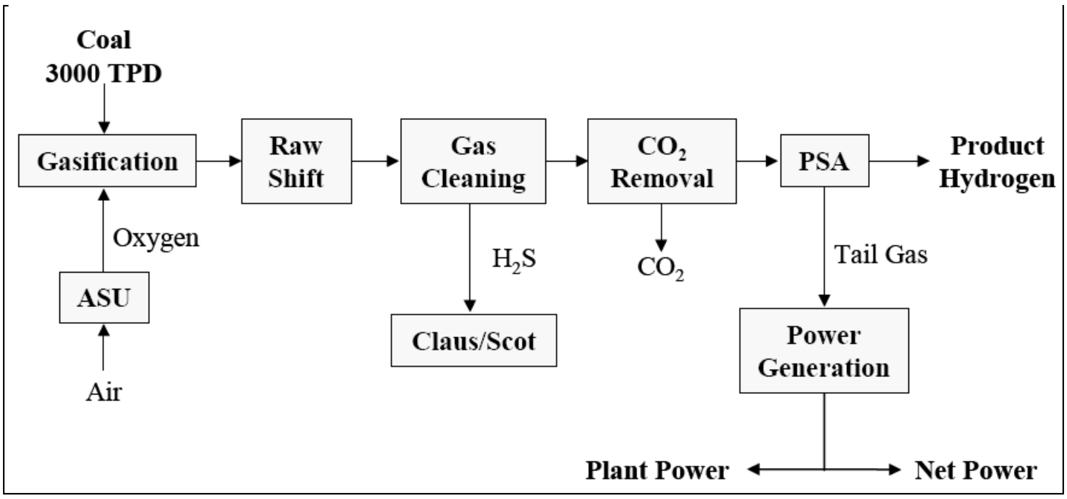
- It takes full advantage of the CCGT power plants : high efficiency, high flexibility and low emissions (SO_2, NO_x, Dust) .
- It contributes to an easy removal of CO_2 because it is not mixed with nitrogen that is present in a classical combustion.

3.2 Gasification: H_2 production process

This section presents the GE Energy quench gasifier (former Texaco)

The GE Energy quench gasification is presented on Figure 2 and includes conventional water-gas shift, cold gas cleaning, CO_2 removal and pressure swing adsorption (PSA). The tail gas of the PSA unit feeds a power generation gas turbine. Hydrogen outputs from the PSA.

Figure 2: H_2 production process with GE Energy gasifier



Source: Hydrogen from coal [36]

3.3 Carbon storage and sequestration

The carbon capture is already included in the gasification process.

This report doesn't give details on the storage and sequestration. Nevertheless the economical study includes the cost evaluation of these steps.

3.4 NH_3 production process

The ammonia production process used in this study is the classical Haber-Bosch one.

A stochiometric mixture of hydrogen and nitrogen is needed for the conversion of the gas mixture to ammonia.

Hydrogen is issued from the gasification process and nitrogen from the air separation unit and from an additional controlled input of air.

The energy necessary to run this process is provided by the excess of energy from the gasification process.

4 Cost Evaluations

4.1 Introduction

The competitiveness of green NH_3 fuel versus renewable energy sources in the United States and Europe is assessed in this chapter.

For this purpose, green NH_3 Combined Cycle Gas Turbine electrical power costs are compared with classical electricity production costs.

In the first step, H_2 and Green NH_3 production costs are computed in sections 4.2.1 and 4.2.2 respectively.

In the 2nd step, Green NH_3 production costs, including transport and storage for FOB delivery, are calculated in section 4.3. A comparison with the NH_3 price on the US market is given in section 4.4.

In the 3rd step, Section 4.5 deals with the green NH_3 CCGT electrical power costs versus the electricity production costs in the US.

In the 4th step, Green NH_3 production costs including insurance and freight for CIF delivery in Europe are calculated in section 4.6.

In the 5th step, section 4.7 deals with green NH_3 CCGT electrical power versus the electricity production costs of classical and renewable energies in Europe.

Each cost computation is made for 6 different coal qualities. The first coal quality is the one used in the reference gasification process [36]. The next five apply to coal extracted in the US. Their price and heat values can be found in [48]. This is summarized in Table 1.

