*CCSP FP2 – WP3.4.1*

*Deliverable 316. Techno-economical studies about performance of industrial scale CLC power plant*

Note! The on-line toolkit linked to this deliverable can be found here.

Scope

In this report the main work approach together with example results of techno-economical analyses are presented for industrial scale CLC power plant using coal as a fuel. The study with and without CCS is based on greenfield 482 $MW_{fuel}$ plant situated on the coast of the Gulf of Bothnia emitting approximately 1.3 Mton $CO_2$ / year without CCS. Primary focus has been on economic evaluations of the CLC plant operation with different input parameters and on comparison to both oxy-fired CFB plant and normal air-fired CFB plant.

Approach for economic and environmental analyses

The economics of CCS are evaluated from investor's (local energy company) point of view including the effects on the existing energy system. Effect of CCS on greenhouse gas (GHG) emissions and operation economics of the CCS cases are compared to the reference system with varying parameters of operation. Regarding the GHG emissions, besides the site emissions, the main effects on global GHG emissions are also taken into account by using streamlined LCA and impacts on overall electricity production system.

In the study the whole CCS chain, including $CO_2$ capture, processing, transport and storage, was included by utilising CCS plant economics toolkit (system model *CC-Skynet*™ developed by VTT). In the toolkit, the profitability of each case can be analysed according to different market situations by adjusting plants operation and the most significant input values. In addition to plant and case specific technical inputs, the economic parameters can be varied, including interest rates, studied time frames, fuel taxes, subsidies and market prices for different fuels, electricity and $CO_2$ emission allowances (in the EU ETS) as well as CCS related costs, for example required investment, transportation costs, prices for oxygen carrier materials etc.

As there is no storage capacity in Finland the captured $CO_2$ has to be transported and stored abroad. The storage phase in this study is evaluated according to Teir et al. (2011) [1]and the $CO_2$ transportation including costs related are assumed according to Kujanpää et al. (2010)[2]. In LCA calculations, the studied system is expanded from direct emissions to include GHG emissions also from replaced/replacing electricity production (by default condensing electricity production by coal), fuel production, construction of new plant with and without CCS and $CO_2$ transport (ship construction, fuel consumption and $CO_2$ cooling splits.

The overall additional investment due to CCS is based on the presentation given by Simonsson et al. (2009)[3] based on CFB technology with and without oxyfuel. By default CLC investment is assumed similar to oxy-CFB due to easier comparison and variations in the investment estimations given in the public literature. CLC plant with an air reactor and a fuel reactor involves additional costs, but the investment would probably be

[1] Teir, S; Arasto, A; Tsupari, E; Koljonen, T; Kärki, J; Kujanpää, L; Lehtilä, A; Nieminen, M; Aatos, S. Hiilidioksidin talteenoton ja varastoinnin (CCS:n) soveltaminen Suomen olosuhteissa. 2011. VTT, Espoo. VTT Tiedotteita - Research Notes : 2576

[2] Kujanpää, L; Rauramo, J; Arasto, A. Cross-border CO2 infrastructure options for a CCS demonstration in Finland Proceedings of the International Conference on Greenhouse Gas Technologies (GHGT-10), 19-23 September 2010, Amsterdam, The Netherlands. Energy Procedia. Elsevier. Vol. 4 (2011), 2425-2431

3 Simonsson, Eriksson, Shah. Circulating fluidized bed technology – A competitive option for CO2 capture through oxyfuel combustion? IEA 1st Oxyfuel Combusstion Conference, Cottbuss, 9th September 2009.

less than double of normal air-fired CFB plant as only the boiler/reactor components are significantly different.

According to Lyngfelt (2013)[4] CLC of solid fuels clearly has a potential for a dramatic reduction of energy penalty and costs for $CO_2$ capture. The energy penalty for chemical-looping combustion would ideally be equal to the power needed for $CO_2$ compression of around 2.5%-units. In addition, penalty is derived e.g. from fluidisation of the reactors (additional reactor, probably heavier fluidisation material), possible need for $O_2$ polishing or carbon stripper etc.

Annual fixed operation and maintenance (O&M) costs are estimated roughly based on the general approach to assume these costs to be dependent on the required investment. Similar approach is used for example by IEA (2008)[5], where they assumed fixed and variable O&M costs to be 4 % of the investment cost. In this study, variable O&M costs are estimated separately and therefore smaller values for fixed O&M costs are used.

