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Life cycle assessment of power-to-gas applications via co-electrolysis of CO_2 and H_2O

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Abstract
Solid-oxide electrolysis technology (SOEC) can efficiently convert electricity from renewable sources into H_2 via steam electrolysis, or syngas (a mixture of H_2 and CO_2) via co-electrolysis of steam and CO_2. Co-SOEC provides the advantage of better thermal integration for standalone applications or with other industrial processes. In this paper two promising cases are investigated from the perspective of life-cycle assessment to evaluate the potential of reducing carbon emissions: (1) coupling co-SOEC with a cement plant, and (2) integrating co-SOEC into a biomass gasification plant. Life cycle assessment was performed based on the collection of comprehensive information regarding the electricity sources for different scenarios and a sensitivity analysis was included to verify the consistency of the results. The results show that in both cases the co-electrolysis system can be beneficial in terms of reduction of global warming potential, although it depends heavily on the geographic location and on the share of renewable energy. The highest benefits among the cases reviewed were found in the case of a coal-fed cement plant, where annual CO_2 savings reached up to 2.39E + 05 tonnes CO_2-eq in France with 23.6% of the electricity provided by photovoltaics (PV). In Germany, on the other hand, both cases first show benefits when the renewable share reaches a very high percentage of the electricity input: 50% provided by PV for the case of the cement plant and 82% for the case of a biomass-gasification unit. Since electricity input is the main impact concerning power-to-gas applications, the carbon content of the electricity grid mix is very important. As grid mixes become 'cleaner' in the future with more renewable share in the electricity generation in every country, the investigated applications are expected to provide even higher benefits.

1. Introduction

In a world more and more concerned with the issue of global warming and environmental pollution and with the increasing use of renewable, fluctuating sources for electricity production, highly efficient pathways are needed to help balance the production/consumption mismatches and, in particular, to store excess electricity as hydrogen or hydrocarbons, for example, for seasonal storage. Though hydrogen is an excellent energy carrier, methane has a significant advantage over hydrogen: the existing natural gas network and storage tanks. Currently, approximately 50% of the total electricity produced from renewable sources could be accommodated as methane in existing underground storage facilities (Eurostat 2018). The use of electricity to produce synthetic methane is considered as part of the energy transition. Methane (or other hydrocarbons) is produced in two steps: (i) an electrochemical conversion of steam into hydrogen (steam electrolysis), or together with CO_2, hydrogen and CO (co-electrolysis) followed by (ii) catalytic conversion to methane.

High temperature electrolysis (or solid oxide electrolysis/SOEC) provides a solution to produce methane through the highly efficient production of syngas from steam and CO_2. SOEC theoretical electrical efficiencies can approach 100% (Sun *et al* 2012) and are thus the highest achievable among electrolysis technologies. In addition, co-electrolysis helps to efficiently use CO_2 emitted from industrial sources such as cement and steel industries or from biogas. Operation at high current densities increases the production rate of hydrogen and CO, and thereby improves the overall economy. Another advantageous feature of co-SOEC is the option for efficient integration with the catalytic conversion of the formed synthesis gas to methane. For this integration, it is desired that the operation of the SOEC is at temperatures below ca. 750 °C, which are the current typical temperatures for state-of-the-art SOEC, and at elevated pressures, for thermodynamic reasons. Furthermore, an operation under dynamic conditions is preferred, reflecting the fluctuating electricity input from renewable sources.

First tests of SOEC under these conditions have been carried out providing valuable data about performance and durability under such relevant conditions (Brisse *et al* 2008, Hauch *et al* 2008, O'Brien *et al* 2009, 2012, Ebbesen *et al* 2011, Petitjean *et al* 2011, Diethelm *et al* 2013, Mougin *et al* 2012, Mougin *et al* 2013, Sun *et al* 2015, Rinaldi *et al* 2015) as well as a few at larger scale (stacks with 25 cells or more) (O'Brien 2012, Stoots *et al* 2009, Reytier *et al* 2013, Li *et al* 2014, Reytier *et al* 2014). Several studies have demonstrated the technological feasibility of co-electrolysis (Stoots *et al* 2009, Ebbesen *et al* 2011) and have proven that similar performances can be obtained in steam electrolysis or in co-electrolysis under specific operating conditions (Graves *et al* 2011, Kim-Lohsoontorn and Bae 2011, Aicart *et al* 2015, Reytier *et al* 2015). Even internal methane formation is possible in the SOEC stack, if these conditions are applied (Jensen *et al* 2017).

Though scientific development of SOEC has been carried out, little has been studied regarding the environmental performance of this technology and how it could help reduce fossil-CO_2 emissions when applied as a replacement or complement to existing technologies. Within the scope of the EU H2020 project ECo (Efficient Co-Electrolyser for Efficient Renewable Energy Storage, http://eco-soec-project.eu/), this study presents the first attempt at analyzing the environmental performance of a SOEC power-to-gas system applied in two different scenarios (a cement plant and a biomass gasification unit) in different European countries in order to evaluate the significance of the environmental benefits.

2. Methods and description of the cases

This study performs an environmental assessment of two different power-to-gas (PtG) plants coupled with a co-SOEC. More specifically the life cycle assessment (LCA) methodology was chosen in order to provide an evaluation of the opportunities of CO_2 recycling through PtG plants compared to baseline scenarios without co-SOEC.

To demonstrate the potential environmental benefits using the LCA approach, the co-SOEC has been evaluated for two different applications. The first case study is a cement plant (large-scale) with the objective of recycling CO_2 emitted by the plant back into the plant as a constituent of substitution fuel to reduce the fossil fuel dependency and carbon footprint of the plant. The second case study is a biomass gasification plant (medium-to large-scale) with the objective of increasing the biomethane production via use of renewable power.

