Comparison of Life Cycle GHG Emissions and Energy Consumption of combined Electricity and H₂ production pathways with CCS: Selection of technologies with Natural Gas, Coal and Lignite as fuel for the European HYPOGEN Programme

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Abstract

The European DYNAMIS project is part of the HYPOGEN quick-start programme and aims at investigating viable routes for large-scale cost-effective combined hydrogen and electricity production with integrated CO₂ Capture and geological Storage. This paper presents the environmental evaluation carried out for each technology option studied, producing Hydrogen and Electricity with CCS. The methodology used is based on Life Cycle Analysis (LCA) principles and concentrates on the assessment of two criteria: GHG emissions and non-renewable primary energy consumption. As with other evaluations performed in DYNAMIS (mainly focused on technical and economic aspects), these results lead to the selection of best concepts in terms of environmental efficiency by comparing and weighing up positive and negative effects (i.e., GHG emissions reduction and increase of non-renewable primary energy consumption).

1. Introduction

The European DYNAMIS project is part of the HYPOGEN quick-start programme and aims at investigating viable routes for large-scale cost-effective combined hydrogen and electricity production with integrated CO₂ Capture and geological Storage (CCS).

This paper presents the environmental evaluation carried out for each technology option studied, producing Hydrogen and Electricity with CCS. The methodology used is based on Life Cycle Analysis (LCA) principles and concentrates on the assessment of 2 criteria: greenhouse gas (GHG) emissions and non-renewable primary energy consumption. The selection of these criteria is based on the assumption that CCS implementation enables GHG...
emissions to be significantly reduced but induces at the same time additional energy consumption, mainly for CO₂ capture processes but also for CO₂ transportation and storage. Furthermore, this study aims at assessing the environmental impact of electricity and hydrogen production considering whole pathways, i.e., by taking into account the following steps:

- Natural Gas, Bituminous Coal and Lignite supply (extraction, treatment and transport to the power plant),
- 400 MW Electricity and 50 MW Hydrogen production plant including CO₂ capture process (power plant operation and construction),
- CO₂ transportation and geological storage.

This study mainly provides detailed environmental assessments (providing the share of each step in overall assessment) and 2 environmental rankings (one for each criteria) of all options studied in the DYNAMIS project. As with other evaluations performed in DYNAMIS (mainly focused on technical and economic aspects), these results lead to the selection of the best concept for each fuel in terms of environmental efficiency by comparing and weighing up positive and negative effects (i.e respectively: GHG emissions reduction and increase of non-renewable primary energy consumption).

2. Methodology and data sources

2.1. Life Cycle Assessment methodology: basic principles

Environmental issues are increasingly taken into account for the development of energy pathways, but environmental assessments only make sense if they are conducted on the whole chain i.e., on the entire life cycle of the product or unit of energy service studied. If only a part of the pathway is studied, what could appear as an environmental improvement on this part could lead to a worsening of the environmental impact on other upstream or downstream parts of the pathway. That is why the global approach of Life Cycle Assessment (LCA) methodology is relevant and even necessary in order to avoid these pollution transfers.

LCA methodology is applied in this project to the various options chosen for the hydrogen and electricity production pathways (different origin and type of fuel, different technologies for HYPOGEN power plants, different locations and depths for CO₂ storage...), using TEAMᵀᴹ LCA software. The basic LCA principles followed in this study are detailed in the standards ISO 14040 [2].

2.2. Definition of indicators assessed

The focus in this study is on the assessment of Non-Renewable (NR) energy consumption and greenhouse gas (GHG) emissions for different pathways of electricity and hydrogen production. The flows studied are the 3 main GHG (i.e., CO₂, CH₄ and N₂O) and the non-renewable energy flows expressed in MJ. The following indicators are used for the assessments:

- **GHG emissions**: The 3 main GHG (CO₂, CH₄ and N₂O) are converted into CO₂ equivalent (CO₂eq) using coefficients called Global Warming Potentials (GWP at 100 years time horizon) defined and estimated by IPCC [3].
- **NR primary energy consumption**: several indicators can be used to state the NR primary energy consumption such as NR primary expended energy, NR primary energy input or NR primary energy yield (Fig. 1). **Later in this paper, the results are expressed using only the second indicator (NR primary energy input, expressed in MJ)** which states for the amount of NR primary energy required to produce the desired quantity of product of interest.
2.3. Definition of scope

The system considered in this study is the production of power (400 MW elec) and hydrogen (50MW HHV), from raw material acquisition to the production of electricity and hydrogen. 12 options are evaluated and compared:

- 9 pathways including 9 different plants for electricity and H₂ production with CO₂ capture - 3 for each fuel (Natural Gas, Bituminous Coal and Lignite) – selected thanks to previous work in the Dynamis project
- 3 additional reference pathways for electricity and H₂ production without CCS – 1 reference for each fuel – in order to evaluate the environmental benefits of this technology on the whole pathway.