Variable O&M costs are estimated with focus on oxygen carriers. The values used for different carriers are presented in Table 1. In addition to these values, a recovery factor for the price for resale of used oxygen carriers was given (Table 2). In addition, other variable O&M costs are estimated to be about 10 % higher for both, oxyCFB and CLC, than in air-reference case.

The results are presented in four main figures. The 1st one represents overall annual operating costs and company's profits, the 2nd one cost of electricity production with varying ETS prices, 3rd one the emissions balances and the 4th one break even prices (BeP's) as a function of electricity price for $CO_2$ emission allowances where CCS turns feasible over the reference case.

*Case descriptions*

Evaluations are conducted for four different cases. In all cases the new plant produces condensing electricity with given utilization rates. Net electric penalty for overall CCS chain can be given as input for CLC and oxy-CFB.

1. Air-reference: Air-fired CFB plant

2. Oxy-reference: Oxy-fired CFB plant

3. CLC I: CLC plant with input parameter set I

4. CLC II: CLC plant with input parameter set II

The properties of oxygen carriers are presented in table 1 and other variables used in evaluations in table 2.

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[4] Anders Lyngfelt, Chemical-looping combustion of solid fuels – Status of development, Applied Energy, Available online 12 June 2013, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2013.05.043.
[5] IEA, $CO_2$ capture and storage – A key carbon abatement option. OECD/IEA, France 2008.

**Table 1. Properties of oxygen carriers.**

| Oxygen Carrier Material | Cu synthetic | Iron ore / Ilmenite | Manganese / Manganese ore | Ni synthetic | Fe synthetic | |
|---|---|---|---|---|---|---|
| Oxygen Carrier Lifetime | 25 000 | 1 310 | 63 | 33 000 | 4 000 | h |
| Oxygen Carrier Price | 6 000 | 100 | 135 | 13 300 | 1 000 | €/tn |
| Inventory | 1.00 | 5.50 | 3.75 | 1.00 | 2.00 | tn/MWth |
| *Calculated make-up consumption* | *0.02* | *2.02* | *28.69* | *0.01* | *0.24* | *tn/h* |

**Table 2. Key variable defaults used in evaluations.**

| | | |
|---|---|---|
| Reference, air fired CFB | | |
| fuel input | 482 | MW |
| max net electric output | 213 | MW |
| investment (whole plant) | 622 | €/$kW_{fuel}$ |
| variable O&M costs | 1 | €/$MWh_{fuel}$ |
| fixed O&M costs | 13 | €/$kW_{fuel}$ |
| | | |
| oxy-CFB | | |
| fuel input | 482 | MW |
| additional investment due to CCS | 418 | €/$kW_{fuel}$ |
| extra variable O&M costs from CCS | 0.1 | €/$MWh_{fuel}$ |
| fixed O&M costs | 2.0 | % of the investment |
| | | |
| CLC I & CLC II | | |
| fuel input | 482 | MW |
| additional investment due to CCS | 418 | €/$kW_{fuel}$ |
| variable O&M from oxygen carriers | See table 1 | |
| default oxygen carrier recovery value | 70.0 % | resale price / purchase |
| other extra variable O&M costs from CCS | 0.1 | €/$MWh_{fuel}$ |
| fixed O&M costs | 2.2 | % of the investment |

## Main results

The main output is a Flash-based toolkit to visualise the costs and $CO_2$ impacts with different inputs by selecting key variables using interactive menus. The toolkit can be found here.

Example figures of the results are shown in figures 1-4 based on selected input values shown in table 3.

**Table 3. Key input values in evaluations.**

| General variables | | Case variables | air-reference | oxy-reference | CLC I | CLC II |
|---|---|---|---|---|---|---|
| Fuel of compensating power | Coal | Utilisation of the plant (h/a) | 8000 | 8000 | 8000 | 8000 |
| ETS price, €/tn | 80 | Net electric penalty (CCS) | | 8.0 % | 3.0 % | 5.0 % |
| System price of electricity, €/MWh | 100 | Sensitivity factor for CCS investment | | 0 % | 0 % | 0 % |
| Price of coal, €/MWh | 10 | Oxygen carrier material | | | Iron ore / Ilmenite | Iron ore / Ilmenite |
| Sensitivity factor for transport & storage | 0 % | Oxygen carrier price factor | | | 0 % | 0 % |
| Hurdle rate for investment | 10 % | | | | | |
| Economic life for investment, a | 20 | | | | | |
| General discount rate | 5 % | | | | | |
| Technical life for investment, a | 40 | | | | | |