2.1. LCA methodology

LCA is a methodology used for the analysis of the environmental impact of a product, process, or activity over the course of its lifetime by identifying and quantifying the energy and materials used and wastes released to the environment (EPD 2017, Guineé *et al* 2002, NREL 2012, PE International 2011, SETAC 2017). There are two standards for LCA created by the International Organization for Standardization (ISO): ISO 14040 (Environmental management—LCA—Principles and framework) and ISO 14044 (Environmental management—LCA—Requirements and guidelines) (ISO 2017). This study has been carried out using both the ISO standard stated above and the FC-Hy Guide guidelines specifically developed for LCA users applied to hydrogen technologies (Masoni and Zamagni 2011). The GaBi Professional software (Thinkstep 2017) was used to perform the LCA of the different systems.

In both case studies, the following impact categories were selected for the analysis: global warming potential (GWP), primary energy demand (PED)—separated into renewable and non-renewable resources to highlight these differences among the different energy sources—and blue water consumption. These three categories were chosen as the most important regarding these case studies since most of the impacts are related to energy use. GWP is the most common category to analyze, and here is the most pertinent, to showcase the CO_2 emissions that are saved (or spent) by the co-SOEC process. The IPCC AR5 GWP100 (Intergovernmental Panel on Climate Change Fifth Assessment Report over a 100 year time horizon) excluding biogenic carbon method was chosen to analyze the GWP. PED is also a very common category to analyze and given that most inputs are energy sources, it is important to measure this impact and see how the co-SOEC solution affects it. Finally, blue water consumption was chosen to measure the differences between energy sources and how this would affect the co-SOEC solution's impact—blue water signifies that rainwater is not included in the impact although this does not cause a big difference here as agriculture is not involved in the case studies.

2.2. Co-SOEC and PtG process

In the co-SOEC process, steam and CO_2 are simultaneously electrolyzed using electricity to synthesize gas: hydrogen and CO. The CO_2 source and electricity input were determined by the specific case and the dimensioning of the co-SOEC plant was also based on the specific case. Data were obtained from state-of-the-art SOEC technology (explained later on). The electricity input for the SOEC was implemented according to the case in the specific local/geographic situation. The obtained synthesis gas is converted through methanation by conventional catalytic processes.

2.3. Case study 1: cement plant

A representative cement plant was modeled based on data from Verein Deutscher Zementwerke e.V (VDZ—German Cement Works Association) and from literature, in particular a CSI/ECRA Technology paper (European Cement 2017). The reference cement plant considered has a typical 1 Mtonne yr^{-1} clinker production capacity, with 126 tonne/h clinker production in operation. The thermal energy input for this plant was considered as 84% from fossil fuel (either coal or natural gas), 10.2% from 'alternative' fuel and 5.8% biomass fuel (CSI/ECRA hypothesis).

A cement plant from a given location would mostly use a single type of fossil fuel, which happens to be the most economically viable locally, and is, most of the time, coal. Natural gas can also be used, and is often present even in a coal-based plant, but mostly used for its flexibility in managing 'transitory' situations (e.g. heating up before switching to coal or other fuels). In this analysis, only a steady state operation was considered which leverage typically a single kind of fossil fuel (coal).

Alternative fuels are very context-specific, non-conventional fuels that cement plants use as part of their energy mix, due to their low cost or even incentives for burning them, e.g. wastes.

When operating on coal, this energy mix leads to 842 kg CO_2/tonne clinker of gross CO_2 emissions for the plant, with 536 kg CO_2/tonne clinker from the process (mineral carbon), and the resulting 306 kg CO_2/tonne clinker from fossil energy inputs (European Cement 2017). Leveraging emission factors from the European carbon trading system (EU-ETS), estimates of the CO_2 emission shares from coal and alternative fuels were performed (biomass was not considered as having fossil CO_2 emissions).

When using the co-SOEC process in conjunction with the cement plant, the principle was to produce a synthetic gas that substituted part (or all) of the fossil fuel input for the plant. Only fossil fuel was considered to be potentially substituted, as alternative fuel is of an uncertain nature and may be covered by economic incentives.

From a CO_2 point of view, the co-SOEC system application creates a recycling loop where part of the CO_2 from fumes is recovered, sent into the co-SOEC, and, finally, converted to fuel directly used by the cement plant, replacing the fossil fuel normally used to feed the plant. In this way, the fossil fuel dependency is reduced which in turn reduces the CO_2 emissions from the plant, decreasing the plant's carbon footprint, as illustrated in figure 1.

The scheme for the CH_4 synthesis via co-electrolysis-methanation is shown in figure 2. The capture of CO_2 from the cement plant fumes is assumed to be based on amine capture.

For its integration in the cement plant environment, the co-SOEC process was subject to several constraints influencing its sizing:

- Availability of $CO_{2.}$
- Amount of fossil fuel that can be substituted.
- Availability of heat: the co-SOEC process requires heat from the cement plant to achieve maximum efficiency. In particular, the use of heat for generating water vapor at 10 bar requires a heat source >210 °C, and the stripping of CO_2 from the amine solution requires a source >160 °C (presence of a secondary thermal source to limit the risk on amines).