Table 1 : Description of Coal used in this study

ID	*#0*	#1	#2	#3	#4	#5
Origin	*Reference Coal*	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
Year/reference	*1998 [36]*	2012 [48]	2012 [48]	2012 [48]	2012 [48]	2012 [48]
Price [$/t]	*27.30*	61.84	70.99	51.26	9.37	39.13
HHV [Btu/lb]	*10,665*	12,500	13,000	11,800	8,800	11,700

4.2 H_2 and NH_3 production cost

4.2.1 H_2 production cost

The production cost of H_2 is calculated in Appendix 1.

Basic assumptions are:

- Gasification process: GE Energy

- Coal input : 3000 t/d as a basis for a coal with a HHV of 10665 Btu/lb
- A H_2 production of 281.1 t/d

A breakdown of the daily production cost include the coal and water consumptions, the CO_2 storage, the amortization and operating costs.

They enable to compute the cost of H_2 in $/t and are summarized in Table 2.

Important Note: This evaluation includes the CO_2 avoided cost representing the taxes relevant to a hydrogen production from methane (CH_4) without sequestration.

Table 2 : Production cost of H2 in a production facility of 281.1 t/d

ID	*#0*	**#1**	**#2**	**#3**	**#4**	**#5**
Type of Coal	*Reference Coal*	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
Coal consumption [t/d]	*3,000*	2,560	2,461	2,711	3,636	2,735
Coal cost [$/d]	*81,900.00*	158,284.81	174,714.48	138,981.61	34,066.12	107,011.11
Annuity [$/d]	*152,355.99*	152,355.99	152,355.99	152,355.99	152,355.99	152,355.99
Water cost [$/d]	*9,000.00*	9,000.00	9,000.00	9,000.00	9,000.00	9,000.00
CO2 Storage [$/d]	*47,526.09*	47,526.00	47,526.00	47,526.00	47,526.00	47,526.00
Total daily cost [$/d]	*290,782.08*	367,166.79	383,596.47	347,863.59	242,948.11	315,893.10
H_2 cost [$/t]	***1,034.44***	**1,306.18**	**1,364.63**	**1,237.51**	**864.28**	**1,123.78**
Avoided Cost of CO2 [$/t] (*)	*75.90*	75.90	75.90	75.90	75.90	75.90
Adjusted H_2 cost [$/t]	***958.54***	**1,230.28**	**1,288.72**	**1,161.61**	**788.37**	**1,047.87**

(*) Base for computation : 24$/$t_{CO2}$; 281.1 t_{H2}/day ; avoided CO_2 compared to ammonia produced from Natural Gas : 889 t_{CO2}/day.

4.2.2 NH_3 production cost

The production cost of NH_3 is calculated in Appendix 1.
Basic assumptions are:

- Production process: Haber-Bosch
- H_2 input: 281.1 t/d
- NH_3 output: 1593 t/d

A breakdown of the daily production cost include H_2 cost, amortization costs and operating costs.
They enable to calculate the cost of NH_3 in $/t and are summarized in Table 3.

Table 3: Cost of NH_3 production in a production facility of 1593 t/d

ID	#0	#1	#2	#3	#4	#5
Type of Coal	Reference Coal	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
H2 cost [$/t]	958.54	1,230.28	1,288.72	1,161.61	788.37	1,047.87
H2 cost [$/d]	269,446.08	345,830.89	362,260.56	326,527.69	221,612.20	294,557.19
Annuity cost [$/d]	44,812.86	44,812.86	44,812.86	44,812.86	44,812.86	44,812.86
Operating cost [$/d]	24,799.81	24,799.81	24,799.81	24,799.81	24,799.81	24,799.81
NH3 production cost [$/d]	344,557.65	344,558.65	344,559.65	344,560.65	344,561.65	344,562.65
NH3 production cost [$/t]	**217.20**	**266.13**	**276.66**	**253.77**	**186.56**	**233.29**

4.3 Cost of NH_3 production, including transport and storage, for FOB delivery

The Iowa State University study [18] assesses the cost for the pipeline transport of ammonia over a distance of *1,610 km* and its storage for *45 days* at $34/t and $32/t respectively, i.e. $66/t in total for 2007 or 71.6 $/t for 2011 [47]. This cost added to the costs presented in the previous table gives the FOB price of NH_3.

