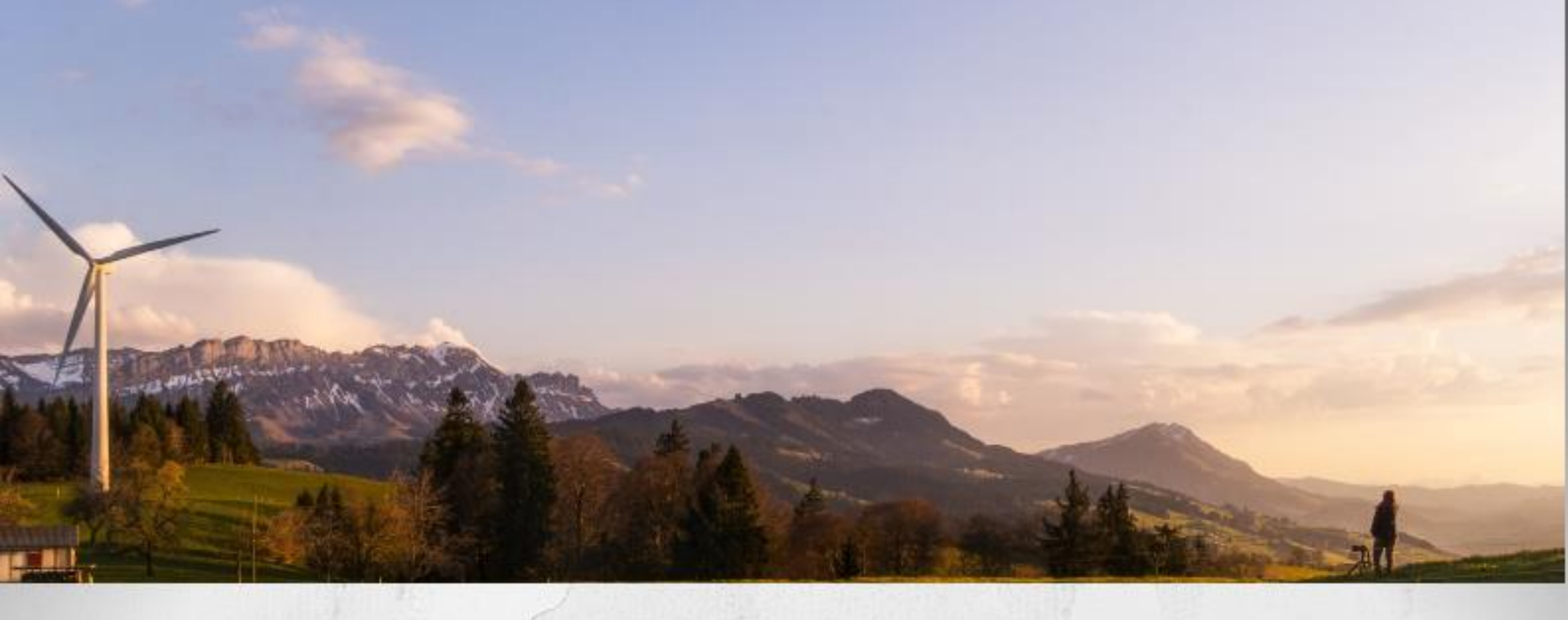

A Life Cycle Assessment of chemical energy carriers for the seasonal storage of renewable power under a net-zero CO2 emissions contstraint

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Summary

The purpose of this research is to assess the environmental impact of three chemical energy carriers for seasonal energy storage, so called Power-to-Fuel-to-Power (P-X-P) systems. Hydrogen, methane and ammonia are picked as storage media and the systems are designed to have net-zero CO_2 emissions. In order to find the degree of storage needed in the systems, first a demand-supply model is created. The electricity is assumed to be produced by a mixture of wind and PV. The result of the model is that between 8.1% and 8.8% of demand will come from the storage medium.

A life cycle assessment is then performed on the systems and these results are compared to the CCS system where electricity is produced by a natural gas combined cycle (NGCC) with both post combustion capture, Direct Air Capture (DAC) and underground CO_2 storage in order have a net-zero CO_2 emission system. The results show that hydrogen scores best on all seven impact categories if compared with the other storage media. If compared with the CCS system however there is no clear winner. The hydrogen system has a global warming potential of 0.073 kg CO_2 eq./kWh compared to 0.134 kg CO_2 eq./kWh of the CCS system. But on marine eutrophication and mineral resource scarcity the P-X-P systems score four times higher than the CCS system.

As the EU has pronounced that it is its goal to become a climate neutral society, this research also looked into systems where there is zero global warming potential in the entire lifetime. First the origin of the residual background emissions of the net-zero CO_2 systems is analysed. As the emissions are spread over a large amount of processes and a lot are outside of the EU, completely abating these emissions will be difficult for the EU. Secondly the impact is determined with the residual global warming potential being abated by the implementation of Direct Air Capture and Storage (DACS). Completely abating the global warming potential of the systems would lead to an 11% increase in other impact categories for the P-X-P systems and a 21% increase in the CCS system.

Contents

Introduction

Background

There is a distinct move from fossil fuels towards the use of electricity in the demand for heat as well as transport (Heinen, Mancarella, O'Dwyer, & O'Malley, 2018; Nathanail & Island, 2019). However, in 2017 in the EU 44.4% of electricity was still produced by the burning of fossil fuels (De & Sakhel, 2017). Electrification is seen as a key step towards reducing emissions in the EU. However, a switch towards electric heating and transport only has the desired impact on emissions if the emission intensity of electricity itself can be sharply reduced.

Considering the goals of the EU and the Paris agreement, we need to have a climate neutral society by 2050 (EU Commission, 2018). All scenarios of the International Panel on Climate Change's fifth Assessment Report agree that climate stabilisation needs near-zero carbon electricity (Audoly, Vogt-Schilb, Guivarch, & Pfeiffer, 2018). The transition to a near-zero emissions energy system is likely to depend on the availability of vast amounts of emission-free electricity and mechanisms to balance large differences in demand and supply due to intermittent Renewable Energy Supply (iRES) (Davis et al., 2018; Hertwich et al., 2014).

At this moment, gas fired power plants with carbon capture and storage (CCS) and Coal with CCS are, in most reports, represented as the future in combination with an increased amount of renewables (EU roadmap 2050). Both options are necessary to reach the EU emission reduction targets, but they also have their drawbacks. The implementation of CCS for instance leads to higher resource depletion and other negative environmental effects like increased acidification potential and human toxicity potential (Zapp et al., 2012). Most renewables, solar- and wind energy, are intermittent resources that are not capable of producing a stable level of production (Brouwer et al., 2014; Holttinen et al., 2016). The exception here is hydropower; however, the European opportunities to increase the production capacity are limited. In 2011, 50% of all technical potential was already installed and it is unclear what percentage is still economically feasible (Hydro in Europe, Eurelectric 2011).

If intermittent resources in electricity supply reach a certain percentage, there will be issues in connecting supply and demand (Bussar et al., 2016). Currently gas and coal fired power plants are used to balance the asymmetric production of the renewable energy. In a future energy supply based on iRES, the long term storage of electricity is indispensable (Bussar et al., 2016). If renewables could be connected to a storage option and produce a stable or responsive energy supply, the percentage of renewables could increase without losing the security of the energy supply.

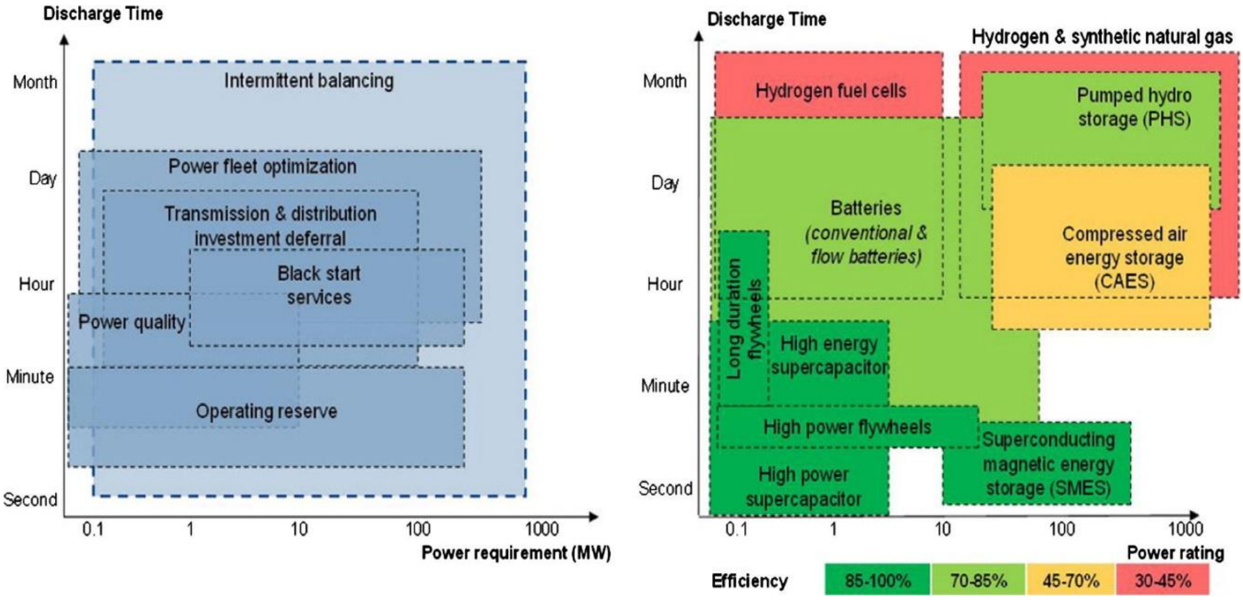

Figure 1: Left gives the different storage uses and gives the different storage media. The y-axis gives the timescale and the x-axis the power rating. The colors on the right give the efficiency. (Aneke & Wang, 2016)

To balance seasonal differences in renewable energy production a storage medium is need that can store energy for months. The storage options for long term storage, with a discharge time of months, in figure 1 are limited to pumped-hydro and chemical energy carriers. The first is however only applicable when the topography is suitable (Budt, Wolf, Span, & Yan, 2016). Most other storage options are either short-term like flywheel energy storage (Amiryar & Pullen, 2017) or very expensive compared to existing storage options like batteries (Poullikkas, 2013).

The only option for long term storage on a large scale left is by chemical energy storage, using electrolysis to produce hydrogen from surplus electricity. The hydrogen could then be burned when the demand for electricity exceeds the supply. (López González, Isorna Llerena, Silva Pérez, Rosa Iglesias, & Guerra Macho, 2015). Hydrogen is difficult to store because as a gas it has a relative low energy density. Another option is to let the hydrogen react with CO_2 to produce methane, or with N_2 to produce ammonia. Methane has the upside that it can use the already present natural gas infrastructure, reducing the cost of storage. Ammonia can be stored as a liquid at only 10 bars of pressure, which reduces the size and thus cost of storage.

Both methane and ammonia storage would need large quantities of respectively CO_2 and N_2. As 80% of our atmosphere consists of N_2, it would be relatively easy to obtain this by air separation. Air Separation Unit's (ASU) are currently used to produce pure streams of N_2 and O_2 for the chemical industry. Although the atmospheric CO_2 concentration is rising, at around 400 ppm it is still a thousand fold lower than that of N_2. A low concentration results in a high energy need for the separation, which is why research on capturing CO_2 is mainly focussed on flue gasses of fossil fuel plants as these contain higher CO_2 concentrations. The use of CO_2 for fuel production and energy storage is called Carbon Capture and Utilisation (CCU) and is seen by some researchers as a vital part in the improvement of carbon capture technologies as it could provide an economic value to carbon capture.

Knowledge gap

There has already been a lot of research on the environmental performance of electricity storage mediums. For instance Oliveira performed a life cycle assessment of compressed air energy storage, pumped hydro, hydrogen and several types of batteries (Oliveira et al. (2015). The research showed that the electricity feedstock is detrimental for the performance of storage systems and that the sodium sulphur battery was the best performer in all impact categories. The P-H-P system had a global warming potential ranging from 0.05 kg CO_2 eq./kWh with electricity from wind to 0.3 kg CO_2 eq./kWh if electricity from PV would be used.

Reiter did research on the global warming potential of Power-to-Gas, both hydrogen and methane, but the function as a storage medium is not taken into account here (Reiter & Lindorfer, 2015). The same holds for the research done by Zhang on Power-to-Gas (Zhang, Bauer, Mutel, & Volkart, 2017). Sternberg has compared the production of syngas and methane in an LCA study, but here it is does not include the step from the fuel to power (Sternberg & Bardow, 2016). There has also been research into the economics of power to gas technology as a technology to store intermittent renewable electricity, this has found that it might be hard to make it profitable (Götz et al., 2016).

Grinberg Dana has researched Power-Ammonia-Power (P-A-P) systems, but only on a technical level and did not include any level of environmental indicator(Grinberg Dana, Elishav, Bardow, Shter, & Grader, 2016). Studies on net-zero CO_2 emission power production have been done, however environmental performance was not measured (Baak, Pozarlik, Arentsen, & Brem, 2019; Davis et al., 2018; Nami, Ranjbar, & Yari, 2018).

It has been found that there is a gap in current research. Energy storage media have been researched and compared with each other, but these only include hydrogen storage. There is a lot of interest for power to gas systems, but these assessments do not include the last step towards power and thus the function as a storage medium. Net-zero CO_2 emission systems with chemical storage have been proposed and assessed, but only on a technological level and the zero emissions only apply to CO_2 in the foreground. A comprehensive overview of different chemical storage media and their environmental performance compared to electricity production from an NGCC with CCS can help fill these gaps. It would allow for a comparison between the two main options for emissions reduction in the power sector, increased penetration of intermittent renewables and implementation of carbon capture and storage.

Goal & research questions

There is no research that compares the environmental performance of different Power-Fuel-Power (P-X-P) systems with a system based on the combustion of natural gas combined with carbon capture. The EU's future energy scenarios show a big role for both CCS and increased renewables and electricity storage. These two things have been seen as separate fields; however a comparison could lead to interesting insights. This research aims to fill this gap by investigating systems that produce a responsive and dispatchable electricity supply based on intermittent renewable energy supply (iRES) and chemical energy storage and has zero direct CO_2 emissions. These systems will be examined in an LCA and compared to a reference scenario where electricity demand is fulfilled by a gas turbine with carbon capture and additional direct air capture (DAC). This leads to the central research question:

- What is the environmental performance of net-zero CO_2 emission power systems based on seasonal energy storage and iRES?

    - How could a net-zero CO_2 emission system, with no emissions in the foreground, be designed using chemical energy storage and iRES?

    - How does the environmental performance of different chemical energy storage media compare to each other and to a CCS based system?