Heat integration computations showed that heat availability at >160 °C and >210 °C was in fact the limiting factor driving the sizing of the co-SOEC process. At 10 bar, the saturation steam temperature is around 180 °C. A minimum temperature difference of 30 °C is assumed for heat transfer, which yields 210 °C. The temperature limit of 160 °C is due to the CO_2 capture process, since the amines capture CO_2 in the CO_2 absorber at a low temperature, e.g. 40 °C–60 °C. To regenerate the amines and release the captured CO_2, the amines solution

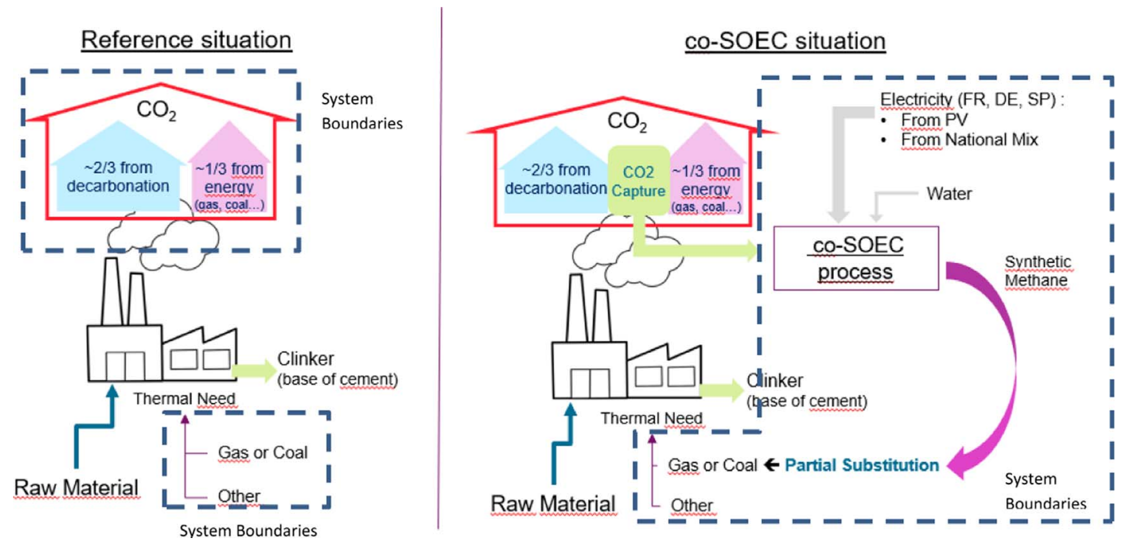

Figure 1. Principle of fossil fuel substitution in the cement plant co-SOEC case with the system boundaries used for the LCA analysis displayed in blue dotted lines.

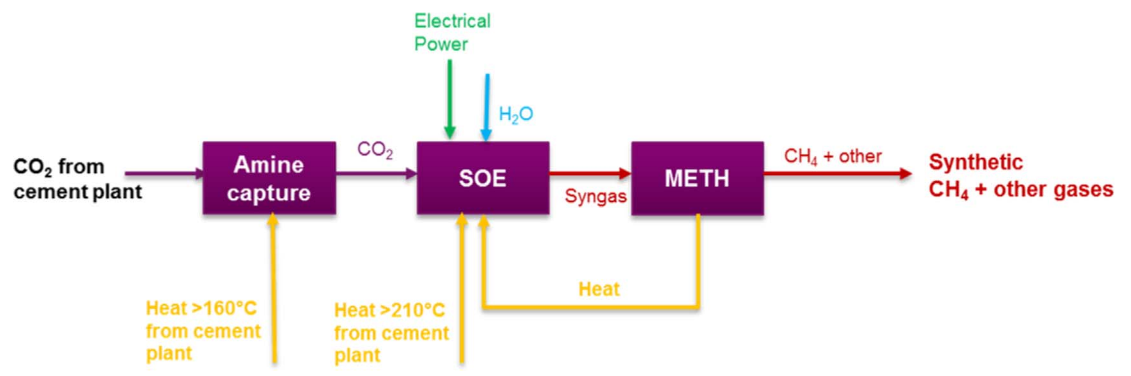

Figure 2. Co-SOEC process flows for the cement plant case.

bound with CO_2 needs to be heated up with a heat source over the saturation temperature of the solution, which can be 160 °C, considering also a minimum temperature difference required for heat transfer.

This led to a 69 MW_e electrolyzer, and consequently only 51% of the fossil fuel energy input could be substituted. Due to the large amounts of CO_2 from mineral origin, the CO_2 source was far from being a constraint.

The different inventories for the cement plant LCA were developed on this assumption of a 69 MW_e electrolyzer. The study focused on a coal-fired cement plant as this is the most common fossil fuel used in cement plants. A sensitivity analysis was also performed for three geographic locations: Spain, France, and Germany.

This LCA as well as the LCA for the gasification unit have been performed only on the operational phases (use phase) and do not take into account the production or end of life phases. The system boundaries of the reference case only include inputs to and outputs from the cement plant (energy fed to the plant, and outputs of clinker and CO_2 emissions) as well as some consumables (such as catalysts) but no equipment was considered in the system boundaries. The co-SOEC scenario perimeters include the cement plant as well as the SOEC solution, consisting of heat recovery, CO_2 capture, co-electrolysis, and methanation steps (see figure 2). The functional unit decided for this case study was one tonne of clinker produced by the cement plant.

2.4. Case study 2: gasification unit

The second case study focused on an existing 20 MW_{SNG} biomass gasification plant with the goal of assessing the environmental impacts of installing the co-SOEC solution to treat the CO_2 output of the gasification installation and produce methane from it. The study was performed on four geographic locations: Denmark, France, Germany, and Sweden.