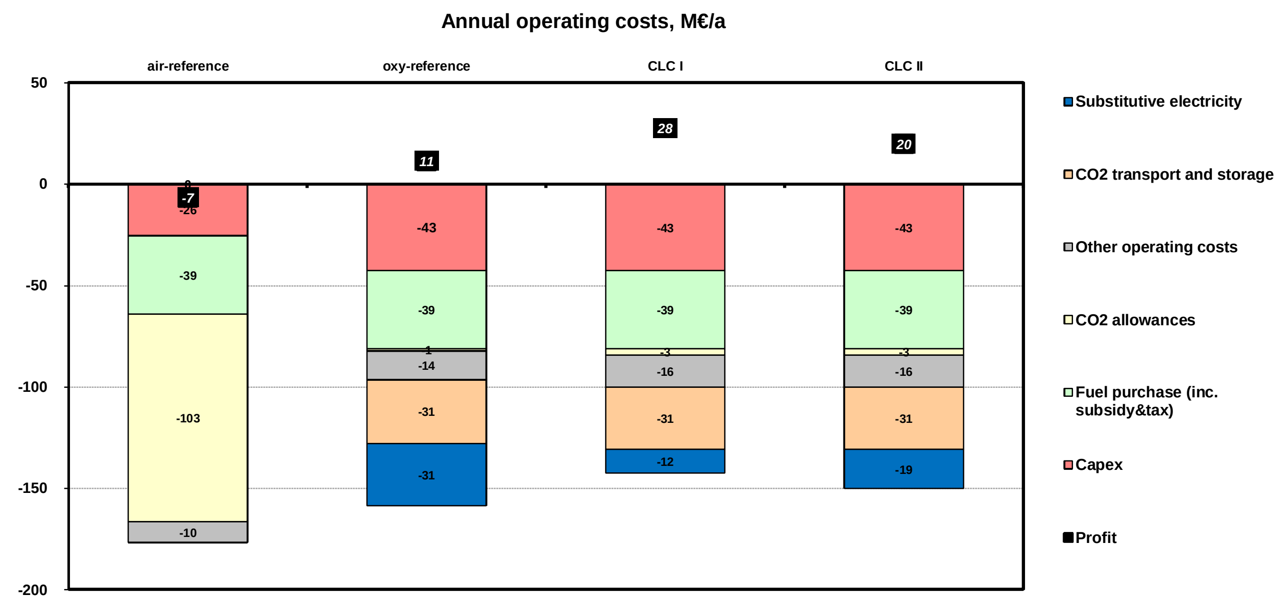


**Figure 1. Annual operating costs and overall profit of the case plants.**

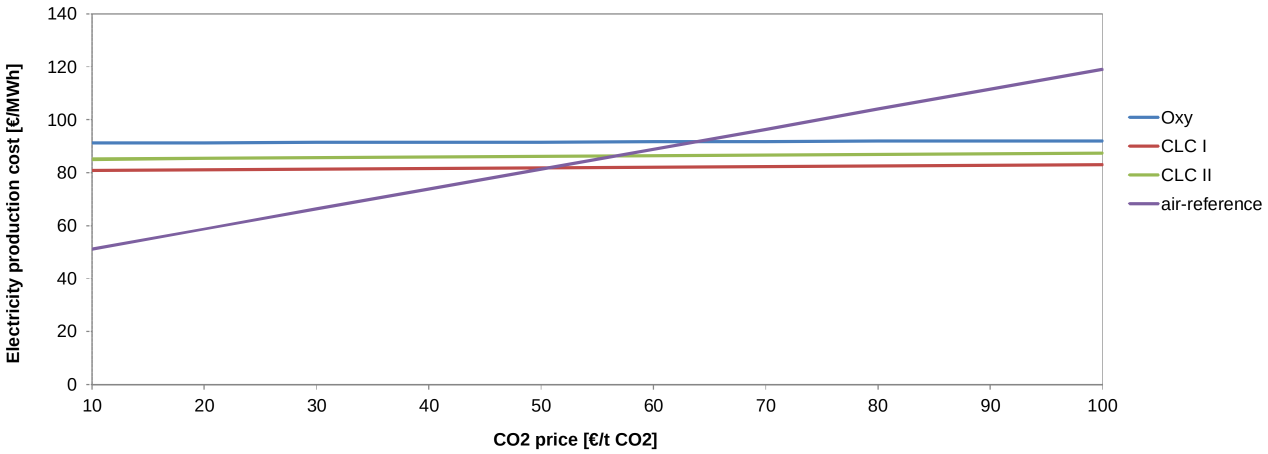


**Figure 2. The cost of electricity production.