The functional unit is the quantified product unit for which all indicators are assessed. In the present study, in order to compare all the pathways on the same basis, GHG emissions and NR energy consumption are calculated for a defined quantity of energy (1 kWh) of electricity and hydrogen produced, with a slight difference on the H₂ ratio (energy produced as H₂ / Total Energy produced) varying in a small range (from 8.6% up to 11.1%).

2.4. Boundaries and data sources

The assessment includes all steps from material extraction to the production of electricity and hydrogen with CO₂ capture and storage but does not take into account the use of electricity or hydrogen. The main objective of this study is the comparison between various production pathways and, as the use is the same for each production route, this is not a relevant step to include in the environmental assessment.

General data used at several of the following detailed stages are extracted from general LCA databases (ECOINVENT, DEAM, GEMIS etc.), IFP LCA database or from expert literature sources.

2.4.1. Fuel supply to the power plant

The fuel supply assessment accounts for the NR energy consumption and GHG emissions associated to all steps required to deliver the fuel to the power plant i.e. extraction, treatment of the fuel and its transportation/distribution.

Supply sources are selected for each fuel according to the context of the project i.e. for a plant located in Europe in 2010. The assessments thus correspond to a defined supply scenario associated to specific extraction and treatment techniques and to specific transportation distances.

For natural gas, the average European supply in 2010 is chosen and assessed. The corresponding breakdown between the various sources (Russia, Norway, Libya, Algeria, Nigeria, Middle East) is calculated thanks to data provided by BP, Cedigaz, Gaz de France, IEA and IFP (Prieur and Tilagone [4]).

For bituminous coal (BC), it is considered that the fuel is extracted from a South African underground mine and treated there; South Africa being one of the leading producers and exporters of coal. Transportation of BC is divided into 3 stages: 500 km by train from the mine to the export harbor, 7000 nautical miles by Capesize to the import harbor and finally 250 km by train to the power plant.
In our scenarios, lignite is extracted in West-Germany. The specificity of lignite concepts is that lignite power plants are supposed to be located near the lignite mine. Transportation of lignite is therefore not considered.

2.4.2. Power plant operation and construction

This step refers to the production of electricity and hydrogen. Two contributions are presented in the results section which correspond respectively to the power plant operation (including CO$_2$ capture, drying and compression) and the power plant construction.

The GHG emissions and NR energy consumptions associated to power plant operations are calculated from data provided by previous work in the Dynamis project (both for plants with CO$_2$ capture, drying and compression and reference plants without CO$_2$ capture) : fuel consumption, fuel LHV, hydrogen and net electric output, CO$_2$ capture rate, CO$_2$ specific emissions, economic life duration and operation hours.

The contribution of power plant construction in the environmental assessment corresponds to infrastructure construction (civil engineering) and major plant components production. In this study, that the materials and energy needed for this step are supposed to be the same for a given fuel (same contribution in the overall assessments for all power plants running on the same fuel). Furthermore, additional materials needed for major plant components are evaluated on the basis of data provided by Dynamis partners. The corresponding impacts are amortized on the energy amount (electricity and hydrogen) produced during the economic life duration of the plant (25 years).

2.4.3. CO$_2$ transportation and injection

The energy and material consumptions which are taken into account for this stage correspond to both production of pipelines and energy needed for CO$_2$ injection (compression before storage). The amounts of steel needed for pipelines are estimated on the basis of data extracted from expert literature and databases. Several transportation distances are considered within the range 30 – 300km. The corresponding GHG emissions and energy consumptions are amortized on the CO$_2$ amount conveyed in pipelines during their lifetime. The energy requirement for CO$_2$ injection is calculated for 2 storage depths: 1000m and 2500m.