    - What are potential designs of a system without global warming potential in its entire life-cycle, including the background processes?

The scenarios in the EU roadmap 2050 vary in the amount of renewables and the scale of CCS implementation. According to the roadmap the share of Renewable Energy Supply (RES) in electricity consumption will rise to at least 55% in 2050, with an increase to 97% if large scale electricity storage is present (EU Roadmap 2050, 2012). This research hopes to shed light on the environmental trade-offs between electricity production by CCS based technologies and iRES combined with electricity storage.

Method

Life cycle analysis as an analytical tool

In this research we are interested in an analytical tool that focuses on the technical aspects of a system. To answer the research question the tool should include at least the environmental impacts. And, as this research is on an energy and fossil resource related topic, also the impact on natural resources is of interest. The object of the research is a responsive electricity supply, which is a function. Taking these requirements into consideration the Life Cycle Analysis (LCA) is chosen as the most appropriate environmental assessment method for this research. It must be noted that LCA is a data intensive method, but even for early stage research as this it could still be an important method (Von Der Assen, Voll, Peters, & Bardow, 2014).

In order to calculate and compare the environmental performance of the proposed systems, it is necessary to look at the entire lifecycle of the systems. The end goal is to compare and find the optimal system with the best environmental performance (ISO, 2006b). The International Standardisation Organisation has made several standards, containing rules and regulations for execution of an LCA. The most widely used of these is the ISO 14040:2006 standard, which will also be used for this research (ISO, 2006a).

The first phase of an LCA is the goal and scope definition. Here the purpose of the research is stated; what are results that are sought after and what will it be used for. The scope phase is used to clearly determine what system is being studied and with what exact method. It includes, but is not limited to: Time scope, system boundaries, functional unit, reference system, impact categories and data quality requirements. The next phase is the life cycle inventory (LCI) phase where all the data is collected that is needed for the system that was described in phase 1. This step can have a big impact on the uncertainty of the end results. The data will be used to model all the flows within our system boundaries.

The results of phase 2 will then be used as input for the third phase, the life cycle impact assessment. In this phase the flows in our system will be converted to impacts, in the categories we chose in phase 1, using impact factors. In the final phase these impacts will be assessed and interpreted. It is important to keep in mind that, an LCA is an iterative process and there will be adjustments during the LCA. The process is re-iterated until the results are satisfactory.

For this research SimaPro 8.5.2.0 software is used to calculate and evaluate the environmental impact. The software is coupled to the extensive EcoInvent database. This database contains information on emissions to air, water and ground that result from the production, use and processing of products like steel and electricity. By combining all the different steps in the life cycle under consideration SimaPro can then calculate the environmental impact.

LCA in this research

Goal

The goal of the research is to compare different options of flexible and dispatchable electricity production. The environmental performance of iRES with different chemical energy storage mediums is compared with each other and with electricity produced by a fully abated Natural Gas Combined Cycle (NGCC) with Carbon Capture and Storage (CCS). CCS includes Post Combustion Capture (PCC), Direct Air Capture (DAC) and storage in the subsurface. To achieve this, an LCA is performed on electricity systems containing different forms of chemical energy storage (Hydrogen, Methane and Ammonia) and a scenario where electricity is produced in a NGCC with CCS.

Temporal scope

The temporal scope of the research is set to 2050. This is because the EU has set targets to be climate neutral by 2050 and iRES with chemical energy storage media is expected to be implemented on substantial scale by then. This is partly because the current iRES is still limited and thus the need for storage is limited, but also because some of the technologies are not mature yet.

Geographical scope

The geographical scope of the paper is Central West Europe (CWE), and constitutes Austria, Belgium, France, Germany, the Netherlands and Switzerland. Europe is divided in seven Wholesale Electricity Markets where electricity is traded over national borders (Markets, 2018). The CWE is chosen in this research because it has a large interconnection capacity between the member states and it uses a more advanced method to calculate the optimal use of this capacity called flow-based market coupling (CWE NRAs, 2015; Jegleim, 2015). The CWE region has an amount of solar irradiation high enough to make solar power interesting, has both on-shore and off-shore wind, but has big seasonal differences and therefore presents a meaningful case study for seasonal energy storage in chemical energy carriers. Going farther north to the Scandinavian countries would lead to very low average irradiation, possibly making the use of solar PV less attractive in general. While going further to the south would decrease the seasonal differences in irradiation.

Net-zero emission constraint

The systems under consideration are configured in such a way, that direct CO_2 emissions to the atmosphere are set to zero. Either the system does not have direct CO_2 emissions or the system is expected to take up the same amount through DAC from the atmosphere as is emitted during power production. The systems thus have net-zero CO_2 emissions.

Functional unit

The research focuses on a system that provides large-scale, flexibly dispatchable and net-zero CO_2 electricity. Intermittent resources like wind and solar energy cannot fulfil this on their own because their supply is weather dependant and can unlikely follow demand curves as exactly as necessary. Storage can be used to transform intermittent electricity supply into a stable and responsive supply. The chosen functional unit of this research is 1 kWh of flexible electricity generation, which is distinctively different from previous research on seasonal energy storage. Previous research focused on comparing different storage technologies and used storage size as the functional unit. However, in this research we would like to compare the environmental performance of the seasonal energy storage systems with systems based on burning natural gas.

In order to do this a novel functional unit was used. The functional unit of flexibly dispatchable electricity includes that only a certain percentage of iRES has to be stored before it is used. As the functional unit of 1 kWh dispatchable electricity is supplied to the grid, instead of to the end consumer, the system boundary is cradle-to-gate.

Reference system

A reference system is needed in order to bring the results into perspective. Generally the ‘current practice’ is taken as a reference so that a proposed new production process can be compared to it. However, there is not a single current practice of producing our functional unit. Flexible electricity production could originate from any fossil resource, hydro power or even to some extent nuclear energy. Electricity production from a NGCC without CCS is chosen because it offers the opportunity to compare it to the system using the NGCC with CCS. This could also give insights to the trade-offs that adding CCS has on the environmental impact of electricity production.

Impact categories

In order to quantify the performance of the different system configurations, a selection of six environmental impact categories was evaluated. To solely focus on GHG emissions would provide a one-sided picture of the systems. The impact assessment calculation methodology used is ReCiPe 2016, where the most relevant heuristic midpoint categories are assessed. The selection of impact categories is based on the measure of insight it gives in trade-offs between the systems. Also the reliability of the underlying methodology is taken into account, as not all impact categories in the ReCiPe 2016 package are equally well-embedded and substantiated by scientific research(Huijbregts et al., 2016). Therefore the following seven impact categories were selected:

I. Global warming potential
II. Ozone formation
III. Particulate matter formation
IV. Terrestrial acidification
V. Marine eutrophication
VI. Fossil resource scarcity
VII. Mineral resource scarcity

System design

In order to determine the environmental impact of the systems under consideration, these first have to be constructed and explained. For instance, there are several electrolyser technologies that al have different operating conditions and efficiencies. And there is more than one way to produce methane from hydrogen. For all four systems there are various assumptions that need to be made, these will be discussed in the next section. Table 1 already gives a short overview of the systems, including whether they are net-zero CO_2 and need the use of DAC.

Abbreviations for the systems are used in order to improve readability of graphs of tables. The general term for electricity supply through a storage medium is Power-to-X-to-Power (P-X-P). The energy storage systems using hydrogen, methane and ammonia are respectively abbreviated to P-H-P, P-M-P and P-A-P. The net-zero CO_2 system using natural gas combined with CCS is abbreviated to the CCS system.

Table 1: Systems and their properties

	Includes storage	Net-zero CO_2	DAC	Post Combustion Capture
Reference NGCC				
CCS		X	X	X
P-H-P	X	X		
P-M-P	X	X	X	X
P-A-P	X	X		

Natural Gas Combine Cycle with Post Combustion Capture and DAC (CCS)

This research compares the proposed net-zero CO_2 emission systems with a system where a NGCC with PCC and added DAC supplies flexibly dispatchable electricity. The system in figure 2 is adjusted in such a way that the residual CO_2 emissions of the NGCC with PCC are captured by the DAC. This makes the reference system a net-zero CO_2 emission system, allowing a comparison to the renewable energy systems with chemical electricity storage. The electricity and heat input for the DAC originate from within the system, where heat is produced using an industrial heat pump. The natural gas input enters the system with an environmental burden. The captured CO_2 is transported and stored in a geological formation where it will remain for thousands to tens of thousands of years, depending on the leakage rate (Glavic, Sikdar, & Jain, 2004). For this research the leakage rate is considered to be negligible and is not taken into account. Also the environmental impacts of CO_2 storage on the subsurface are not taken into account.

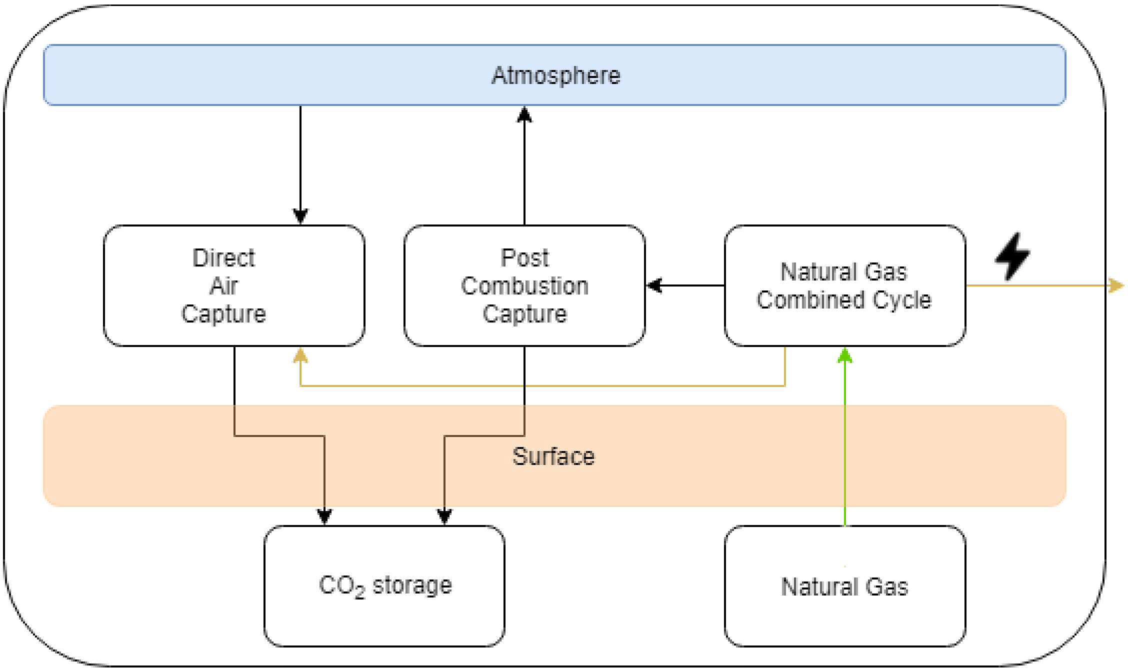

Figure 2: The CCS system: Yellow is electricity, black is CO_2 and green is natural gas.

Table 2: Technological data of the CCS system, LCI data of system processes can be found in the appendix A.

NGCC efficiency including post combustion capture	**50.2%**
Capture efficiency post combustion capture	**95%**
DAC electricity demand (kWh/kg CO_2)	**0.250**
DAC heat demand (kWh/kg CO_2)	**1.750**

Chemical energy storage systems

The first step in the chemical storage of intermittent renewable electricity is the production of hydrogen through the electrolysation of water. Proton Exchange Membrane Electrolysis Cells(PEMEC) are projected to be the dominating technology in the near-future, replacing Alkaline Electrolysis Cells (AEC)(Schmidt et al., 2017). Although Solid Oxide Electrolysers (SOEC) could surpass PEM for certain purposes if their electrode polarisation potential can be sufficiently lowered, they cannot operate as flexible as PEMEC and are thus not a good combination with iRES (Ursúa, Gandía, & Sanchis, 2012).

The second step is the long-term storage of the produced hydrogen and can be done mechanically (high pressure, cryogenic), chemically (Methane, Methanol or Ammonia) or through physisorption (Fullerenes, Nanotubes) (Niaz, Manzoor, & Pandith, 2015). As this thesis builds on previous work (Sutter, van der Spek and Mazzotti, under review) the same storage options are used: compressed hydrogen (100 bar), methane and ammonia.

Of the four different modes of storage, compressed hydrogen is the most straightforward and least complex option. Methanol is chosen as it is a widely used chemical that is liquid and easy to store (Wender, n.d.). The third storage option is methane, which could make use of the present infrastructure for natural gas transport and storage and thus has a major advantage from an investment perspective. The last system will be based on storage in ammonia (NH_3), as it is also carbon free and research has shown its potential in power-to-fuel-to-power systems (Grinberg Dana et al., 2016).

Power-to-Hydrogen-to-Power (P-H-P)

Figure 3 shows the hydrogen system where there are no direct CO_2 emissions to begin with. The energy that is needed for the production and compression of hydrogen is assumed to be produced by the same mix of renewables and thus only runs when there is sufficient iRES. Hydrogen production was assumed at 30 bar with subsequent compression to 100 bar, hydrogen storage is expected to be facilitated underground in a salt cavern as they are present in the CWE, have high storage capacities and have high flexibility regarding injection and withdrawal (IEA, 2012; Michalski et al., 2017). Considering the fact that it will not always be possible to build the electrolyser plant exactly on top of the underground storage location, a conservative transport distance of 50 km is assumed between hydrogen production and storage as well as between the storage location and the fuel cell facility. Hydrogen losses due to transport are 5 times higher compared to natural gas in steel pipes, but when polyethylene pipelines are used they are still only 0.0005-0.001 % of total transported volume (Haeseldonckx & D'haeseleer, 2007).

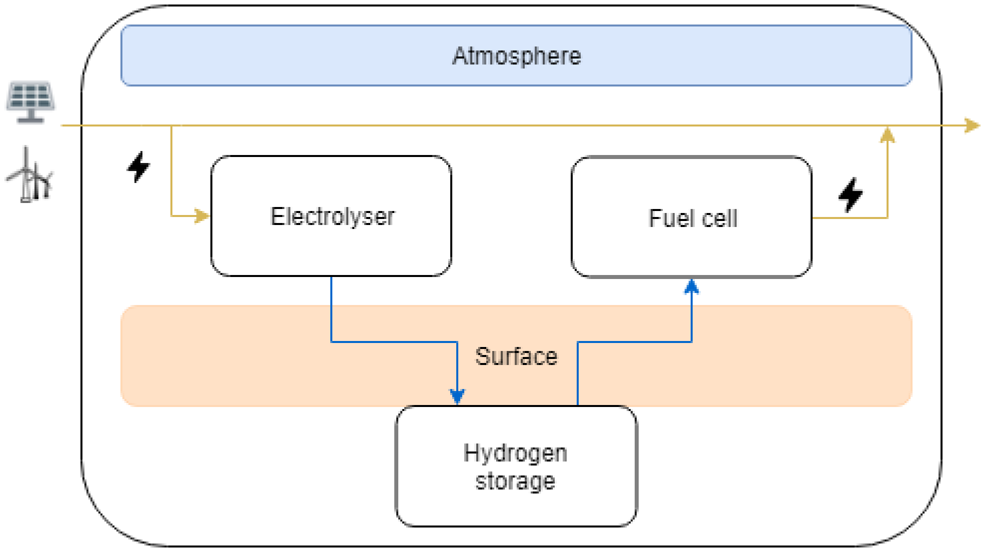

Figure 3: System based on compressed hydrogen storage: Yellow is electricity, blue is hydrogen.