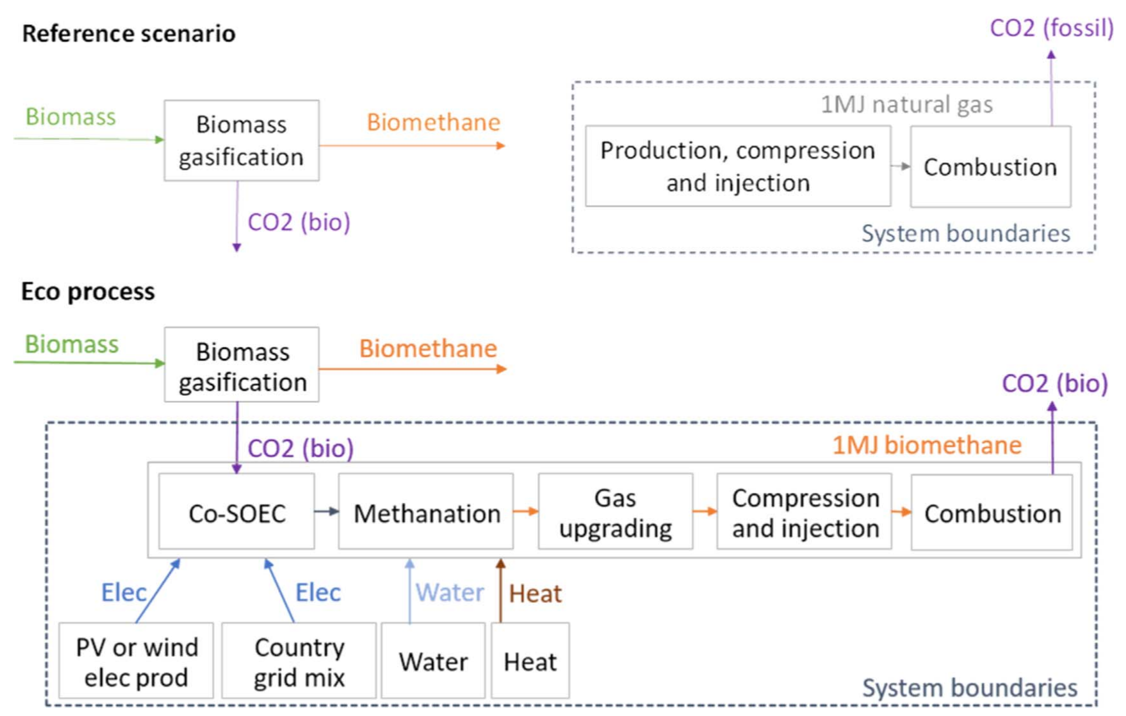

Figure 3. Systems under study in case study 2, the gasification unit, with the system boundaries for the LCA analysis shown in dotted lines.

The gasification of biomass produced synthesis gas, which is converted into biomethane, which in turn can be injected into the natural gas network. The main output of the co-SOEC-methanation process is methane using CO_2 waste of the gasification. This methane was also injected into an existing natural gas network for use in a downstream combustion process. In the study the impacts of such a system were compared with the impacts of a reference system where the gasification plant was simply emitting its (biogenic) CO_2 and the equivalent quantity of natural gas was injected in the network. This was to ensure that the two systems compared fulfill the same functional unit.

The functional unit considered was the injection of 1 MJ biomethane in the high pressure natural gas network (around 68 bar) and the aim was to compare the impacts associated with the production and injection of 1 MJ biomethane from the co-SOEC process (see figure 3) with the production and injection of 1 MJ natural gas in the same network, including the emissions of fossil CO_2 that would occur when the natural gas is combusted.

Figure 3 presents an overview of the processes included in the study. In particular, it is important to note that the gasification process is excluded from the boundaries as it is not affected by the decision to install the co-SOEC process and it exists in both scenarios.

Since electricity is a major input in the co-SOEC process, different scenarios were modeled regarding its supply and in particular how much of it came from a renewable origin and how much from the grid, as well as the nature of the renewable electricity (PV versus wind). Various scenarios were implemented with varying sizing of the renewable source of electricity, source of renewable electricity and different geographical locations of the installation (with effects on the electricity grid mix used when no renewable energy is available). The purpose of that variation was to evaluate how the composition of the electricity sourcing could affect the LCA (and especially the carbon footprint) of the methane which was produced by the co-SOEC process.

In the baseline scenarios for Denmark, France, Germany, and Sweden, the renewable energy source was sized on the maximum power required by the co-SOEC process (28 MW) including a 10% margin. For Denmark, France, and Germany, a sensitivity analysis was performed in order to evaluate the sensitivity of LCA results to the electricity sourcing for the biomethane production. Table 1 lists the ten scenarios evaluated.

For PV scenarios, the case study considered a load factor of 16% i.e. PV would provide on average 16% of the electrical power need (4.5 MW), with the remaining electricity being provided by the grid (23.5 MW). For the wind case, the case study considered a load factor of 27% (capacity factor of wind farm in Sweden) i.e. a mean power of 7.6 MW, with the remaining electricity being provided by the grid (20.4 MW).

Sensitivity analyses were performed for the French and German cases to evaluate the impacts of an increase in the size of the PV plant to provide along the year enough energy to produce:

Table 1. Scenarios analyzed in case study 2.