Table 4: NH_3 cost delivered FOB

ID	*#0*	#1	#2	#3	#4	#5
Type of Coal	*Reference Coal*	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
FOB cost of NH_3, 2011[$/t]	***288.80***	**337.73**	**348.26**	**325.37**	**258.16**	**304.89**

4.4 Comparison with ammonia price on US market

As we can see thereafter, ammonia produced by coal gasification with CCS is competitive with fossil NH_3 sold on the world market.

Table 5: Green ammonia produced from coal compared to market price

Fossil NH_3 CFR Tampa price, 2011 [43]	560 $/t
Green NH_3 FOB cost, 2011, depending on coal price, refer to Table 4	258.33 to 348.98 $/t

4.5 Electricity production cost via green NH_3 CCGT versus classical **electricity production cost in the U.S.**

The detailed calculation of the electricity production cost via a combined cycle using NH_3 in the U.S. is presented in Appendix 1 and summarized in the following table

Table 6: Electricity produced from Ammonia

ID	*#0*	#1	#2	#3	#4	#5
Type of Coal	*Reference Coal*	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
Electricity cost [$/MWh]	***116.67***	**134.20**	**137.98**	**129.77**	**105.68**	**122.43**

Table 7: Electricity production cost comparison for 2011 in the U.S.

Electricity production	**Cost [$/MWh]**
Natural Gas CCGT [1]*	**79**
Natural Gas CCGT with CCS [1]*	**96**
Green NH_3 CCGT	**106 to 138**

*adjusted to 2011$, [47]

It appears that electricity production cost from green ammonia with CCS is up from 10% to 43% against the electricity production cost from natural gas with CCS.

Electricity production cost from green NH_3 appears to be in line with photovoltaic electricity and in line with electricity from solid biomass and off-shore wind in the United States.

4.6 Cost of NH_3 production, including insurance and freight, for CIF delivery in Europe

Reference [53] provides CIF and FOB numbers for Anhydrous Ammonia US imports from the major supply countries that are Trinidad and Tobago, Canada, Russia, Ukraine, and Venezuela. The difference between CIF and FOB values gives the cost of insurance and freight. Between 2005 and 2009 insurance and freight costs fluctuate between 60$/$t_{NH3}$ and 75.75$/$t_{NH3}$.

In this study, we estimate the insurance and freight for transportation from the US to Europe at 70$/$t_{NH3}$.

Table 8: NH_3 cost delivered CIF in Europe

ID	*#0*	#1	#2	#3	#4	#5
Type of Coal	*Reference Coal*	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
CIF cost of NH_3, 2011 [$/t]	***358.80***	**407.73**	**418.26**	**395.37**	**328.16**	**374.89**

4.7 Electricity production cost via green NH_3 CCGT versus renewable energies in Europe

The detailed calculation of the electricity production cost via a combined cycle using NH_3 in Europe is presented in Appendix 1.

Table 9: Electricity production cost via green NH_3 CCGT for 2011 in Europe

ID	*#0*	#1	#2	#3	#4	#5
Type of Coal	*Reference Coal*	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
Electricity cost [$/MWh]	*132.62*	148.40	151.80	144.41	122.73	137.81

Table 10: Electricity production cost in Europe [1]*

Production way	Feedstock cost in 2008	Production cost $/MWh in 2008	Production cost $/MWh in 2011**	Country
Hydroelectric	/	74	75	Sweden
Solid biomass	US$69.06/MWh	129	131	Netherlands
Biogas	US$2.65/MWh	79	80	France
On-shore wind	/	90	91	France
Off-shore wind	/	138	139	Germany
Photovoltaic	/	287	289***	France
Natural Gas CCGT(incl. carbon Cost)[1]	/	90	91	Belgium

* interest rate of 5%,
** adjusted to 2011 with [51]
***PV electricity production market knows a fast decrease of its costs. Therefore production cost to take into account is evaluated to 0.15 $/kWh in 2011 depending on the sun exposure.

Electricity production cost from green NH_3 appears to be in line with photovoltaic electricity and in line with electricity from solid biomass and off-shore wind in Europe.