Table 3: Technological data for the P-X-P system, LCI data of system processes can be found in the appendix A.

Electrolyser efficiency	**70%**
Fuel cell efficiency	**50%**
Hydrogen storage pressure (bar)	**100**

Power-to-Methane-to-Power (P-M-P)

Methane is produced by a hydrogenation reaction called methanation and is widely researched in literature. Methanation can be achieved in both biological and catalytic reactors. In this research, we have chosen to look at catalytic reactors as this is the only technology that is available on the required scale and data on this process is readily available (Götz et al., 2016). Catalytic methanation is a highly exothermic process and the excess heat, 165.1 kJ per mole of CO_2, can then be used for the heat demand of the DAC unit or for electricity production if the heat demand of the DAC unit is already fulfilled.

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

The system comprises the methane production and the consecutive methane incineration in a NGCC with CCS. The technical specifications of the NGCC are identical to the NGCC in the CCS system. The direct emissions to the atmosphere in the system are set to zero by capturing an equal amount of CO_2 with DAC as is emitted in the NGCC flue gas. The short-term hydrogen and CO_2 storage are added so that the methanation plant and DAC unit can run at a high capacity factor. Heat from the methanation reaction > 90° C is used to fulfil the heat demand of DAC. Any residual heat from methanation is a by-product of the system. The methane is expected to use existing infrastructure for transport and storage, with an assumed distance from production to storage and storage to use of 50 km to account for the infrastructural needs and methane leakage.

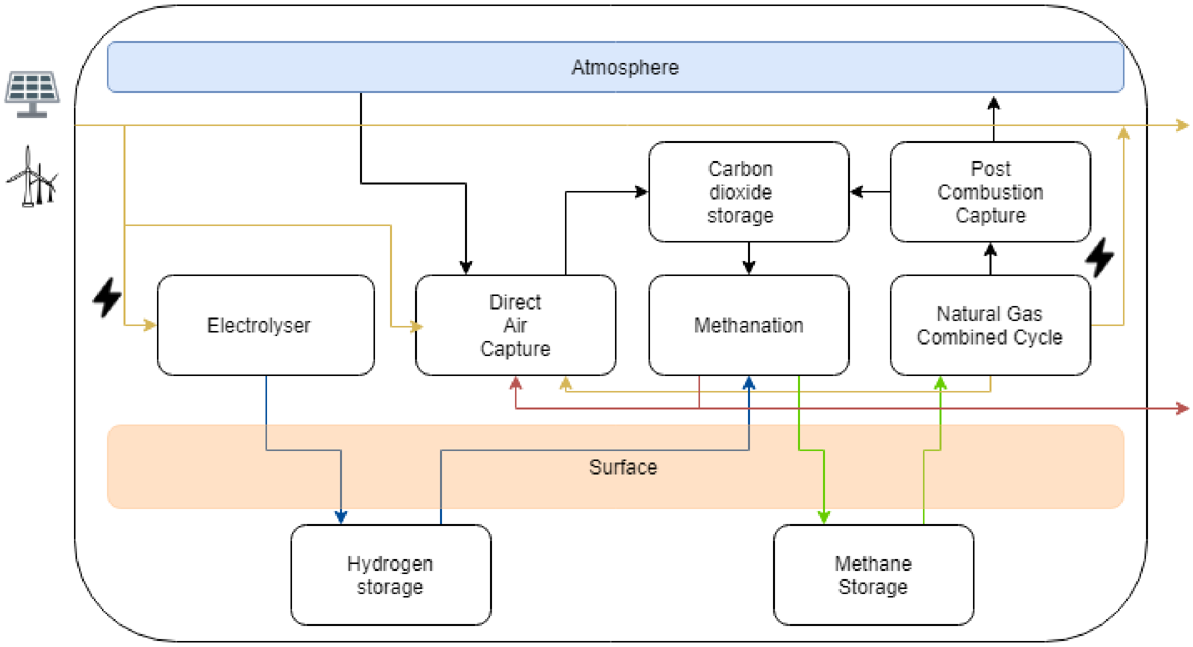

Figure 4: P-M-P system: Yellow is electricity, blue is hydrogen, black is CO_2, green is methane and red is heat.

Table 4: Technological data for the P-M-P system, LCI data of system processes can be found in the appendix A.

NGCC efficiency including post combustion capture	**50.2%**
Capture efficiency post combustion capture	**95%**
Electrolyser efficiency	**70%**
Methanation efficiency	**83.5%**
DAC electricity demand (kWh/kg CO_2)	**0.250**
DAC heat demand (kWh/kg CO_2)	**1.750**
Hydrogen storage pressure (bar)	**100**

Power-to-Ammonia-to-Power (P-A-P)

Hydrogen for ammonia synthesis is nowadays produced by steam reforming of natural gas, in this research however the hydrogen is produced by PEMEC. In contrast to the CO_2 cycle that is added in the P-M-P system, the P-A-P system has a nitrogen cycle. Ammonia is produced from hydrogen and nitrogen in the reaction shown below.

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$

The process needs a high temperature and pressure, although there is on-going research done on catalysts that could operate under atmospheric conditions (Vojvodic et al., 2014). In analogy with the methane system, there is short-term hydrogen to increase the capacity factor, and decrease the capacity of the chemical production plant. The electricity supply to the ASU and Ammonia plant are thus continues and does not originate fully from iRES. In times when iRES is limited the electricity is supplied from the Ammonia Combined Cycle (ACC). Ammonia is stored as a liquid in tanks that are on site and under 10 bars of pressure.

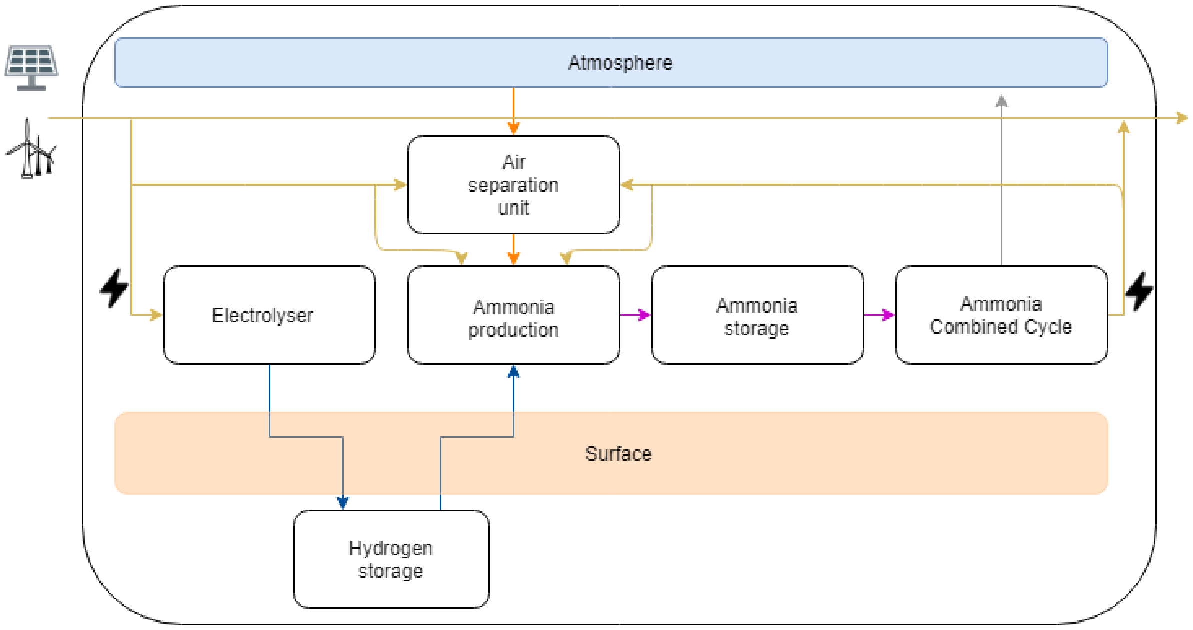

Figure 5: System with ammonia storage: Yellow is electricity, blue is hydrogen, orange is nitrogen and purple is ammonia.

Table 5: Technological data for the P-A-P system, LCI data of system processes can be found in the appendix A.

Electrolyser efficiency	**70%**
Ammonia combined cycle efficiency	**53.1%**
Ammonia production efficiency	**80.5%**
Hydrogen storage pressure (bar)	**100**
Ammonia storage pressure (bar)	**10**

System dimension

One of the most decisive parameters in our system is the percentage of iRES that has to be stored in order to produce the functional unit. The new functional unit of 1 kWh dispatchable electricity results in the need for a modelling approach using electricity supply and demand data to determine the amount of electricity storage that is needed and the size of the different components the systems. In this research electricity generation in the system is considered flexible if it can follow a demand curve. This is of course a major simplification because our systems would in reality not be stand-alone, but be part of a complex electricity market. This assumption is necessary because modelling the intricate workings of the electricity market is not possible within the time frame of a master thesis.

To determine the dimensions of the different components and flows of the systems, an electricity demand-supply model is constructed in Python. This model calculates, based on estimated future demand and iRES production curves, the necessary storage capacity of the system. Using an optimisation model the program minimizes the total iRES needed. With every kWh of electricity that is stored there are losses, increasing the iRES needed to fulfil demand. The model thus tries to minimize the use of storage.

The future demand curve is taken from Zappa et al. (2019) which is based on assumptions in the EU Energy Roadmap 2050 on increased electricity demand for heating (500 TWh y -1) and transport (800 TWh y -1) in the EU (roadmap 2050, EU) . They took a 2015 demand profile from the ENTSO-E database and the increased demand for heating and transport was added for each country (Zappa, Junginger, & van den Broek, 2019). For this research the demand profiles of the countries constituting Central West Europe (CWE) where added up in order to get a demand profile for the CWE region. This means we assumed there would be unlimited transmission capacity between these countries. Our systems were not expected to fulfill the demand for the complete CWE region, but should have a maximum capacity of 1 GW. Therefore the CWE demand curve was scaled down so that at its maximum value was 1 GW and is shown in figure 6. It can be clearly seen that there is a strong seasonal difference as well as fluctuation between day and night.

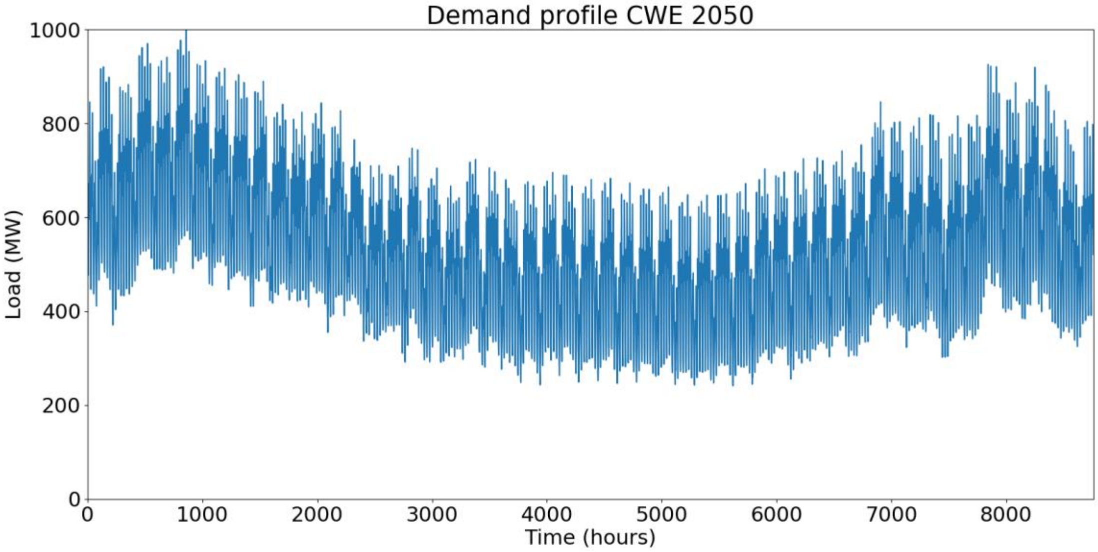

Figure 6: The predicted electricity demand profile of the CWE region in 2050, the maximum value has been set to 1 GW.

The iRES production profiles are constructed using the ‘Renewables.ninjas’ site that is based on research from Pfenninger and Staffel (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016). For wind production the ‘long-term future fleet’ datasets are used and for the solar energy production the MERRA-2 data is used. These datasets contain 30 years of hourly values for the capacity factor of wind and solar production and is available per country. These capacity factors are based on weather data from the years 1985-2015. In order to predict the total production of wind and solar energy in the CWE in 2050 these capacity factors are multiplied by the planned installed capacity in 2050 in these countries. These figures are taken from the ‘Energy, Transport and GHG emissions Trends 2050’ from the EU (add reference). The wind and solar profiles of the CWE countries are combined in order to get the iRES supply profiles of the whole CWE. Because the dataset we started with was based on 30 years of different weather profiles we also have 30 different CWE iRES profiles. Figure 7 shows the profile based on the 2015 weather data.