Number	Scenario	Type and scaling of renewable energy installation	Country
1	DK	Wind mill installation with sizing scaled based on the maximum power required by the co-SOEC process	Denmark
2	FR	PV installation with sizing scaled based on the maximum power required by the co-SOEC process	France
3	DE	PV installation with sizing scaled based on the maximum power required by the co-SOEC process	Germany
4	SW	Wind mill installation with sizing scaled based on the maximum power required by the co-SOEC process	Sweden
5	DK 50%	Wind mill installation with sizing scaled based on 50% of the electricity consumption for the co-SOEC process being provided by wind	Denmark
6	DK 75%	Wind mill installation with sizing scaled based on 75% of the electricity consumption for the co-SOEC process being provided by wind	Denmark
7	FR 50%	PV installation with sizing scaled based on 50% of the electricity consumption for the co-SOEC process being provided by PV	France
8	FR 75%	PV installation with sizing scaled based on 75% of the electricity consumption for the co-SOEC process being provided by PV	France
9	DE 50%	PV installation with sizing scaled based on 50% of the electricity consumption for the co-SOEC process being provided by PV	Germany
10	DE 75%	PV installation with sizing scaled based on 75% of the electricity consumption for the co-SOEC process being provided by PV	Germany

1. Up to 50% of the additional Synthetic Natural Gas (SNG) production: 96 MW PV plant + battery storage (14 MW of the power provided by PV and 14 MW from the grid).
2. Up to 75% of the additional SNG production: 144 MW PV plant + battery storage (21 MW of the power provided by PV and 7 MW from the grid).
   A sensitivity analysis was also performed on the Danish case to evaluate the impacts of an increase in the size of the wind farm to provide along the year enough energy to produce:
3. Up to 50% of the additional SNG production: 96 MW wind farm + battery storage (14 MW of the power provided by wind and 14 MW from the grid).
4. Up to 75% of the additional SNG production: 144 MW wind farm + battery storage (21 MW of the power provided by wind and 7 MW from the grid).

3. Life cycle inventory

3.1. Case study 1: cement plant

As details of the life cycle inventory are confidential, a list of inputs and outputs with their corresponding GaBi processes for the cement plant case study is presented in table 2. Since three geographic locations were studied, the GaBi processes are listed reflecting these three countries. For the replacement parts for the SOEC cells and stack, data from literature was used so as not to complicate the model with all the different components. The nickel and aluminum oxide inputs have been considered to represent the impact of the methanation catalyst replacement, Ni–Al_2O_3.

3.2. Case study 2: gasification unit

In all scenarios of the gasification unit case study, the same size of the co-SOEC process was considered. Indeed, the co-SOEC process is sized according to the flowrate of CO_2 to be converted into biomethane, which only depends on the size of the gasification plant. For a 20 MW SNG gasification plant, the inputs and outputs of the co-SOEC process unit are:

1. Consumption of CO_2 flowrate: 1.13 kg s^{-1}.
2. Heat consumption power: 2.8 MW_{th} (provided by the gasification plant).
3. Total electricity power: 28 MW_e.
4. Consumption of water flowrate: 0.98 kg s^{-1}.
5. Production of biomethane flowrate: 2128 Nm^3 h^{-1} (92.4% of CH_4).

Table 2. List of background processes used in case study 1.

Input	GaBi process
Coal as energy input to plant	Thermal energy from hard coal {DE/FR/ES}
Electricity input to plant	Electricity grid mix {DE/FR/ES}
Electricity input to plant	Electricity from photovoltaic {DE/FR/ES}
Water input to co-SOEC process	Water production, deionized, from tap water, at user {Europe without Switzerland}
MEA consumption from amine capture	Market for monoethanolamine {GLO}
Electricity input to co-SOEC process	Electricity grid mix {DE/FR/ES}
Electricity input to co-SOEC process	Electricity from photovoltaic {DE/FR/ES}
co-SOEC process; methanation catalyst replacement	Market for nickel, 99.5% {GLO}
co-SOEC process; methanation catalyst replacement	Market for aluminum oxide {GLO}
co-SOEC process cell and stack replacements	N/A—impact data taken from literature
Output	**GaBi Flow**
CO_2 emissions from cement plant	Carbon dioxide, fossil [long-term to air]
Clinker production from cement plant	N/A
O_2 emissions from co-SOEC process	Oxygen [inorganic emissions to air]

Table 3. List of background processes used in case study 2.

Input	GaBi process
Water input to co-SOEC process	Water production, deionised, from tap water, at user {Europe without Switzerland}
Thermal energy (NG) input to co-SOEC process	Heat production, natural gas, at industrial furnace >100 kW {Europe without Switzerland}
Electricity input to co-SOEC process	Electricity grid mix {DE/FR/DK/SE}
Electricity input to co-SOEC process	Electricity from photovoltaic {DE/FR}
Electricity input to co-SOEC process	Electricity from wind power {DK/SE}
co-SOEC process; methanation catalyst replacement	Market for nickel, 99.5% {GLO}
co-SOEC process; methanation catalyst replacement	Market for aluminum oxide {GLO}
co-SOEC process cell and stack replacements	N/A—impact data taken from literature
1 MJ natural gas (reference case)	Natural gas mix {DE/FR/SE}
Output	**GaBi flow**
1 MJ biomethane produced	Biomethane [other fuels]
CO_2 emissions from combustion of natural gas (reference case)	Carbon dioxide, fossil [long-term to air]

In all scenarios, full-time use of the co-SOEC process is considered, meaning 8000 h per year of operation. The gas upgrading is done by membrane technology.

Background processes originate from the GaBi database and are listed in table 3. In this case study, heat is provided by the gasification process, but as this heat would have otherwise been used by another user, it was decided to model its consumption as consumption of heat produced by a natural gas combustion process. Since four geographic locations were studied, the GaBi processes were listed reflecting these four countries. As with the cement plant case study, for the replacement parts for the SOEC cells and stack, data from literature was used so as not to complicate the model with all the different components. Additionally, the nickel and aluminum oxide inputs have been considered to represent the impact of the methanation catalyst replacement, Ni–Al_2O_3.