5 Efficiency of the process versus efficiency of coal power plant

At Table 11, the calculation of the energy efficiency of the global process is performed. For comparison, Table 12 provides efficiency figures for other coal fired power plants.

Table 11: Energy efficiency of the global process

Efficiency: Coal to electricity	
Coal to hydrogen (incl. CCS), % HHV [36]	59
Hydrogen to ammonia, % LHV [18]	81.8
Ammonia to electricity, % LHV [39]	60
Total energy efficiency, %	**28,98**

Table 12: Energy efficiency of coal power plant in the USA

Coal-fired power plant	**Efficiency, % LHV**
Pulverised coal PCC without CCS [1, USA]	39
IGCC without CCS [1, USA]	39
IGCC with CCS [1, USA]	32
IGCC with CCS [58]	33-35

The global process efficiency appears to be comparable to the one of a IGCC (Integrated Gasification Combined Cycle) with CCS (Carbon Capture & Storage).

6 Sequestration potential of carbon dioxide

6.1 Potential

Geological storage [42]: injecting CO_2 in dense form into a rock formation below the earth's surface. Porous rock formations that hold or have previously held fluids are particularly suitable for CO_2 storage.

Geological storage options [42]:

- Storage in depleted oil and gas reservoirs
- Use of CO_2 in enhanced oil and gas recovery (EOR)
- Deep saline formations (on- or off-shore)
- Enhanced coal bed methane recovery (demonstration phase)

"The U.S. Department of Energy (DOE) estimates overall potential for storage in the U.S. to be at 3,600 to 12,900 billion metric tons of CO_2. Texas and Louisiana have the highest potential, while states like Maine, Vermont, and Wisconsin have no storage potential at all." [54]

6.2 References

Project	Sequestration capacity
The Mountaineer Carbon Capture and Sequestration Project	100 kt CO2/year
Maasvlakte CCS Project – ROAD (2015) 1070 MWe	1100 kt CO2/year (90%)

7 Marketing

The green ammonia market is closely linked to the CO_2 market.

The target is the reduction of CO_2 emissions.

Penalizing CO2 emissions is one way of achieving this objective.

Subsidizing green ammonia production is another route.

Both routes are hardly supported by the different countries.

The 'quotas idea' on the contrary could receive global agreement.

How does it work?

A Central Authority fixes a limit for the *global* CO_2 emissions.

A 'quota' is allocated to the companies limiting their *specific* CO_2 production.

These quotas can be purchased or sold.

How does it work for green ammonia?

If green ammonia, for instance, is bought by a European Power Plant its CO_2 quota permit will be increased by the relevant avoided CO_2 emissions. The resulting saved quota will become a free for trade benefit for the Company.

The 'quotas system' ensures flexibility and incentives for the green ammonia market with the guarantee of a *global* pollution limit. Since this is an upper limit it will not be reached.

In addition, this global pollution limit can be reduced gradually by the Central Authority.

The quota system is therefore an efficient tool for reducing CO_2 emissions.

8 Conclusion

Going green deserves a serious debate. We have to pave the way for adequate solutions for the CO_2 emissions problem.

The first positive answer is given by the renewable and CO_2-free energies: hydraulic, geothermal, biomass, wind and solar.

They are commonly accepted around the world.

Their *intermittent* action is so far complemented by the *continuous* action of *storable* fossil energies which, unfortunately, are also responsible for CO_2 emissions.

The CO_2 emissions problem is consequently not completely solved.

This study proposes *green ammonia from coal* as a substitute fuel for the fossil energies.

The CO_2-free emissions, storability and competiveness represent its main *worldwide* benefits.

Green ammonia production *costs* ranging from 258 to 349 $/t FOB US port must be compared with the non-green ammonia market *price* assessed at 560 $/t FOB US port.

Biogas, off-shore wind and solar energy costs in Europe, respectively 80, 139, 289 $/MWh, have to be compared with green ammonia energy costs ranging from 123 $/MWh for coal from the Powder River Basin to 152 $/MWH for coal from US Northern Appalachian.