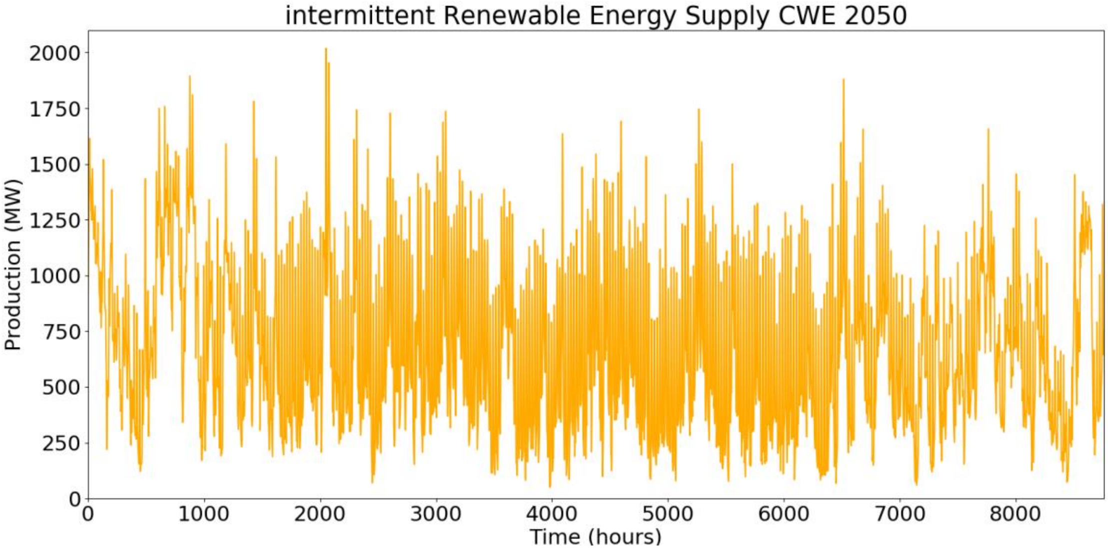

Figure 7: One of the predicted iRES profiles of the CWE region in 2050, based on weather data from 2015.

Chemical energy storage is seen as an option for long term storage of renewable electricity. If we would use the hourly data we acquired for the model this implies that intraday storage is also a function of our systems. However, due to the low efficiency of chemical energy storage it is expected that in reality other storage technologies will be used for this short term storage. Therefore the hourly data points were accumulated into daily data points, restricting the model to the storage of electricity for at least one day. It is important to note that the added intraday storage technology is not taken into account in the life cycle analysis.

We model three different systems, but the general principle is exactly the same. Using equation 1 the model finds the optimal operation of charging and discharging. Where charge is the surplus renewable electricity that can be stored at certain day t. Discharge is the shortage of electricity at a certain day t, and means that a certain amount of hydrogen, methane or ammonia is needed to fulfil the demand. The Demand and iRES are known inputs, MF is the multiplication factor and is necessary because before running the program the total amount of renewable energy to fulfil demand is not yet known. This depends on the overall efficiency of the system, which is an unknown.

$$Charge(t) - Discharge(t) = Demand(t) - iRES(t) * MF$$

equation 1

At the same time the amounts of hydrogen, methane and ammonia that are in storage (state of charge) are monitored through equation 2. The value of the State of Charge is of course not permitted to become negative. In the P-M-P and P-A-P systems there are two storage media, these are both monitored.

$$State\ of\ Charge\ (t) = State\ of\ Charge\ (t-1) - \frac{Discharge(t)}{Efficiency\ of\ Discharge} + Charge(t-1) * Efficiency\ of\ charge$$

equation 2

As the weather, and thus the iRES profiles are not the same every year the system was run for the entire 30 years of production data we had. This ensured that the system that we created was able to fulfil demand no matter the weather profile. Even in a year with relatively low solar and wind energy production the system would be able to function. The model output that will be used in the further research is not only the percentage that goes through storage. Also the minimum storage capacities, the capacity factors and minimum size of the electrolyser, fuel cell, NGCC and ACC will be of importance.

Uncertainty Analyses

The three major sources of uncertainty in an LCA are: parameter uncertainty, model uncertainty and uncertainty due to choices (LCA guidelines). Model uncertainty and uncertainty due to choices exists due to the definition of system boundaries, selection of processes and impact assessment methods and choice of the functional unit. These uncertainties are addressed by thoroughly discussing and substantiating the assumptions and choices that are made.

Parameter uncertainty results from imprecise or uncertain parameter values found in literature. Understanding of the magnitude of uncertainty due to parameter uncertainty will be tackled by doing a scenario analyses and a sensitivity analyses.

Scenario Analyses

In a typical scenario analyses three different scenarios are created in order to identify the range of the results. Our original scenario is our baseline, the other two scenarios are a best and a worst case scenario. This way the total range of possible values will become visible and can be assessed. Table 6 shows the parameter values used in the different scenarios.

Table 6: The list of parameters that are varied in the scenarios. For the environmental burden of iRES and natural gas it is a relative change of the burden. The '% iRES stored' is a change in percentage points.

	Scenario A	Scenario B	Scenario C
Electrolyser efficiency[1]	65 %	70 %	75 %
Fuel cell efficiency[2]	45 %	50 %	55 %
Methanation efficiency[3]	80 %	83.5 %	88 %
NGCC + PCC efficiency[4]	50.2%	50.2 %	55.2%
Ammonia production efficiency[5]	72 %	80.5 %	88 %
Ammonia combustion efficiency [6]	50 %	53.1 %	59 %
iRES environmental burden[7]	- 0%	- 0%	- 40%
Natural gas supply environmental burden	+ 15%	- 0%	- 15 %
DAC heat/electricity use (kwh/tCO_2)[8]	1750/250	1750/250	1250/150
% of iRES stored	- 2.5%	+ 0%	+ 2.5%

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[1] Lehner (2014)
[2] US DOE (2015)
[3] Müller (2011)
[4] ETRI (2014)
[5] Avery & Nielsen (1988)
[6] ISPT (2017)
[7] ETRI (2014)
[8] Climeworks

Scenario A – Worst Case

This scenario is based on a future where the increase in the share of renewables is limited; this means a limited necessity for the storage of iRES and limited improvement of electrolyser, fuel cell, methanation and ammonia processing efficiencies. Old natural gas fired power plants are kept in operation and the use of gas will replace that of coal. Due to the increase in natural gas use in the EU the supply will have to be imported from longer distances, thus increasing its environmental burden.

Scenario B – Baseline

This is our baseline scenario and thus has the values that are used in the general results.. Environmental burdens are based on SimaPro data of the CWE countries. The '% of iRES stored' is based on own calculations done with future supply and demand profiles.

Scenario C – Best Case

This scenario is based on a future where the EU chooses to do everything they can to limit emissions, with a focus on increasing the share of renewables. This will increase the share of renewables that need to be stored and increases efficiencies of energy storage related processes through investments in R&D and through technological learning. The environmental burden of iRES is reduced by pressuring manufacturers to use sustainable practices and energy. Due to the focus on iRES, the demand for natural gas diminishes. This reduces the length of the supply chain of the natural gas supply and reduces its environmental burden.

Sensitivity Analyses

The scenario analysis gives insight in the range of the end results while changing a set of parameters at once. A sensitivity analysis shows the sensitivity of the end result to changes in a single parameter. This helps to understand what are the most influential parameters and where an imprecise or incorrect value has the largest effect. It can also show the easiest pathway to further improve the system.

Table 7: Shows the percentage with which parameters are changed in the sensitivity analysis.

	Minimum	Maximum
Electrolysis efficiency	**-10 %**	**+10%**
Fuel Cell efficiency	**-10 %**	**+10%**
NGCC+PCC efficiency	**-5 %**	**+5 %**
Methanation efficiency	**-5 %**	**+5 %**
ACC efficiency	**-10 %**	**+10 %**
Ammonia production efficiency	**-10 %**	**+10 %**
iRES background impact	**-10 %**	**+40 %**
Percentage of iRES stored	**-25 %**	**+25 %**
DAC energy use	**-15 %**	**+15 %**
Natural gas background impact	**-10 %**	**+20 %**

Table 7 shows the relative change of the parameters that will be used to check the sensitivity. The ranges are in accordance with the values used in the scenario analyses. However, they are expressed in a percentage change of the original value in order to visualise the results in a single graph.

Results

System design

The python model returns daily values for the operation of the electrolyser and, depending on the system, either the fuel cell, NGCC or ACC. Figure 8 shows the operation of the P-M-P system using the meteorological data from 2015. It can be clearly seen that the electrolyser is operated more in the summer months, whereas the NGCC is more active in the winter months. This means that we have modelled seasonal storage.

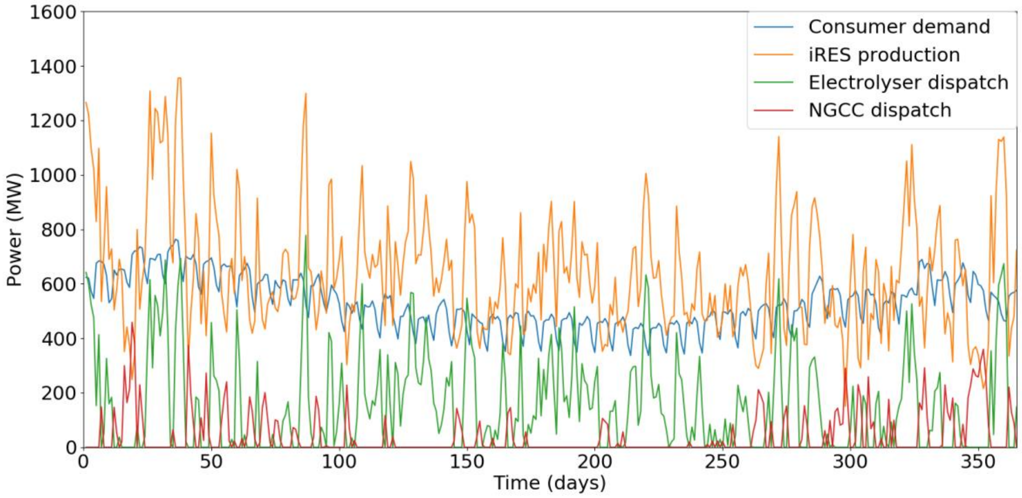

Figure 8: Graph showing the daily operation of the P-M-P system with meteorological data from 2015.

Figure 9 shows the storage capacity of the P-M-P system for the same year. Again we see that energy is stored in the summer months, as the storage capacity rises, and it is mainly used in the winter months.

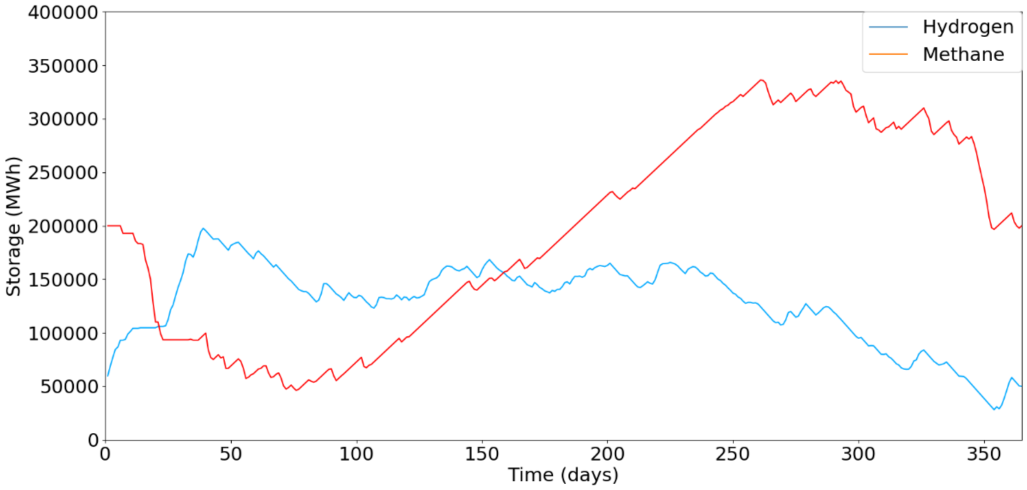

Figure 9: Graph showing the storage fluctuations of the P-M-P systems with meteorological data from 2015.

With the values for the daily operation of our system several other important parameters can be found. Table 8 gives these values and starts with the electricity flows in the system which show the percentage of electricity that is directly delivered to the grid and what is chemically stored. It also shows the capacity factor and minimum size of all plants and storage media.

Table 8: Data gathered from running the python demand-supply model.

Output python	P-H-P	P-M-P	P-A-P
Demand (GWh/yr)	4628	4628	4628
iRES production (GWh/yr)	5500	5647	5628
Electricity directly delivered (GWh/yr)	4221	4254	4250
Electricity stored (GWh/yr)	1279	1392	1378
Electricity from Power plant/fuel cell (GWh/yr)	407	373	377
Demand delivered by power plant/fuel cell	8.8 %	8.1 %	8.1 %
iRES used for hydrogen production	23.2 %	24.7 %	29.8 %
Capacity factor electrolyser	16.6 %	17.3 %	17.2 %
Capacity factor Methane/Ammonia plant	X	92.5 %	91.6 %
Capacity factor Power plant/Fuel cell	8.4 %	7.8 %	7.9 %
Electrolyser size (MW)	881	859	913
Power plant/Fuel cell size (MW)	553	548	549
Methane/Ammonia plant (MW)	X	110	110
Hydrogen storage (GWh)	1140	347	330
Methane/Ammonia storage (GWh)	X	859	763

Intermittent renewable electricity stored

An important factor in the final environmental impact of the system is the percentage of electricity that needs to be stored. If a lower percentage of supply needs to be stored in order to fulfil demand it would decrease electricity losses of the system and the necessary size of the different components. Rodriquez et al. found that with 100% renewable production in Europe, unlimited interconnection and using hourly data almost 15% of demand needs balancing (Rodríguez, Becker, Andresen, Heide, & Greiner, 2014). In our system only 8.1-8.8% needs balancing, however this is with daily data points. If the hourly data points are used this value rises to 12-13%.

Capacity factors

The capacity factor of the electrolyser ranges from 16.6% in the P-H-P system to 17.3% in the P-M-P system. Capacity factors are a key economic indicator as it shows how efficient the units are used. These low capacity factors show that a big part of the electrolyser capacity is barely used during the year. And considering that PEM electrolysers are expected to have a CAPEX between 250-1270 €/kW in 2030, a low capacity factor means inefficient and expensive use of electrolysers (FCH JU, 2014). The same holds for the capacity factor of the power plants and fuel cell, which range from 7.8% to 8.4%. Construction of a power plant that operates less than 10% of the time cannot be expected to be profitable. In the P-M-P system it is possible to use the remaining capacity for the combustion of fossil based natural gas, thus increasing the economic viability. This is however not possible for the other systems, as there is no fossil hydrogen or ammonia to combust.

Storage size

In figure 9, using the 2015 weather data, the methane storage level fluctuates between 50 GWh and 350 GWh. However, the minimal methane storage for the P-M-P system over the complete 30 years of weather data in table 8 is 859 GWh. This shows that there is a large difference in storage necessity over the years and that it depends on the production profile of the renewable electricity. The necessity for storage in all P-X-P systems is close to 1 TWh. To put this into perspective, the potential for hydrogen storage in northwest Germany alone is around 13.9 TWh (Michalski et al., 2017).