2.4.4. CO$_2$ storage

The energy consumption and GHG emissions associated to this stage correspond to material requirements needed for drilling and well construction. Techniques used for such drillings are similar to those used in the oil industry. Material and energy consumption for the well construction are thus based on the general casing design. Data were obtained from IFP oil experts. The corresponding GHG emissions and non-renewable energy consumptions are amortized on the CO2 amount stored in the sink during 25 years. Calculations are made for both onshore and offshore storage in an aquifer located between 30 and 300km from the power plant.

3. LCA results for the selected electricity and hydrogen production pathways

The base scenario is defined to show if the contribution of CO$_2$ transportation and storage may really be significant in the GHG and non renewable energy consumption balances of the whole pathway. Thus, in the base scenario, CO$_2$ transportation and storage is maximized. This scenario includes the fuel supply, the studied power plant operation and construction, 300 km CO$_2$ pipeline transportation (only for pathways with CCS) and CO$_2$ onshore storage in an aquifer at 2500 m depth (only for pathways with CCS).

Results are given with details of the contribution at each step.
Figure 2 – Detailed assessment of non-renewable primary energy consumptions for the 12 studied pathways producing electricity + H2 (9 Dynamis cases with CCS + 3 reference cases without CCS).

Figure 3 – Detailed GHG emissions assessment of the 12 studied pathways of electricity + H2 production (9 Dynamis cases with CCS + 3 reference cases without CCS).
The results presented in Fig. 2 show that CCS leads to significant increase of the energy consumption when compared to the reference pathway. The non-renewable primary energy consumption increases from 19% (L3) to 52% (NG3). Power plant construction, CO₂ transportation and storage account for less than 1% in the global NR energy consumption balance. The 2 remaining steps which have a significant contribution in these assessments are fuel supply and especially power plant operation. This last step represents 75 to 93 % of the total NR energy consumption, which means that the increase in NR energy consumption of the pathway is thus mainly related to CO₂ capture, drying and compression processes.

Referring to the results presented in Fig. 3, several comments can be made. First, CCS leads to a significant reduction of GHG emissions on the whole pathway. This decrease ranges from 70 % to 82 % compared with the GHG emissions balance of the respective reference pathway without CCS. A comparison between the “worst” case with CCS (L3) and the best reference pathway without CCS (Natural Gas reference plant) shows that the GHG emissions reduction is still large: 39%. Assuming a CO₂ capture rate at the power plant ranging from 80.3 % (L3) to 96.1% (NG2) results in a lower overall reduction for the pathway (72% to 82%). It can be easily explained: this decrease on the power plant operation step is partially counterbalanced by an increase of the GHG emissions of the fuel supply step because of the additional fuel amount needed and supplied for CO₂ capture, drying and compression processes. As for the NR energy consumption assessments, the power plant construction, CO₂ transportation and storage account for a minor part of the overall GHG emitted: less than 4%. The smallness of the contribution of these steps can be partly explained. Indeed, even if the NR energy consumption and GHG emissions associated to these steps can be relatively high, it corresponds to infrastructure construction (plant, pipelines, wells ...) which occurs only once (contrary to NR energy consumption and GHG emissions for fuel supply and power plant operation which occur continually) and are considerably reduced by amortizing them on the amount of energy (H₂ and electricity) produced during the economic life time of the plant (25 years) i.e around 8.10¹⁰ kWh.

In addition, the breakdown of the GHG balance (between CO₂, CH₄ and N₂O emissions) is not the same for all these electricity and H₂ production pathways. N₂O emissions (expressed in CO₂eq) account for less than 0.5% of the total GHG. The whole GHG balance consists practically of CH₄ and CO₂ emissions. The relative contribution of each gas in the global GHG assessment of the pathway (with CCS) is nearly the same for a given fuel. For NG pathways, the share of CH₄ in the overall GHG balance is 3% for the reference pathway and 13 to 17% for pathways with CCS. For bituminous coal cases, this share ranges from 7% for the reference pathway to 35% for pathways with CCS. Concerning the lignite cases, CH₄ emissions account for only 0.1% (reference pathway) to 1% (pathway with CCS). This increase of CH₄ share in the GHG balance between reference pathways and pathways with CCS is due to both the additional fuel consumption of the plant (which leads to an increase of the CH₄ losses during NG production and transportation or an increase of the CH₄ emissions during coal mining) and the large reduction of the GHG emissions at the plant.

As a consequence of the critical parameters listed above, possible improvements of environmental performance of pathways could be achieved through an increase of thermal efficiency of power plant and through improvements in fuel supply chains (e.g. reduction of coal mining CH₄ emissions or reduction of NG leakage during its transportation).