4. Results and discussion

The life cycle impact assessment (LCIA) results and interpretation are given below, first for the cement plant case study and its geographic subcases, and then for the gasification unit and its geographic subcases.

4.1. Case study 1: cement plant

4.1.1. LCIA results

Figure 4 presents the GWP results associated with the cement plant reference and co-SOEC scenarios in the three country situations studied in the first case study. It is observed that the co-SOEC process proves beneficial

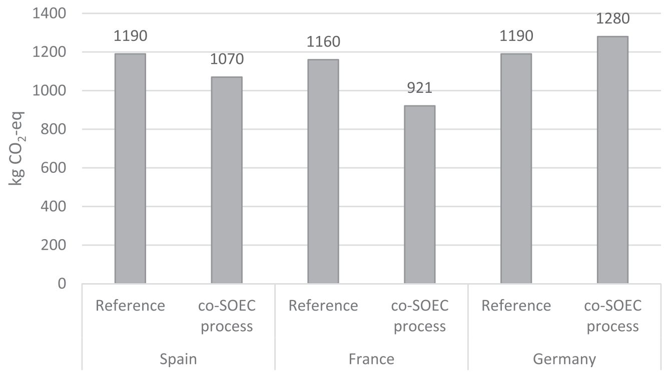

Figure 4. Global warming potential in the cement plant reference and co-SOEC scenarios in the three countries under study for the production of 1 tonne of clinker.

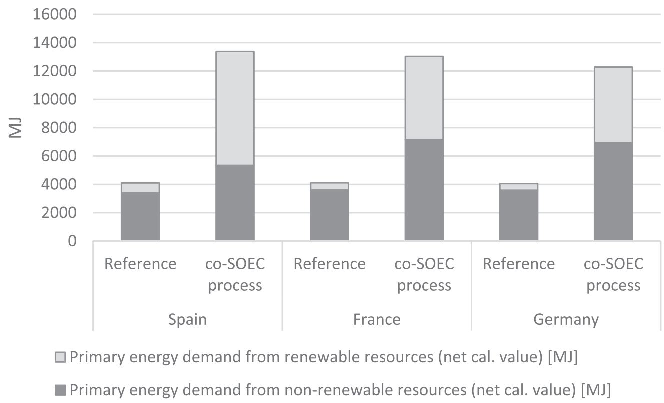

Figure 5. Primary energy demand in the reference and the co-SOEC scenarios in the three countries under study for the production of 1 tonne of clinker.

in the French (−21%) and Spanish (−10%) subcases. However, the co-SOEC process ends up resulting in a larger GWP (+8%) than the reference scenario for the German subcase. These differences are due to the higher carbon content of the German and Spanish electricity mixes compared with the French electricity mix. The majority of the impact originates from the electricity grid mix, besides the emissions coming from the decarbonization, while all other inputs and outputs have negligible contributions to the overall GWP.

A sensitivity analysis was performed on the German subcase to compare different shares of renewable energy for the electricity input (the standard case has around 14% of the electricity provided by PV). If PV supplied 50% of the electricity input (with the other 50% coming from the German electricity grid), the co-SOEC process would demonstrate a benefit on the GWP—it would be 4% lower than the reference case, translating to a yearly CO_2 savings of 5.00E + 04 tonnes CO_2-eq. If PV supplied 75% of the electricity input, this benefit would increase to a yearly CO_2 savings of 1.50E + 05 tonnes CO_2-eq.

Figure 5 presents the PED results associated with the reference and co-SOEC scenarios in the three selected countries. It is observed that in all cases the co-SOEC scenario requires more primary energy, both from renewable and non-renewable resources, than the reference scenario due to the electricity inputs required by the co-SOEC process.

Figure 6 presents the blue water consumption results associated with the reference and co-SOEC scenarios in the three selected countries. As for the previous impact category, it is observed that in all cases the co-SOEC process requires much more water (orders of magnitude) than the reference scenario.

4.1.2. Results interpretation

The LCA analysis has shown that the co-SOEC process has a benefit on GWP in some cases and can save CO_2 emissions when used with a cement plant—this benefit can be more or less significant depending on the country and renewable share used in the electricity input (see table 4 below for a summary of the results). For coal-fired cement plants and standard PV capacity used for the renewable share (14%–25%), the co-SOEC process would have benefits in both France and Spain (yearly savings of 2.39E + 05 tonnes CO_2-eq and 1.20E + 05 tonnes

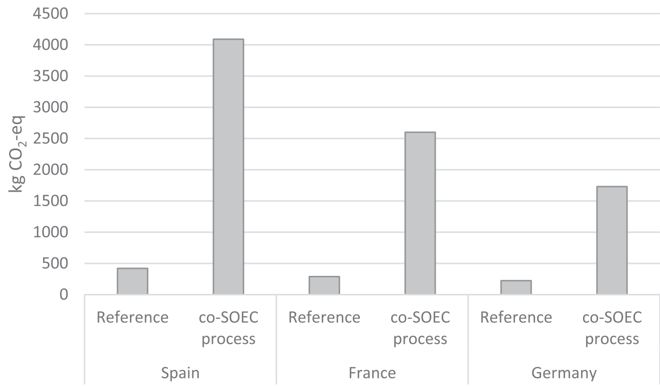

Figure 6. Blue water consumption in the reference and the co-SOEC process scenario in the three countries under study for the production of 1 tonne of clinker.

Table 4. Yearly CO_2 savings for each scenario.