Hydrogen storage vs capacity factor

In both the P-M-P and P-A-P systems there is still need for a relatively large hydrogen storage location of almost 350 GWh. This is necessary because we have assumed that, due to economic reasons, the capacity factor of the methane and ammonia production plants have to be higher than 90%. The hydrogen storage size would greatly reduce if we delete this constraint. However, this would lead to an increase in the size and decrease in the capacity factor of the methane and ammonia plant. There is a clear trade-off between the capacity factor of the hydrogen storage and the methanation and ammonia production plant size.

Life cycle assessment

First the main LCA impacts are discussed in order to find trade-offs between the systems. In the following section we will then focus on each impact individually. It was found that adding CCS to the NGCC reduces the GWP by around 70%, but it has a negative impact on all other impact categories as can be seen in figure 10. The 70% is higher than was found in earlier research by Singh et al. where CCS implementation decreased GWP with 58% to 68% and increased all other impacts (Singh, Strømman, & Hertwich, 2011). This is however to be expected considering that our system assumes a higher CO_2 capture rate at the NGCC and includes DAC to reduce all emissions in the foreground. The increase in fossil resource scarcity is largely due to the reduced efficiency of the NGCC and thus the increased use of natural gas. The P-X-P systems all score comparable on GWP, 17% to 18% of the impact of the NGCC. Due to the fact that they do not burn fossil fuel the P-X-P systems also score very low on fossil resource scarcity. However, they have a relatively high impact on mineral resource scarcity compared with the NGCC systems.

The impact on Ozone formation, which is connected to the occurrence of summer smog, is on average twice as big for the NGCC systems compared to the P-X-P systems. On fine particulate matter formation the NGCC systems score lower than all the P-X-P systems. On terrestrial acidification the difference between the various systems is very small, expect for the high value for the P-A-P system. On marine eutrophication the natural gas based systems have an impact up to 10 times smaller than those of P-X-P systems.

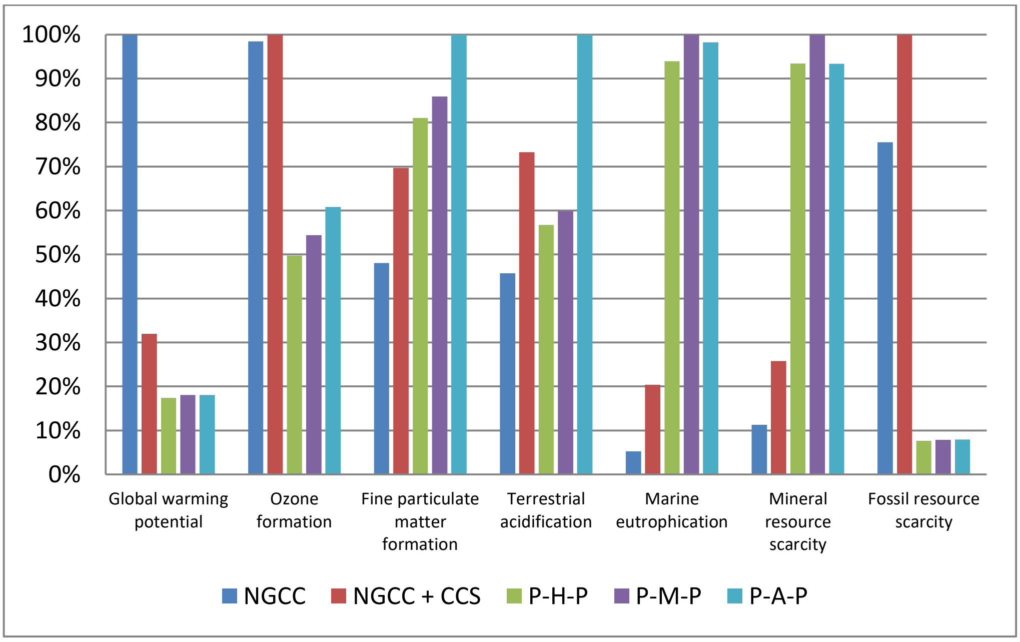

Figure 10: The graph shows the relative environmental impact for all five systems on seven impact categories, where the highest impact is set to be 100%.

Global warming potential

Figure 11 shows a breakdown of the GWP by the most important greenhouse gasses that are emitted in the systems. In all the systems under consideration the emission of CO_2 has the biggest impact, even in the system with CCS and DAC. It is clear that adding CCS and DAC to a NGCC to create net-zero CO_2 emission system decreases the GWP of the electricity production. By adding CCS and DAC to the NGCC the CO_2 emissions decrease by 80%, the remaining 20% is emitted in background processes. Due to the decreased efficiency of the NGCC with CCS the natural gas input per kWh, and with it the methane emissions, increases. This 33% increase in methane emissions slightly negates the positive effects of CCS.

CO_2 and methane emissions dominate the GWP, with dinitrogen monoxide coming third. The largest relative impact of dinitrogen monoxide is in the P-A-P system due to the high emissions of this greenhouse gas during the combustion of ammonia. However, it is still only 4% of the total GWP of the system. The remaining greenhouse gasses are emitted in such small amounts that they are negligible and together constitute less than 1% of the impact in all systems.

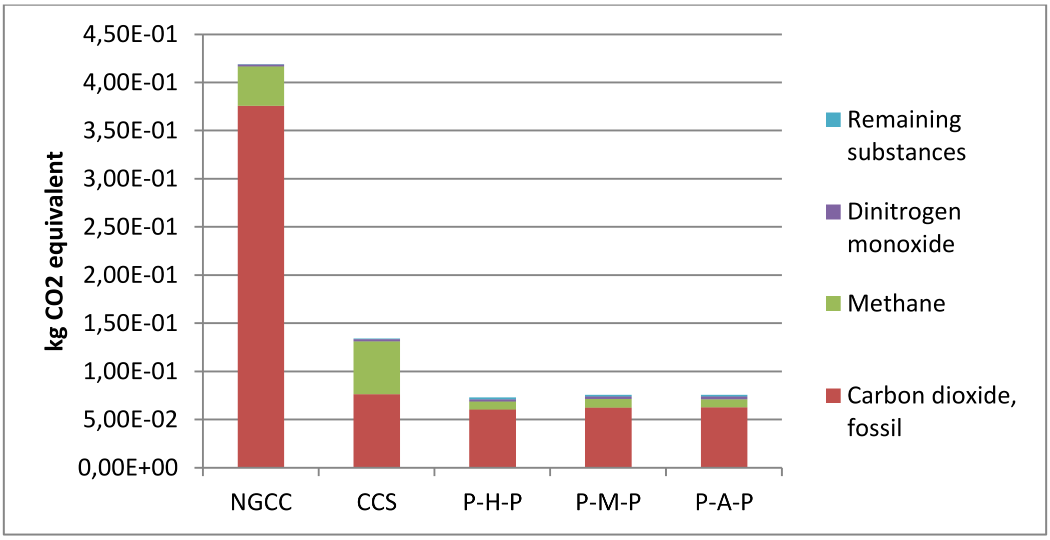

Figure 11: The graph shows the contribution of different emissions to the total GWP in kg CO_2 equivalent per kWh of electricity.

If we look at where in the life cycle these emissions occur, we see that in the NGCC system the direct emissions dominate. In all other systems the input of natural gas or electricity is the major contributor. The impact of the infrastructure in our system is relatively low. It only contributes 1%-4% of the GWP impact. The impact of the infrastructure is highest in the CCS system, mainly due to the CO_2 pipeline and storage.

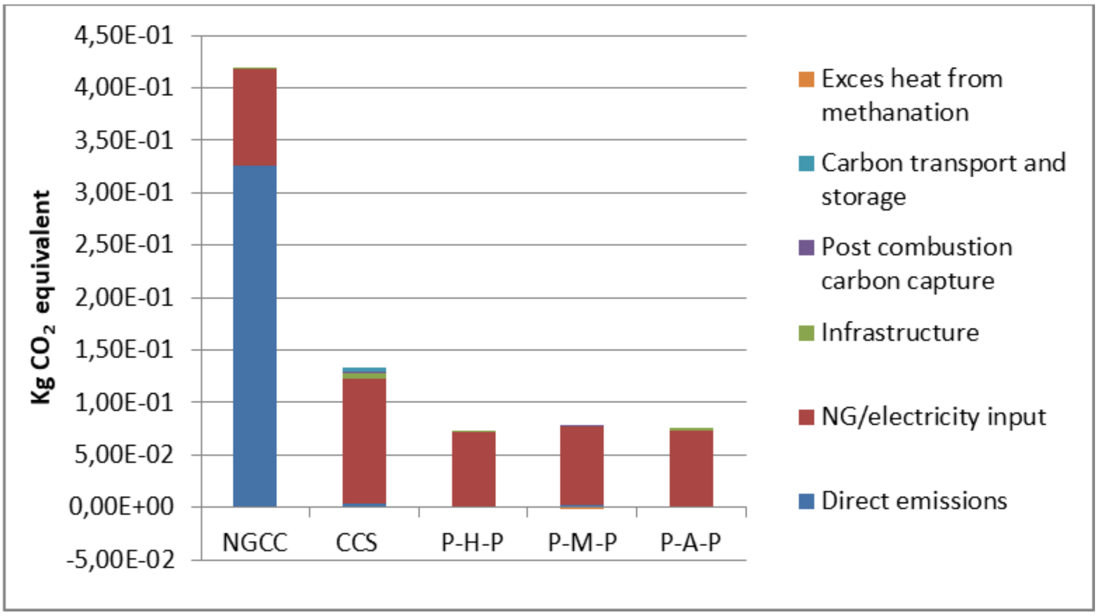

Figure 12: The contribution of the different system components towards the impact on GWP, expressed in kg CO_2 equivalent per kWh electricity production.

Ozone formation

The impact on Ozone formation is lower in the P-X-P systems than the natural gas based systems in figure 13. All of the values are dominated by the background emissions in either the electricity or natural gas supply. Emissions at plant level in the reference NGCC are more than double of those in the NGCC with CCS. This is a consequence of making different assumptions for the NGCC's. The NGCC with CCS is equipped with a Selective Catalytic Reduction (SCR) mechanism, reducing NO_x emissions at plant level. This emission reduction is however balanced out by the decreased efficiency and increased fuel input, resulting in a comparable result.

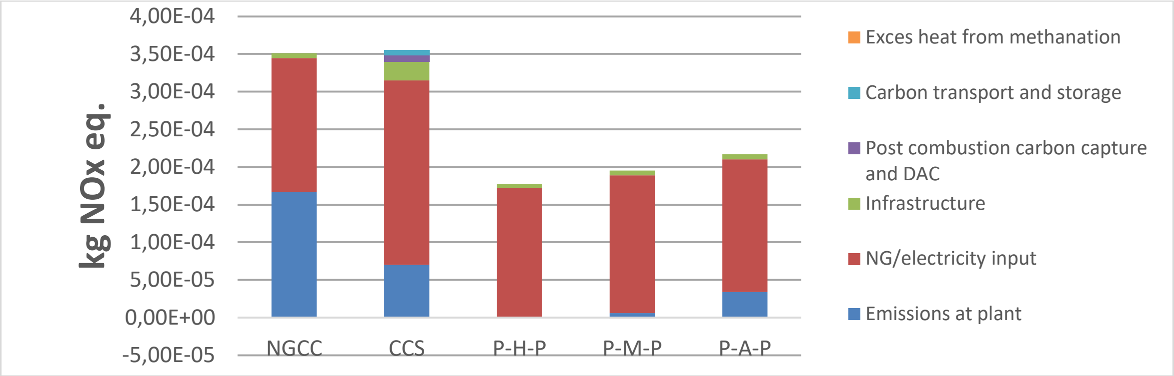

Figure 13: The contribution of the different system components towards the impact on Ozone formation, expressed in kg NO_x equivalent per kWh electricity production.

In figure 14 it is shown that the major substances leading to ozone formation are nitrogen oxides. There is also a small effect due to the emission of non-methane volatile organic compounds. This is a collection of organic, carbon based, compounds that display similar behaviour in the atmosphere.

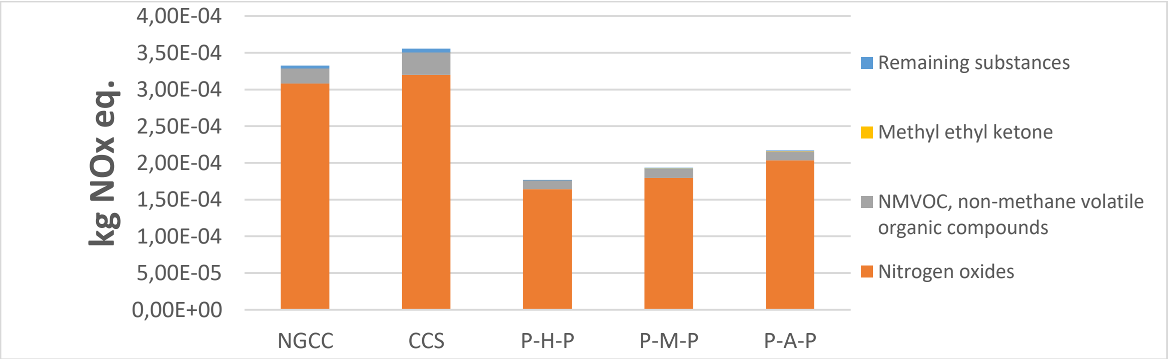

Figure 14: The contribution of different emissions towards the impact on Ozone formation, expressed in kg NO_x equivalent per kWh electricity production.

Fine particulate matter formation

Fine particulate matter formation is higher in the P-X-P systems than in the system based on natural gas as can be seen in figure 15. This is mainly due to the higher background impact of electricity input compared to that of the natural gas input. Emissions at plant level are relatively small in comparison, only in the P-A-P system do they show a steep increase due to unburned ammonia in the flue gas.

Post combustion carbon capture and DAC implementation have a significant influence on the NGCC with CCS system. If we include the effect of the lower efficiency of the plant due to PCC it increases particulate matter formation with 45%.

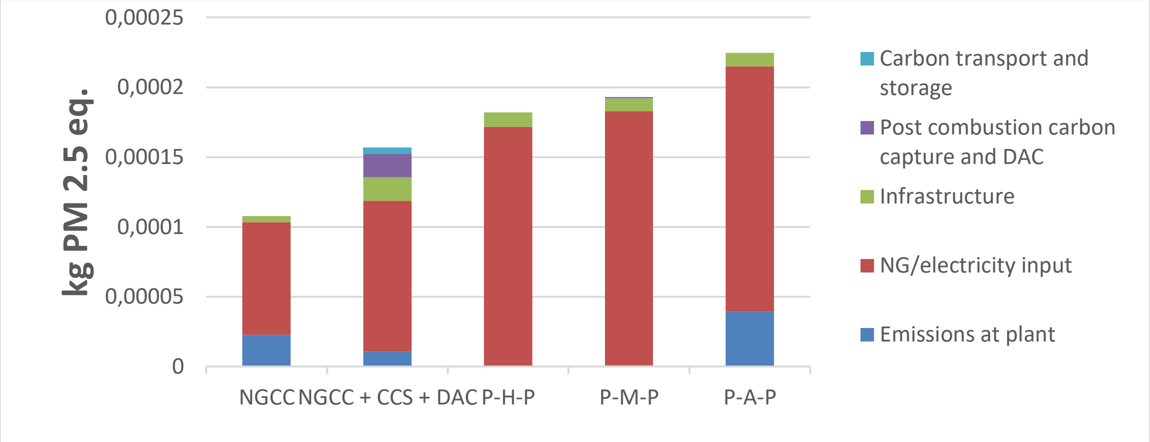

Figure 15: The contribution of the different system components towards the impact on fine particulate matter formation, expressed in kg PM 2.5 equivalent per kWh electricity production.