The United States, China and Russia are all potential *producers* of green ammonia from coal. All these countries would find additional benefits in green ammonia since it replaces imported fossil fuels, ensures national energy independence, extends the energy-mix target, presents competitive green ammonia versus non-green ammonia on the international market and promotes the coal economy. Huge coal reserves, geographical situation, technology, economy and ecological concerns place the United States in a leading position in this respect.

On the other hand potential *consumer-countries* will find additional benefit in the extension of the green-energy-mix target.

Last but not least, the 'CO_2 quota regulations' of some countries might be extended to other countries in order to reach an *international agreement* beneficial to all. Widely accepted in the European Community, the CO_2 quota regulations represent a serious asset for a green ammonia trade kick-off between the United States and the European Union.

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Appendix 1 - Computation details

This appendix provides details of computations. Column #0 figures are eighter figures extracted of ref [36] that studies the gasification of coal with sequestration of CO2 and by mean of the GE Energy quench gasifier. Column #0 also contains common data and figures that are not dependent of the type of coal. Column #1 to #5 contain computation for different coal currently extracted and sold in the United States.

ID	**#0**	#1	**#2**	#3	**#4**	#5
Type of Coal	**Ref Coal used by ref [36]**	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin

1. Coal description						
(description of the coal used as feed stock for computation in this study)						
Reference	1998 [36]	2012 [48]	2012 [48]	2012 [48]	2012 [48]	2012 [48]
Price [$/t]	27,30	61,84	70,99	51,26	9,37	39,13
HHV [Btu/lb]	**10.665**	12.500	13.000	11.800	8.800	11.700
HHV Ratio (reference is Coal #0)	1,00	1,17	1,22	1,11	0,83	1,10

2. Hydrogen (H2) cost computation	-	-	-	-	-	-
H2 characteristics						
LHV [kJ/kg]	120.500,00					
HHV [kJ/kg]	141.000,00					
Densité [kg/Nm³]	0,09					
Gasification of Coal to H2						
Gasifier technical data (ref [36])						
Technology: GE Energy quench gasifier						
Carbon Sequestration method: PSA (pressure swing adsorption)						
Carbon Sequestration percentage	87%					
Electricity Production: HRSG (heat recovery steam generator)						
HHV efficiency %	59,00					
Extra electric power [MW]	26,90					
H2 production [t/day]	**281,10**					
Capital Cost						
Reference instalation : [18], table7, Gray &T.1; NH3 Plant size of 281 t/d						
Capital cost 2007 [Million $]	562,00					
Capital Cost Index 2011/2007	1,11					
Capital cost MM en **2011**	626,50					
IRR	0,05					
Plant life	25,00					

ID	#0	#1	#2	#3	#4	#5
Type of Coal	**Ref Coal used by ref [36]**	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
Capacity factor	0,85					
Operating Cost						
Operating cost over plant lifetime, 1998 [M$] ([36] Net operating cost - Coal)	26,40					
Cost Index 2011/1998	1,50					
Operating cost over plant lifetime, 2011 [M$]	39,70					
Annuity						
Annuity [$/d] (including the capital cost and the Operating cost over plant lifetime)	152.355,99					
Coal						
Price [$/t]	27,30	61,84	70,99	51,26	9,37	39,13
Coal consumption (=3000 / HHV Ratio) [tons/day]	**3.000,00**	2.559,60	2.461,15	2.711,44	3.635,80	2.734,62
Coal cost [$/d]	81.900,00	158.284,81	174.714,48	138.981,61	34.066,12	107.011,11
Water						
Water consumption [m3/d]	9.000,00	9.000,00	9.000,00	9.000,00	9.000,00	9.000,00
Water cost [$/d]	9.000,00	9.000,00	9.000,00	9.000,00	9.000,00	9.000,00
CO2 Management						
Cost of CO2 transport [$/tCO2]	1,00					
Cost of CO2 sequestration [$/tCO2]	3,00					
Cost of monitoring [$/tCO2]	0,30					
Total CO2 cost 2002 [$/tCO2]	4,30					
Total CO2 cost 2011 [$/tCO2]	5,38					
CO2 to sequester [Mt_{CO2}/y] (computed for the reference and estimated equal for other coal types)	3.224,35	3.224,35	3.224,35	3.224,35	3.224,35	3.224,35
CO2 to sequester [t_{CO2}/d]	8.833,85	8.833,85	8.833,85	8.833,85	8.833,85	8.833,85
Cost of sequestration [$/d]	47.526,09	47.526,09	47.526,09	47.526,09	47.526,09	47.526,09
Cost H2 2011 [$/t]	1.034,44	1.306,18	1.364,63	1.237,51	864,28	1.123,78