**

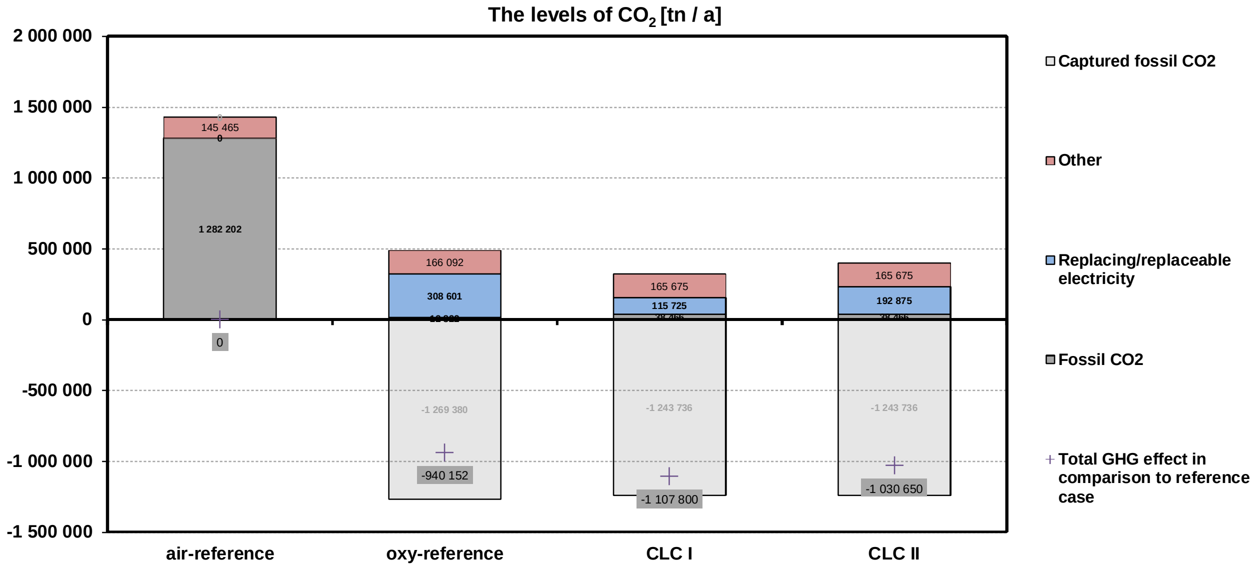


**Figure 3. Annual $CO_2$ emission levels of the case plants.**

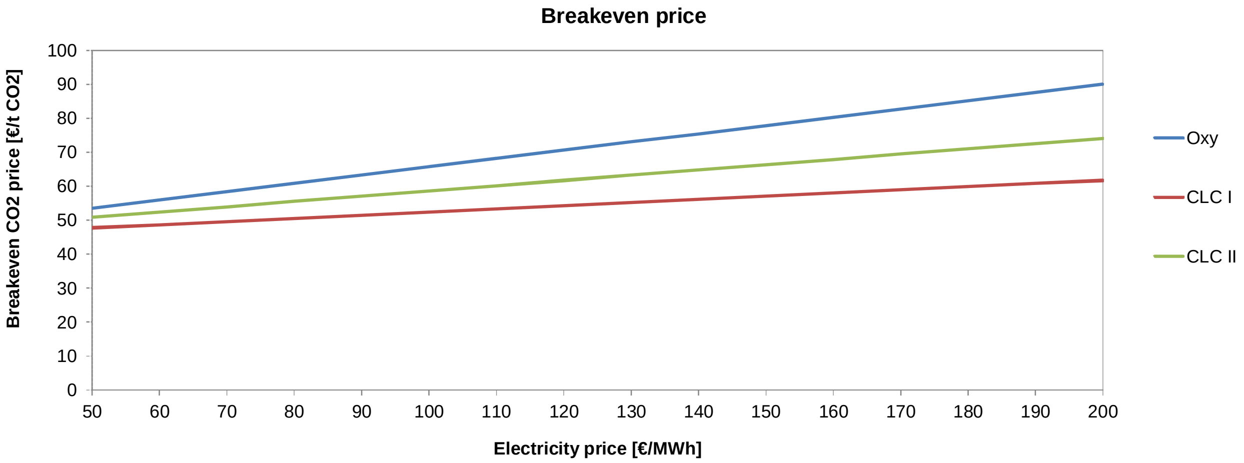


**Figure 4. Breakeven prices for different cases.**