Case (country/renewable share)	Yearly CO_2 savings (tonnes CO_2-eq)
France 23.6% PV	2.39E + 05
Spain 25.4% PV	1.20E + 05
Germany 14.1% PV	No savings
Germany 50% PV	5.00E + 04
Germany 75% PV	1.50E + 05

CO_2-eq respectively). In Germany, the PV share would have to reach 50% for the co-SOEC process to start having a benefit on the GWP and this would reach yearly savings of 5.00E + 04 tonnes CO_2-eq while 75% PV share would reach yearly savings of 1.50E + 05 tonnes CO_2-eq.

Two points can be considered to increase these benefits:

Use lower carbon electricity: this can be done by considering future electricity mixes with higher shares of renewables than today's mix, or taking into account specific ways to source renewable electricity even today, such as buying Guarantees of Origins on the electricity.

Increase the share of fossil fuel that is substituted in the cement plant. As the limiting factor that has been identified is the availability of waste heat in the cement plant, the availability of other sources of waste heat (or renewable heat, like concentrated solar power thermal process) could allow for the increase in the fossil fuel substitution (only 51% in this case), leading to increased benefits from the co-SOEC process.

4.2. Case study 2: gasification unit

4.2.1. LCIA results

Figure 7 presents the GWP results associated with the gasification unit reference and co-SOEC scenarios in the four country situations studied in the second case study. It is observed that the co-SOEC system proves beneficial in the French (−47%) and Swedish (−55%) situations while it does not in the Danish (+35%) and German (+180%) ones. These differences are due to the higher carbon content of the German and Danish electricity mixes compared with the French and Swedish ones.

The majority of the GWP impact originates from the electricity grid mix (e.g. 59% of the total GWP in the Swedish scenario) with the next highest contribution coming from the heat production process (37% of the total GWP in the Swedish scenario), while all other inputs and outputs have negligible contributions to the overall GWP (this is the case in all geographic subcases). Note that the choice has been made to model the heat input with a heat production process from natural gas considering that the waste would otherwise not be wasted but would be used by another process. If the heat input was considered as a use of heat that would otherwise have been wasted, the GWP impact would be reduced accordingly (by 37% in the Swedish scenario).

A sensitivity analysis was performed on the Danish, French, and German cases to compare different shares of renewable energy in the electricity input. The wind and PV shares were increased to 50% and 75% to see if the co-SOEC process would eventually have a benefit over the reference case in the Danish and German cases. In the Danish case a 50% wind energy share (with the other 50% coming from the Danish electricity grid) reaches a 2% lower GWP impact than the reference case, translating to a yearly CO_2 savings of 1.07E + 03 tonnes CO_2-eq.

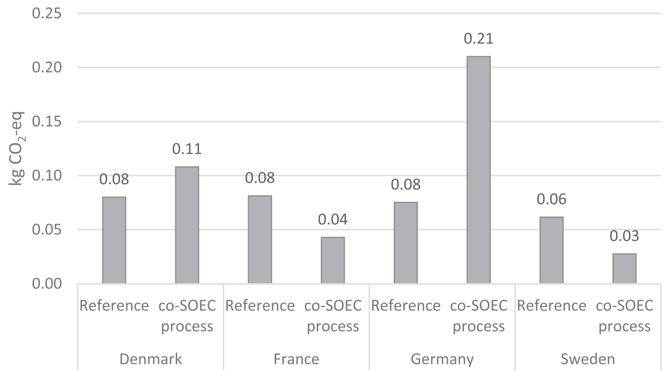

Figure 7. Global warming potential in the gasification unit reference and co-SOEC system scenarios in the four countries under study for the production and injection of 1 MJ biomethane (natural gas in the reference scenario) including emissions during the use phase.

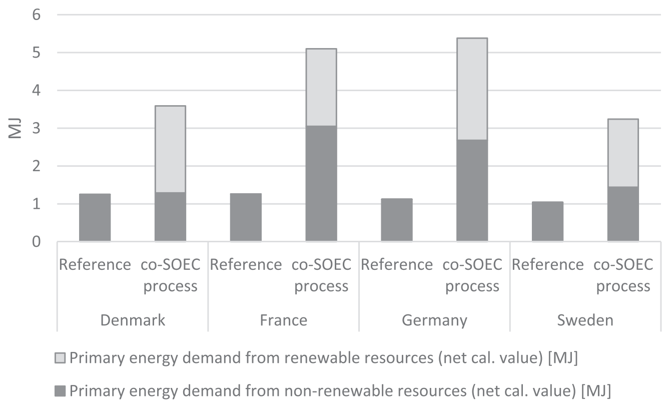

Figure 8. Primary energy demand in the reference and co-SOEC system scenarios in the four countries under study for the production and injection of 1 MJ biomethane (natural gas in the reference scenario) including emissions during the use phase.

In the case of 75% PV share, the co-SOEC process reaches a 43% lower GWP impact than the reference case, translating to a yearly CO_2 savings of 2.05E + 04 tonnes CO_2-eq. What is especially interesting in the Danish case is that at 50% wind energy share, the co-SOEC process also begins to have a lower PED from non-renewable resources, which is not the case in any other geographic case. At 50% wind energy share, the PED from non-renewable resources is 24% lower in the co-SOEC scenario than in the reference scenario, translating to a yearly savings of 1.82E + 08 MJ energy. This increases to annual savings of 4.05E + 08 MJ energy (over double the previous savings) when increasing the wind share to 75%. These energy savings are a result of the high wind power share since wind power infrastructure uses even less energy from non-renewable resources than PV infrastructure. If a sensitivity analysis were done on the other geographic case using wind power, Sweden, these energy savings would most certainly result as well.