2. Avoided CO_2 cost						
Assumption: cost of CO2 [$/$t_{CO2}$]	24,00					
Avoided Cost of CO2 [$/d]	21.336,00					
Avoided Cost of CO2 [$/$t_{NH3}$]	75,90	75,90	75,90	75,90	75,90	75,90
Adjusted H_2 cost [$/t]	*958,54*	*1.230,28*	*1.288,72*	*1.161,61*	*788,37*	*1.047,87*

Note: this Adjusted cost of Hydrogen will be presented and taken into account as an alternative in the following computation.

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3. Ammonia NH_3 Cost computation						
NH3 characteristics						
LHV [kJ/kg]	18.646,00					
HHV [kJ/kg]	22.500,00					
Density [kg/Nm³]	0,76					
Ammonia Plant technical Data						
Technology: Haber-Bosch						

ID	**#0**	#1	**#2**	#3	**#4**	#5
Type of Coal	**Ref Coal used by ref [36]**	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
Mass efficiency H-B	98%					
Electricity consumption [kWh/kg_{NH3}]	0,39					
H2 consumption [kg/kg_{NH3}]	0,18					
Production [kg/d]	**1.561.042,00**					
Capital Cost						
Reference instalation : [18], table12, Gray &T.1; NH3 Plant size of 1650 t/d						
Capital cost 2007 [$]	203.000.000					
Capital Cost Index 2011/2007	1,11					
Capital cost 2011 [$]	226.298.248,95					
Interest rate IRR	5%					
Lifetime [years]	30					
Capacity factor	90%					
Operating Cost						
Annual O&M cost [% invest.]	4%					
O&M cost [$/d]	24.799,81					
Annuity						
Annuity [$/d]	44.812,86					
Annuity [$/y]	14.721.025,85					
Electricity						
Electricity Cost [$/kWh]	0,07					
Electricity consumption (of the H-B process) [kWh/d]	608.806,38					
Requisite power[MW]	25,37					
Net Power (including power recovered from the Gaification) [MW]	-1,53					
Electricity consumption (including energy recovered from the gasification) [kWh/d]	0,00					
Cost of electricity [$/d]	0,00					
Hydrogen (H_2)						
H2 cost [$/t]	1.034,44	1.306,18	1.364,63	1.237,51	864,28	1.123,78
H2 cost (incl.CO_2 Avoided costs) [$/t]	*958,54*	*1.230,28*	*1.288,72*	*1.161,61*	*788,37*	*1.047,87*
H2 consumption [t_{H2}/d]	281,10					
H2 cost [$/d]	290.782,08	367.166,89	383.596,56	347.863,69	242.948,20	315.893,19
H2 cost (incl.CO2 Avoided costs) [$/d]	*269.446,08*	*345.830,89*	*362.260,56*	*326.527,69*	*221.612,20*	*294.557,19*
Total						
Daily cost without transport [$/d]	360.394,75	436.779,56	453.209,23	417.476,36	312.560,87	385.505,86
Daily cost without transport (incl.CO2 Avoided costs) [$/d]	*339.058,75*	*415.443,56*	*431.873,23*	*396.140,36*	*291.224,87*	*364.169,86*
Cost production NH3 2011 [$/t]	**230,87**	**279,80**	**290,32**	**267,43**	**200,23**	**246,95**
Cost production NH3 2011(incl.CO2 Avoided costs) [$/t]	***217,20***	***266,13***	***276,66***	***253,77***	***186,56***	***233,29***

4. Ammonia FOB Cost computation						
Transport And Storage of NH3 (transport over 1610 km storage during 45 days)						

ID	**#0**	#1	**#2**	#3	**#4**	#5
Type of Coal	**Ref Coal used by ref [36]**	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
Transport & stockage cost 2007 [$/t]	66,00					
Transport & stockage cost 2011 [$/t]	71,60					
Cost of NH3 FOB [$/t]	**302,47**	**351,40**	**361,92**	**339,03**	**271,83**	**318,55**
Cost of NH3 FOB (incl.CO2 Avoided costs) [$/t]	***288,80***	***337,73***	***348,26***	***325,37***	***258,16***	***304,89***