Figure 16 shows that particulate matter formation is not only a result of the emission of particulates, but is also influenced by other substances emitted to the atmosphere. The largest effect comes from sulphur dioxide, followed by nitrogen oxides and ammonia. The higher impact in the P-X-P systems is mostly due to the higher emission of particulates < 2.5 µm.

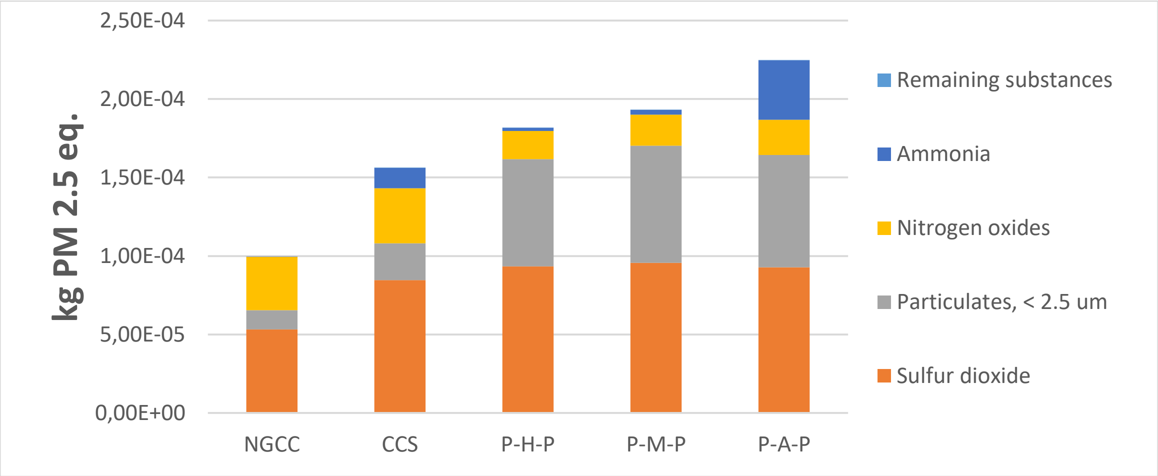

Figure 16: The contribution of different emissions towards the impact on fine particulate matter formation, expressed in kg PM 2.5 equivalent per kWh electricity production.

Terrestrial acidification

The terrestrial acidification impact in figure 17 is dominated in all systems by the input of the fuel, natural gas or electricity. The CCS system has an increased impact compared with the reference because of the ammonia that is emitted during post-combustion capture and ammonia has a high impact factor for acidification. This can also be seen at the P-A-P system, where the direct emissions have a very high impact. This impact is due to the assumed unburned ammonia in the flue gasses. Improving the combustion rate of ammonia could lower this high impact, but ammonia combustion is known to have problems with this due to its low flame speed (Institute for Sustainable Process Technology, 2017).

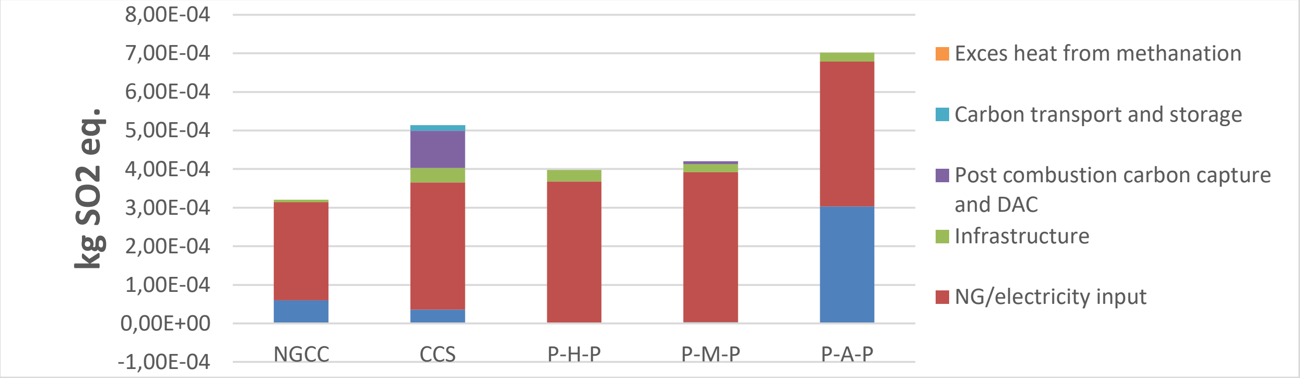

Figure 17: The contribution of the different system components towards the impact on terrestrial acidification, expressed in kg SO_2 equivalent per kWh electricity production.

As figure 18 shows there are three different substances related to acidification. The effect of the remaining substances are negligible. Sulphur dioxide is the most important of the three, however the systems all have comparable amounts of sulphur dioxide emissions. The difference between the systems is made by ammonia emitted in the P-A-P and CCS system.

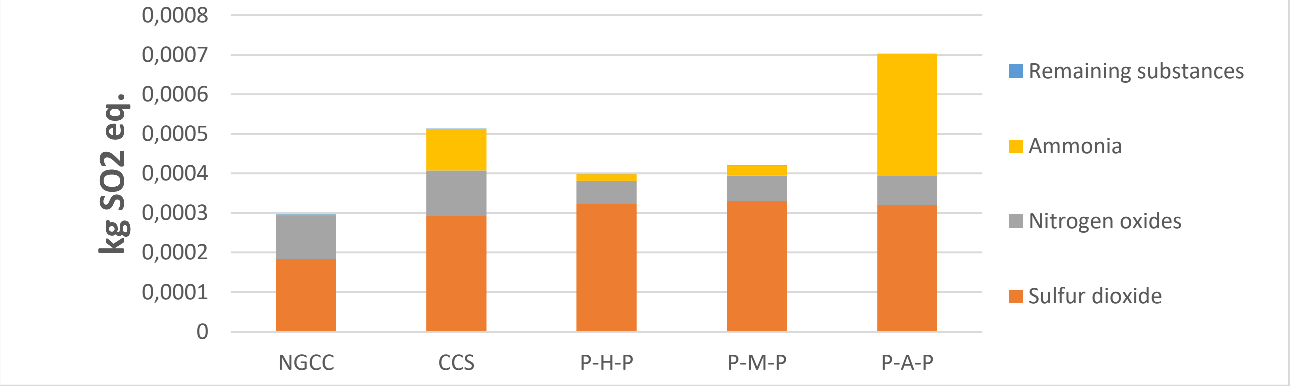

Figure 18: The contribution of different emissions towards the impact on terrestrial acidification, expressed in kg SO_2 equivalent per kWh electricity production.

Marine eutrophication

A closer look into the marine eutrophication in figure 19 shows where the high impact for the P-X-P systems comes from. Up to 99% of the impact is a result from the environmental burden of the electricity input, the remainder being connected to the infrastructure. An increase of 400% is seen by the introduction of CCS to the NGCC system. This is a combination of the emissions connected to the MEA production, the increased infrastructural needs and the transport and storage of the captured CO_2. The positive effect of the residual heat from methanation in the P-M-P system is negligible.

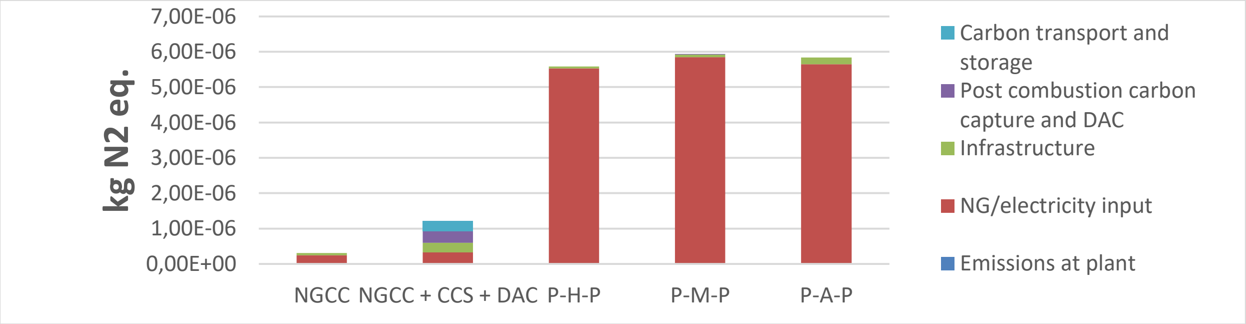

Figure 19: The contribution of the different system components towards the impact on marine eutrophication, expressed in kg N_2 equivalent per kWh electricity production.

The impact on marine eutrophication is only effected by emissions to water. Figure 20 shows that only three chemicals were identified as being emitted to water and having an impact on eutrophication. Nitrate has by far the biggest impact and it is mainly emitted during the production of solar panels. This is why the P-X-P systems score so high on this impact category compared to the natural gas based systems.

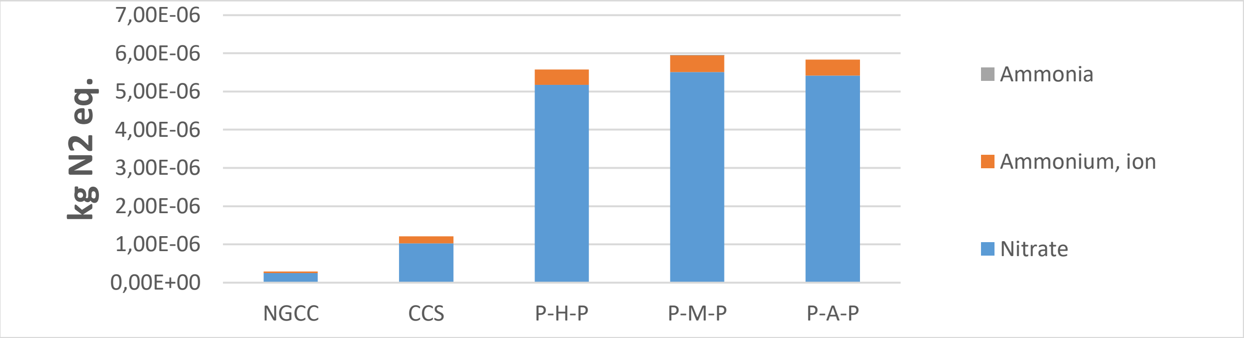

Figure 20: The contribution of different emissions towards the impact on marine eutrophication, expressed in kg N_2 equivalent per kWh electricity production.

Mineral resource scarcity

Mineral resource scarcity is expressed in kg Copper (Cu) equivalents and is effected by a wide range of minerals. There is a very clear difference compared to other impact categories, as mineral resource scarcity has nothing to do with emissions to air or water. The background emissions of the electricity input are the major impact in the P-X-P systems as can be seen in figure 21. This is due to the large amount of minerals necessary for the production of solar panels and wind mills. Compared to this, the mineral necessity for the natural gas supply is very small. The mineral resource scarcity of the P-X-P systems are up to four times higher than that of the NGCC with CCS system.

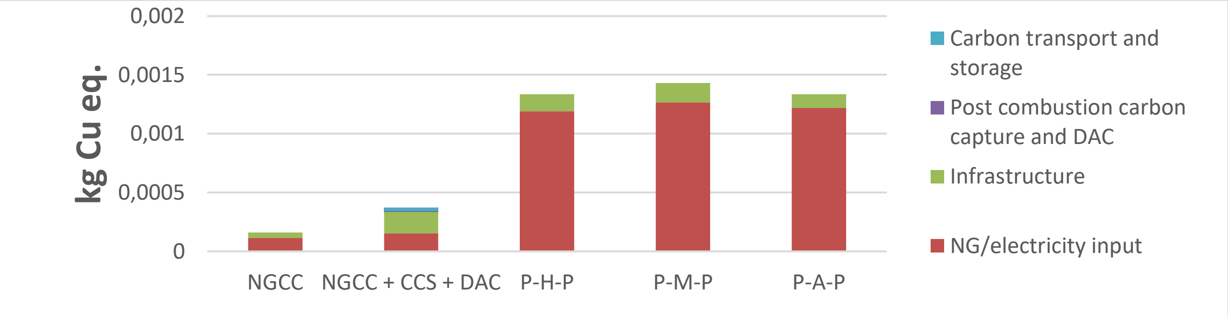

Figure 21: The contribution of the different system components towards mineral resource scarcity, expressed in kg Cu equivalent per kWh electricity production.

Figure 22 shows that mineral resource scarcity is dependent on a wide range of minerals. Iron and Nickel are the biggest contributors and constitute more than 75% of the impact in the natural gas based systems. In the P-X-P systems these two substances are still the biggest contributors, but they only constitute 30% - 36%. The P-X-P systems clearly use more aluminium, copper, platinum and the 'remaining substances' have a larger value and are spread over a large amount substances.

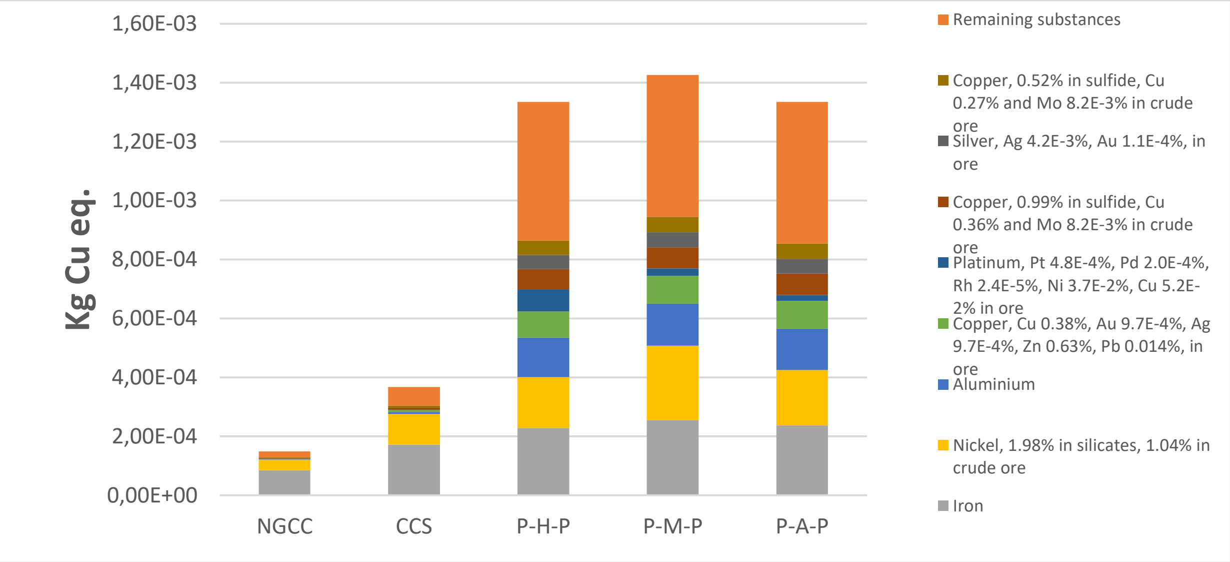

Figure 22: The contribution of the different minerals towards mineral resource scarcity, expressed in kg Cu equivalent per kWh electricity production.