In the French case the 50% PV share achieves a 50% lower GWP impact than the reference case (only 3% more than the standard case), translating to a yearly CO_2 savings of 2.40E + 04 tonnes CO_2-eq. In the case of 75% PV share, the co-SOEC process has a 51% lower GWP impact than the reference case (only 4% more than the standard case), translating to a yearly CO_2 savings of 2.48E + 04 tonnes CO_2-eq. In the German cases none of the two sensitivity scenarios achieved a beneficial situation (the reference case would still have 46% and 16% lower GWPs than the co-SOEC system in the 50% and 75% PV shares respectively). For the co-SOEC process to save CO_2 emissions in the gasification unit in Germany, the PV share would have to reach 82%.

Figure 8 presents the PED results associated with the reference and co-SOEC scenarios in the four country situations studied in the gasification unit case study. It is observed that in all cases the co-SOEC system requires more primary energy than the reference scenario, as in the cement plant case study. This is due to the electricity inputs required in the co-SOEC system.

Figure 9 presents the blue water consumption results associated with the reference and co-SOEC scenarios in the four country situations studied in the gasification unit case study. Unsurprisingly it is observed that in all cases the co-SOEC system requires much more water (orders of magnitude) than the reference scenario (production and injection of natural gas).

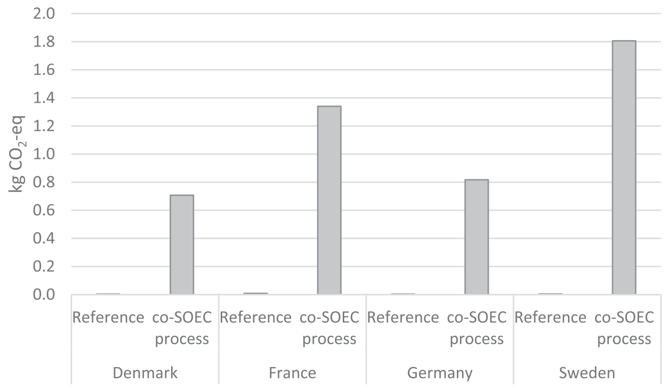

Figure 9. Blue water consumption in the reference and co-SOEC system scenarios in the four countries under study for the production and injection of 1 MJ biomethane (natural gas in the reference scenario) including emissions during the use phase.

Table 5. Yearly CO_2 savings for each scenario.

Case (country/renewable share)	Yearly CO_2 savings (tonnes CO_2-eq)
Denmark 27% wind	No savings
Denmark 50% wind	1.07E + 03
Denmark 75% wind	2.05E + 04
France 16% PV	2.28E + 04
France 50% PV	2.40E + 04
France 75% PV	2.48E + 04
Germany 16% PV	No savings
Germany 50% PV	No savings
Germany 75% PV	No savings
Sweden 27% wind	2.02E + 04

4.2.2. Results interpretation

The LCA analysis has shown that the co-SOEC process has a benefit on GWP in some cases and can lead to CO_2 emission savings when used with a gasification unit—this benefit can be more or less significant depending on the country and renewable share used in the electricity input. In the case of Sweden with 27% of the electricity input coming from wind power, the co-SOEC process provides an impressive benefit on the GWP impact (55% lower), ultimately saving 2.02E + 04 tonnes CO_2-eq every year (see table 5 below). The co-SOEC process would also provide a very noticeable benefit on GWP in France where 16% of the electricity input comes from PV—the GWP in this case is 47% lower giving an annual savings of 2.28E + 04 tonnes CO_2-eq. As the PV share increases to 50%, this annual savings increases to 2.40E + 04 tonnes CO_2-eq and to 75%, 2.48E + 04 tonnes CO_2-eq are saved annually. In Denmark, the wind share must be at least 50% for the co-SOEC process to provide a benefit on GWP, of 1.07E + 03 tonnes CO_2-eq saved per year and increasing to 2.05E + 04 tonnes CO_2-eq annual savings when the wind share reaches 75%. However, in Germany, the standard case does not show the co-SOEC process having any benefit over the reference case and a sensitivity analysis showed that the PV share would have to reach 82% for the co-SOEC process to have a positive impact on GWP.

The savings observed are always at the price of a higher PED and a higher water consumption due to the fact that the co-SOEC process requires much more electricity and water than the reference scenario (production and injection of natural gas in the gas network).

5. Conclusions

The co-SOEC process has proven potentially beneficial in both case studies performed, granted that the right local context is chosen. The highest benefits were seen in the cement plant case study with savings of up to 2.39E + 05 tonnes CO_2-eq annually. The results are variable depending on location and share of renewables in the electricity input. The co-SOEC process was consistently found to be less environmentally beneficial in Germany, due to a higher carbon intensity of the electricity mix, unless the PV renewable share reached 50% or even higher such as in the case of the gasification unit. The energy inputs required make up the majority of the environmental impact of the specific co-SOEC process, while the water input required for the co-SOEC process as well as the replacement parts for the co-SOEC process were shown to have negligible contributions to the impacts. Since electricity input is the main impact concerning the co-SOEC process, the carbon content of the electricity grid mix is a key factor in the environmental profile of the co-SOEC process. As grid mixes become 'cleaner' in the future with more renewable share in the electricity generation in every country, the co-SOEC process will provide even higher benefits. Therefore, despite the fact that currently, the co-SOEC process provides minimal CO_2 savings, this will change as the trend to use more renewables continues, making more GWP savings reachable at some point in the future. Interesting potential studies for future work would be to investigate other geographic locations as well as estimated future grid mixes and to study coupling the co-SOEC system with other CO_2-emitting plants.

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Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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