5. Ammonia CIF Europe Cost computation						
transport from FOB to CIF (evaluated according to [58]: mean value of the differences between CIF and FOB prices observed on US imports of NH_3)	70,00					
NH3 Cost CIF Europe, 2011 (incl.CO2 Avoided costs) [$/t]	*358,80*	*407,73*	*418,26*	*395,37*	*328,16*	*374,89*

6. CCGT NH3 USA						
CCGT characteristics						
Type	CCGT US					
Reference	[1]					
Puissance [MW]	400					
efficiency	54%					
Capacity Factor	85%					
Assumption						
Natural Gas to Ammonia conversion cost [% of investment]	10%					
Ammonia cost [$/t]	288,80	337,73	348,26	325,37	258,16	304,89
Annual electricity production						
Annual production [MWh/y]	2.978.400,00					
Capital Cost						
Investment cost according to reference, 2008 [$/kWe]	969,00					
adapted to ammonia fuel, 2010 [$/kWe]	1.065,90					
Capital Cost Index 2011/2008	1,02					
Capital Cost, 2011 [$/kWe]	1.084,98					
Interest rate	5%					
Lifetime in years	30					
Annuity [$/y]	28.231.808,65					
Cost of investment per MWh [$/MWh]	**9,48**					
Operating Cost						
O&M, 2008 [$/MWh]	3,61					
Index 2011/2010	1,02					
Operating Cost [$/MWh] 2011	**3,67**					
Ammonia consumption						
Consommation [t/MWh]	0,36					
Cost, 2011 [$/t]	288,80	337,73	348,26	325,37	258,16	304,89
Fuel cost [$/MWh]	**103,51**	**121,05**	**124,82**	**116,62**	**92,53**	**109,28**
Total						
Cost of Electricity [$/MWh]	**116,67**	**134,20**	**137,98**	**129,77**	**105,68**	**122,43**

ID	#0	#1	#2	#3	#4	#5
Type of Coal	**Ref Coal used by ref [36]**	US Central Appalachian	US Northern Appalachian	Illinois Basin	Powder River Basin	Uinta Basin
7. CCGT NH3 EU						
CCGT characteristics						
Type	CCGT EU					
Reference	[1]					
Puissance [MW]	800					
efficiency	60%					
Capacity Factor	85%					
Assumption						
Natural Gas to Ammonia conversion cost [% of investment]	10%					
Ammonia cost [$/t]	358,80	*407,73*	*418,26*	*395,37*	*328,16*	*374,89*
Annual electricity production						
Annual production [MWh/y]	5.956.800,00					
Capital Cost						
Investment cost according to reference, 2008 [$/kWe]	1.025,00					
adapted to ammonia fuel, 2010 [$/kWe]	1.127,50					
Capital Cost Index 2011/2008	1,02					
Capital Cost, 2011 [$/kWe]	1.147,68					
Interest rate	5%					
Lifetime in years	30					
Annuity [$/y]	59.726.736,57					
Cost of investment per MWh [$/MWh]	**10,03**					
Operating Cost						
O&M, 2008 [$/MWh]	6,73					
Index 2011/2008	1,02					
Operating Cost, 2011 [$/MWh]	**6,85**					
Ammonia consumption						
Consommation [t/MWh]	0,32					
Cost, 2011 [$/t]	358,80	407,73	418,26	395,37	328,16	374,89
Fuel cost [$/MWh]	**115,74**	**131,53**	**134,92**	**127,54**	**105,86**	**120,93**
Total						
Coût [$/MWh]	**132,62**	**148,40**	**151,80**	**144,41**	**122,73**	**137,81**

Appendix 2 – List of notations

- ASU: Air Separation Unit
- CCGT: Combined Cycle Gas Turbine
- CCS: Carbon Capture and Storage
- CIF: Cost, Insurance and Freight
- FOB: Free on Board or Freight on Board
- IGCC: Integrated Gasification Combined Cycle
- IPCC: Intergovernmental Panel on Climate Change