Fossil resource scarcity

Just as mineral resource scarcity, fossil resource scarcity is an impact connected to depletion of the earth's resources. It is not a surprise that figure 23 shows that the impact is highest in the fossil fuel based systems and that it comes from the natural gas input. In the P-X-P systems the major contributor is the electricity input, even though the electricity itself is from renewable resources. However, the production of windmills and solar panels are still assumed to be powered by fossil power sources. In all systems more than 98% of the impact is due to the natural gas or electricity input.

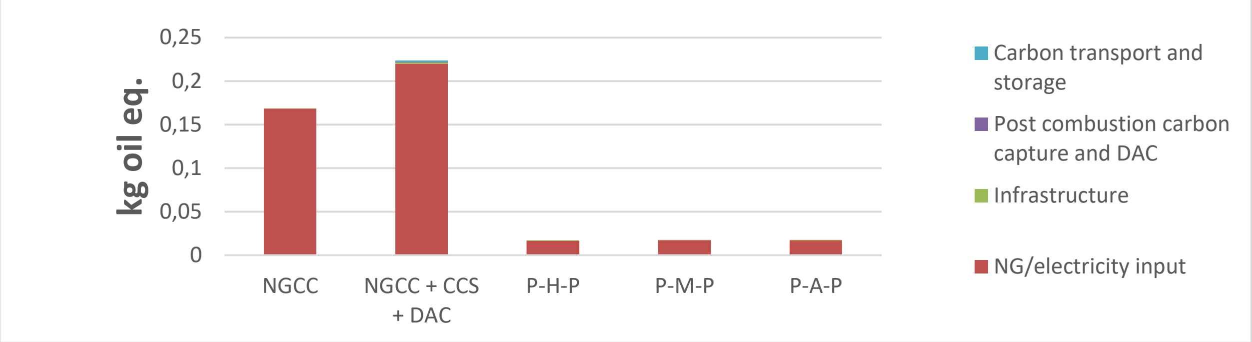

Figure 23: The contribution of the different system components towards fossil resource scarcity, expressed in kg oil equivalent per kWh electricity production.

Figure 24 shows what fossil resources are used in the systems. There is a distinctive difference in the fossil resource that is used between the natural gas systems and the P-X-P systems. In the natural gas based systems more than 98% is from the use of natural gas, the remainder is evenly divided over hard coal and crude oil. In the P-X-P system the major resource that is used is hard coal with 43%-45%. The other half is divided between natural gas (26%-29%), crude oil (20%-22%) and brown coal (8%).

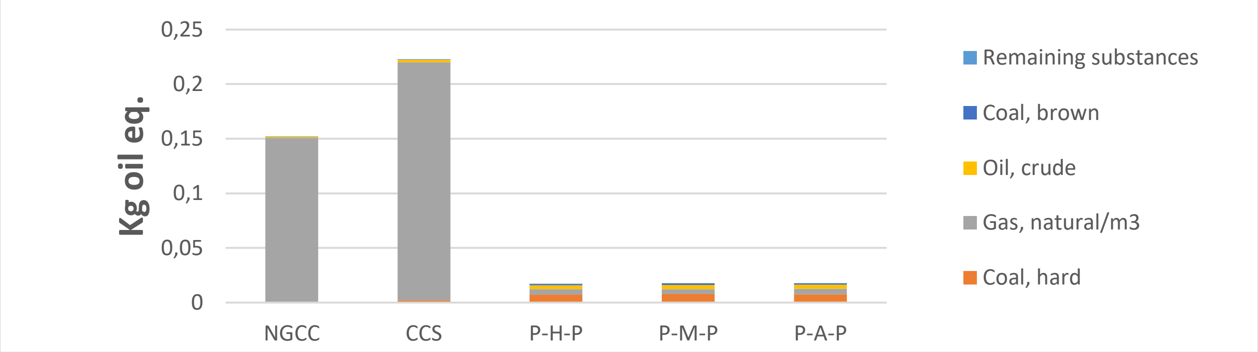

Figure 24: The contribution of the different fossil energy carriers towards fossil resource scarcity, expressed in kg oil equivalent per kWh electricity production.

Net-zero CO_2 to completely zero global warming potential

Currently the term net-zero CO_2 emission systems is being used a lot in research, meaning that there are no CO_2 emissions in the foreground. However the final goal is to have a stable electricity supply without emissions contributing to global warming in the entire lifecycle. There are two pathways in order to reach this, one option is to limit the emissions in the background of the life cycle. The other is to negate the impact through increased implementation of DAC in combination with CO_2 storage or Bio Energy and Carbon Capture and Storage (BECCS).

Limiting background emissions

In order to find how the background emissions can be tackled it is important to find where these residual emissions take place. This is done for both the CCS and the P-M-P system. Because most of the global warming potential of the P-X-P systems are due to the electricity input, and this input is the same in all systems, we assume the P-M-P to be a good representation of a P-X-P system in general.

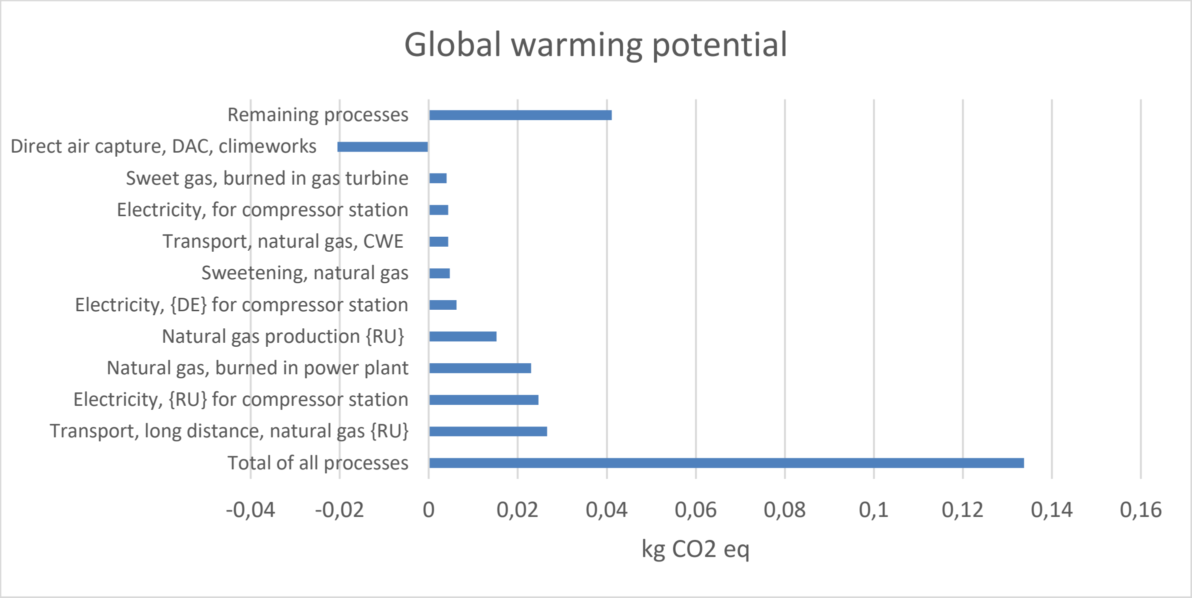

Figure 25: Global warming potential per kWh electricity production for the CCS system separated by process.

Of the five processes in figure 25 with the highest impact, four are connected to natural gas transport or production. These four processes combined contribute 55% of the total global warming potential. This means emissions are relatively centralized, either in the EU or in Russia. A big part of it is in Russia because it is the biggest exporter of natural gas towards the EU and the Russian gas network is spends across vast distances and is relatively inefficient.

The largest constituents of the emissions in the P-X-P systems of figure 26 are the pig iron production and hard coal mining operations in China. The top 5 processes in this system are good for just 18% of the total impact and the top 10 for 25%. This implies that emissions leading to global warming potential in the P-X-P systems are much less centralized than those in the CCS system.

Figure 26 also shows that a limited amount of the emissions occur in the EU. A large part is emitted in coal operations in China. We have already seen that most emissions are connected to the production of solar panels and windmills. Solar panels are currently mainly produced in China and steel production is starting to shift towards Asia as well (*European Steel in Figures*, 2018).

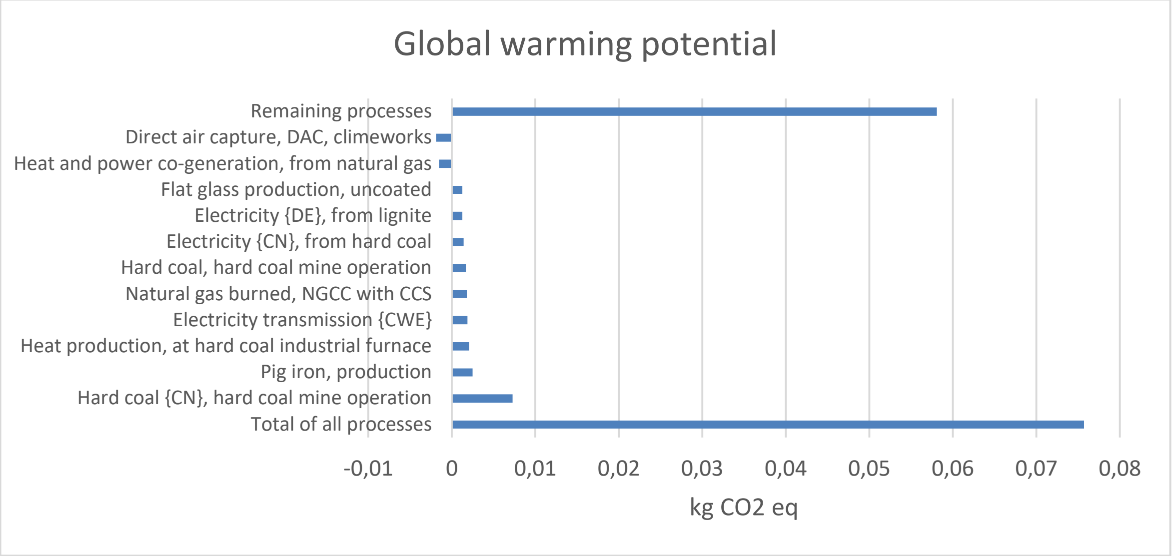

Figure 26: Global warming potential per kWh electricity production for the P-M-P system separated by process.

Direct Air Capture to negate background emissions

We assumed DAC to be used in order negate all GWP impact left in the background system. Naturally the other environmental impacts will increase due to the increased energy needed for DAC. Figure 27 shows the increase in environmental impacts if we increase DAC and CO_2 storage to have a system with no global warming potential in its entire lifetime. The energy required for DAC was expected to come from within the system itself. As we can see the increase for the NGCC system is the highest, with an average increase of 112%. This is due to the fact that it had the highest GWP in the original system, so more DAC is needed to negate the impact. The impact of the CCS system increased on average by 21% and the P-X-P systems with 11%.

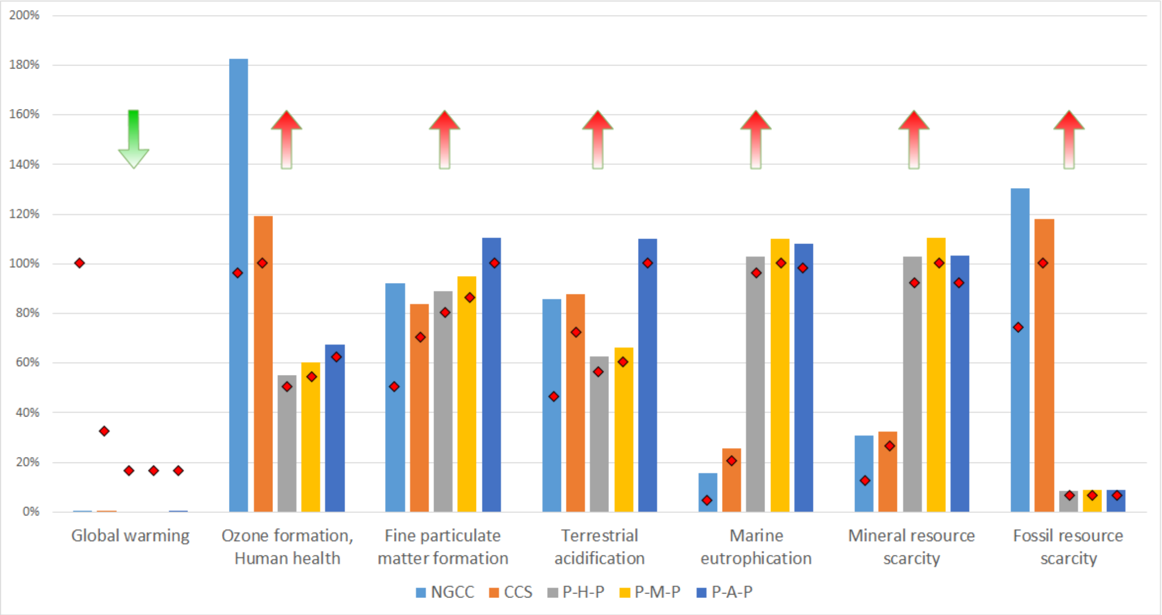

Figure 27: Change in environmental impact per kWh if DAC is used to fully negate the residual GWP. The bars give the impact of the zero emission systems; the diamonds give original values from figure 10. Arrows show whether there is an increase or decrease.

Another reason for the big increase in the reference is that the reduction in global warming potential that is gained by using DAC is strongly influenced by the energy source used for DAC. As it is assumed that the energy is supplied from within the system, DAC will have a lower effect in the NGCC system. Actually we have a circular connection because adding DAC decreases the environmental impact of the system and that improves the effect of DAC.