4. Environmental rankings and selection of concepts

In order to compare the 12 studied pathways of electricity and H₂ production on the basis of both environmental criteria (NR energy consumption and GHG emissions), the results of the assessments are gathered in Fig. 4 which is used for the selection of concepts for a given fuel.

When comparing and weighing up positive and negative effects (i.e respectively: GHG emissions reduction and increase of non-renewable primary energy consumption), the best compromises are NG1 (SMR Parallel) among NG-based pathways, BC1 (Shell technology) among coal-based pathways and L1 (Siemens technology) among lignite-based pathways.
5. Conclusion

Based on the results of this study, several further concluding remarks can be made:

Environmental performance of pathways with CCS: **CCS leads to significant GHG emissions reduction on the whole studied pathways of electricity and H₂ production; this decrease ranges from 70% to 82% when considering CO₂ capture rates between 80.3% and 96.1%. However, this technology requires significant additional energy consumption mainly associated to CO₂ capture processes. CCS technology thus meets the GHG reduction objective but goes against the optimization of available fossil energy resource uses.**

Contribution of power plant construction, CO₂ transportation and storage steps in the global environmental assessments: Considering our assumptions (CO₂ transportation distance < 300 km, CO₂ transportation mode – pipelines – and storage depth), the contribution of power plant construction, CO₂ transportation and storage steps are fairly low in the global assessments of both GHG emissions and NR energy consumption of the studied pathways (gathered contribution < 5%). **These steps can be considered as negligible in the present context.** Consequently, the fuel supply and power plant operation steps clearly determine both the GHG emissions and NR energy consumption assessments and the associated environmental rankings of pathways. However, other studies have shown that CO₂ transportation and storage steps can have a significant contribution in the overall environmental assessments of such pathways when considering longer distances and a different transportation mode (e.g. Mayer-Spohn et al. [5] have studied CO₂ pipelines or tanker transportation distances higher than 1000km).

Critical parameters of GHG emissions and NR energy consumption assessments of electricity and hydrogen production pathways with CCS: As a consequence of the dominance of the fuel supply and power plant operation steps in the overall environmental assessment previously explained, the **critical parameters are CO₂ capture rate and power plant and fuel supply chain efficiencies, both for GHG emissions and NR energy consumption assessments.**
Likely areas for improvements of environmental assessments of these pathways: Concerning coal-based pathways, an important environmental improvement can be achieved through the reduction of CH\textsubscript{4} emissions in coal mines. Since these CH\textsubscript{4} emissions account for a significant contribution in the GHG assessments of coal based pathways (7% for the reference pathway without CCS and 34% for the pathways with CCS), a sensitivity analysis on this parameter has been carried out for the present study. These calculations are based on a possible reduction of these emissions by 20, 40, 60 and 80%. This assumption is realistic since more and more companies try to exhaust these methane emissions in order to use them energetically (power production, fuel use at the mine or additional natural gas supply), for example in Germany. The highest reduction of coal mining methane emissions (80%) enables a 81% or 82% GHG emissions saving to be reached for coal-based pathways when compared to the reference pathway without CCS (i.e. 6 or 7% additional GHG emissions savings when compared to the base case for pathways with CCS without methane emissions capture in coal mines). Considering an 80% methane reduction in coal mines, the GHG results for coal-based pathways with CCS are about 160 gCO\textsubscript{2eq}/kWh compared with about 220 gCO\textsubscript{2eq}/kWh for the Base scenario. As a consequence, the gaps between GHG results of coal-based pathways and other pathways with CCS are considerably reduced: the average difference between GHG emissions of coal-based pathways (with CCS) and NG-based pathways (with CCS) decreases by more than one half (the average GHG emissions of coal-based pathways are respectively 95% and 42% higher than GHG emissions of NG-based pathways).

Further work needed: Some other LCA studies (Mayer-Spohn et al. [5], Schreiber et al. [6]) performed on power generation have shown that CCS could lead both to a huge decrease in GHG emissions and to an increase in other pollutant emissions (especially ammonia and nitrogen oxides) because of the additional energy consumption. Such an analysis should thus be extended to other pollutant emissions (SO\textsubscript{2}, NO\textsubscript{X}, NMVOC in air or NH\textsubscript{3} or heavy metal emissions in water) and thus other environmental impacts such as acidification and eutrophication.

6. Acknowledgements

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