Discussion

In the modelling approach we have chosen to conglomerate the hourly data points into daily data points. The reason for this decision is that the research goal was to determine the environmental performance of seasonal energy storage. Balancing of intraday fluctuations would have increased the need for storage, but this is not seasonal storage. Using the daily data however still has its problems, as the intraday fluctuations were now left outside of the life cycle assessment. Therefore the P-X-P systems cannot produce electricity as flexible and dispatchable as the natural gas based system. This reduces the equivalence of the functional unit of the systems and thus the solidity of the results. In future research it is advised to add a separate storage medium in the LCA for intraday fluctuations.

Considering the results of the life cycle assessment it is not possible to appoint a definitive answer to the question what system is most environmentally friendly. The use of seven impact categories has shown that there are trade-offs between the systems. The P-H-P system scores best on al impact categories if compared with the other P-X-P systems, but the difference between the P-X-P systems are very small. The small difference between these systems is due to the background impact of the electricity input that dwarves the difference between the systems. If compared with the CCS system the P-H-P system scores almost 50% lower on global warming potential and scores better on ozone formation, terrestrial acidification and fossil resource scarcity. The CCS system outperforms the P-X-P systems on fine particulate matter formation, marine eutrophication and mineral resource scarcity. Especially the marine eutrophication impact is considerably lower. It was found that the P-X-P values scored very high on this regard due to nitrogen emitted to water during the production of photovoltaic cells.

This research has focused on the environmental impacts of net-zero CO_2 energy systems. An important factor for the implementation of energy storage systems like these is the profitability(Dvorkin et al., 2017). Economics have not been addressed in this report in detail. However, the report has shown that there are indications that the operation of P-X-P systems might face problems in this sense. The extremely low capacity factors for both the electrolyser and the power production module are reasons to believe that the economic profitably might be in jeopardy. The same hurdle was found in the research by Götz et al. (2016), where it is shown that synthetic natural gas cannot be expected to compete with natural gas prices even when the electricity cost is 0 ct/kWh.

The EU commission has stated that its goal is to be a ‘climate neutral society’ in 2050. What makes a society ‘climate neutral’ is debatable, but it could be read as a society that has no global warming potential if it was submitted to an LCA. This would imply that the electricity supply is expected to have zero global warming potential as well. In order to completely get rid of all background emissions in the system under consideration an immense amount of processes need to be altered. In the CCS system it would be necessary to completely eliminate leakage rates during transport and losses during natural gas production. In the P-X-P systems the emissions are spread out over even more different processes, most of which are outside of EU geographical boundaries. It does not seem realistic that the necessary modifications will have been made before 2050, or that they are

even technologically possible. More in depth research is necessary in order to find the possibilities of reducing background emissions.
Battling global warming potential in the background through capturing CO_2 with direct air capture will at least be technologically possible. However, doing it on the scale that would be necessary to completely negate the remaining emissions will bring great costs with it. As there is no monetary profit to be made from capturing CO_2 and storing it underground it would need a lot of government support and tax-payers money. Secondly, we have shown that the reduction in global warming potential would lead all other impact categories in this study to increase. In the P-X-P systems this increase is 11%, whereas the CCS systems impact increased with 21%. A climate neutral society might be possible in the future, but using DAC to reach this goal might harm the environment around us in different ways.

It should be noted that in all systems, as well as DAC in general, a large part of the background impact is the electricity supply. This is in a sense a positive enforcing loop, because reducing emissions in our system leads to cleaner electricity which improves our system again. SimaPro takes this loop into account and thus less direct air capture is needed compared with the situation were the background emissions of the electricity supply would have been kept stable.

A scenario analysis was performed using three different scenarios. These range from a negative (A) to a baseline (B) and to a positive (C) scenario. Figure 28 shows that the results on global warming potential are conclusive in the sense that the P-X-P systems always score better than the CCS system.

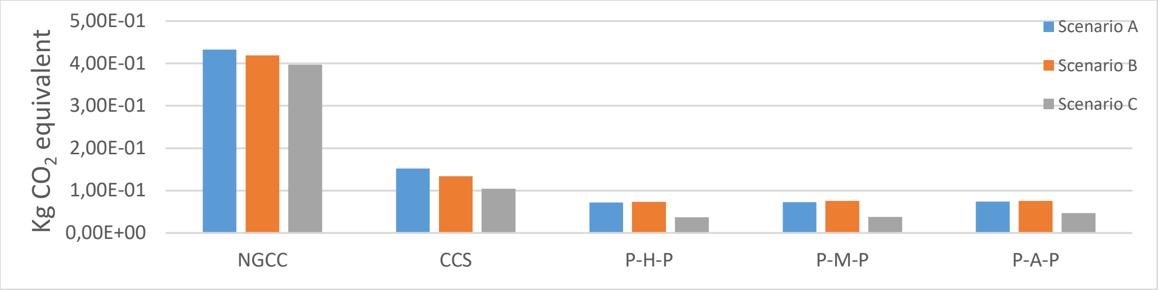

Figure 28: Global warming potential of the systems for the three different scenarios, expressed in kg CO_2 equivalent.

If we look at the data on the fine particulate matter formation in figure 29 the P-X-P seem to score better than the CCS system in scenario C while they are worse in scenario A and B. These differences are however very small and with the uncertainty that is inherent to LCI data it this result cannot be considered conclusive. The graphs of the other five impact categories show equivalent ranges in the scenarios and can be found in Appendix B.

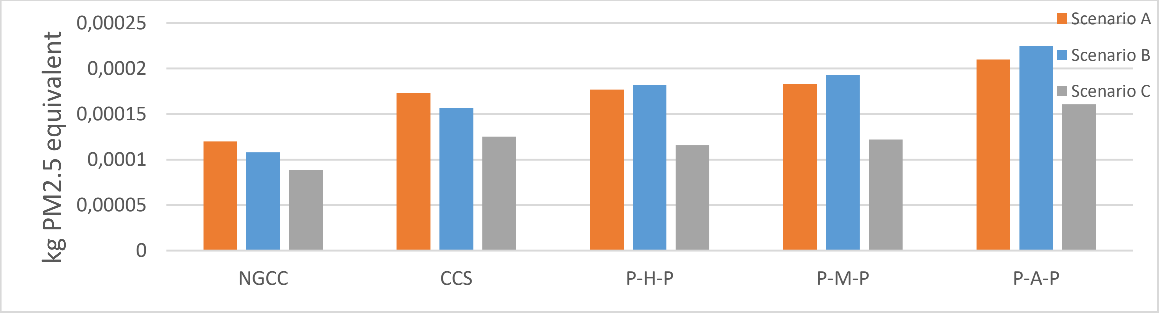

Figure 29: Fine particulate matter formation of the systems for the three different scenarios, expressed in kg PM2.5 equivalent.

A sensitivity analysis was conducted in order to find the system parameters that were most decisive in the LCA results. Figure 30 shows the sensitivity of the global warming potential in the different systems. The CCS system is clearly most sensitive to the background emissions of the natural gas supply. This is not unexpected as we have already seen that a large part of the background emission came from the natural gas supply. The second biggest impact arises from the efficiency of the natural gas combined cycle, as a decrease in this efficiency leads to an increase of natural gas use and brings with it the accompanying emissions.

The P-X-P systems are most sensitive to the environmental impact connected to the electricity supply. As the electricity input was already found to be a big contributor this is not a surprise. It is interesting to see that an increase in the % of iRES stored increases the environmental impact. This is however to be expected as the storage system only increases emissions through losses in the process and an increase in infrastructure.

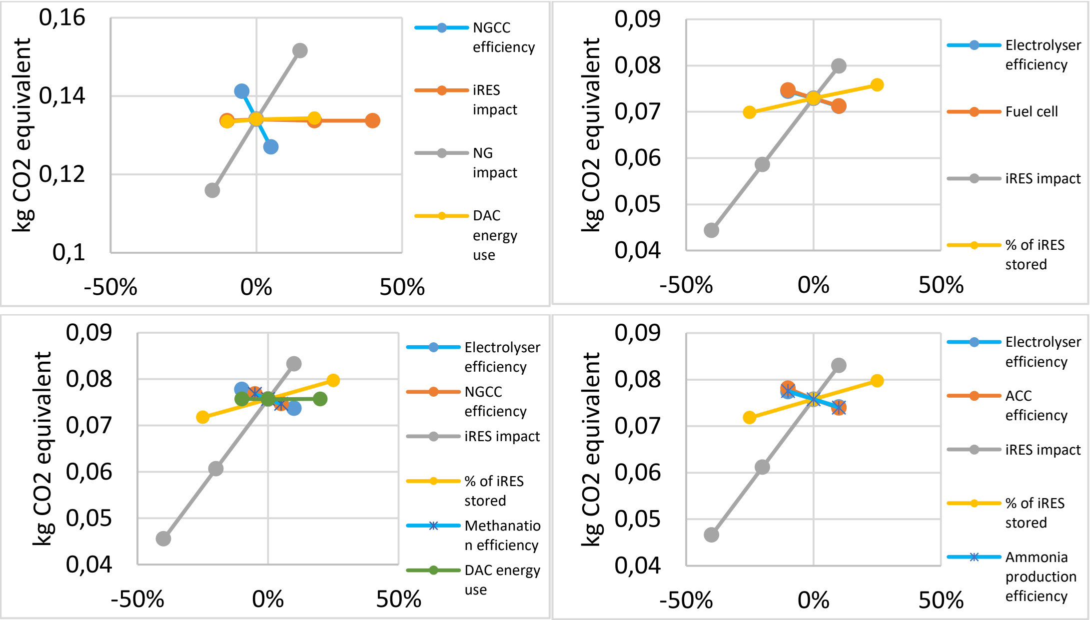

Figure 30: From the top left and clockwise the sensitivity of GWP of the CCS, P-H-P, P-M-P and P-A-P systems to several system parameters.

We have shown the sensitivity of the systems to uncertainties in the input parameters. However, there are also uncertainties that we have not addressed yet. Even if the emissions that result from our systems are 100% correct, there is uncertainty in the impact factor of a certain emission. To illustrate this, the GWP impact factor of methane is 28-36 kg CO_2 equivalent per kilogram of methane. This uncertainty could already impact our results, and the impact factors for GWP are the most researched of all. Uncertainties in the impact factors at other impact categories will be much larger. It is not an easy thing to quantify the impact of an emission to the air on for instance terrestrial acidification and uncertainties will be ever present in these impact factors. This should be always kept in mind when reading or reviewing results from life cycle assessments.

Conclusions

The research has succeeded in designing and modelling three electricity producing systems based on chemical energy storage. Hydrogen, methane and ammonia were assessed as suitable energy carriers in these net-zero CO_2 electricity systems. Using future demand and intermittent renewable supply data the need for seasonal energy storage was quantified. This value was found to be comparable with previous research on electricity storage in 100% renewable electricity systems. These P-X-P systems were then compared in a life cycle assessment to each other and to electricity supplied by a NGCC with CCS and DAC.

Seven different impact categories were used as indicators to compare the environmental performance. The different P-X-P systems mostly had comparable results; this can be explained by noting that the electricity input dominated the overall impact. The P-H-P system was found to outperform the other P-X-P systems on all impact categories, but only by a fraction. In a comparison between the P-X-P systems and the CCS system there was not a single clear winner as several trade-offs were found between. P-X-P systems scored almost 50% lower than the CCS system on global warming potential and scored better on ozone formation and fossil resource scarcity. The CCS system scored better on marine eutrophication and mineral resource scarcity.

Two options towards a system without global warming potential in its entire life cycle, including the background, were assessed. The first option is to abolish the emissions in the background. Most background emissions in the CCS system are connected with natural gas transport and production and are difficult or even impossible to get rid of. The background emissions in the P-X-P are spread over a wide range of processes and include the mining and production of minerals. As minerals are increasingly imported from outside of the EU, mainly China, it would be difficult for the EU to pressure improvements there. The other option is to capture an equal amount of CO_2 from the atmosphere in order to cancel the background emissions. If the systems are equipped with enough DAC to do this it would however lead to an increase in the other impact categories. This demonstrates the importance of using multiple indicators in decision making, as it can show drawbacks of technologies otherwise looked over.

In this research we have shown that P-X-P systems can have a place in future low carbon energy systems, but that it also has its trade-offs and hurdles to overcome. These trade-offs are only visible if decision making is not only focussed on CO_2 emissions but also takes other impacts into account.

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Appendices

Appendix A - LCI data

Hydrogen production from electrolysis, with PEM electrolyser based on work from (Zhang et al., 2017).

Products		
hydrogen, gaseous, 100 bar, from PEM electrolysis	1	Nm3
Technosphere Inputs		
water, deionised, from tap water, at user	1.10E+00	kg
PEM electrolyzer, Balance of Plant	2.53E-11	p
PEM electrolyzer, Operation and Maintenance	1.65E-03	hr
PEM electrolyzer, Stack	6.99E-11	p
PEM electrolyzer, ACDC Converter	2.53E-11	p
diaphragm compressor module, high pressure, at plant	1.51E-08	p
electricity, low voltage	4.75E+00	kWh
Emissions to air		
oxygen	3.53E-01	kg

Direct air capture based on Climeworks data (Wurzbacher & Ag, 2018).

Products		
carbon dioxide, captured from atmosphere	1	kg
Resources		
Carbon dioxide, in air	1.00E+00	kg
Technosphere Inputs		
chemical, organic	3.56E-03	kg
carbon dioxide capture system	1.10E-07	p
Electricity from system	1.13	kWh
Heat pump, 4kW	1.29E-06	p

Direct air capture with waste heat utilisation from methanation

Products		
carbon dioxide, captured from atmosphere	1	kg
Resources		
Carbon dioxide, in air	1.00E+00	kg
Technosphere Inputs		
chemical, organic	3.56E-03	kg
carbon dioxide capture system	1.10E-07	p
Waste heat, from methanation	1.750	kWh
Electricity form system	0.250	kWh

Methane production, based on (Müller, Müller, Teichmann, & Arlt, 2011).

Products		
methane, from thermo-chemical methanation	1	Nm3

waste heat > 90C	7.2	kWh
water	1.606	kg
Technosphere Inputs		
carbon dioxide, from PCC	2.23	kg
carbon dioxide, from DAC	0.118	kg
hydrogen, 100 bar	4.5	Nm3
sabatier reaction methanation unit	6.34E-06	p
Production of Ni-based catalyst for methanation	5.07E-04	kg

Pipeline, supercritical CO$_2$ from (Wildbolz, 2007).

Resources		
Occupation, construction site	3330	m2a
Transformation, from forest	2000	m2
Transformation, to heterogeneous, agricultural	2000	m2
Water, unspecified natural origin/m3	187	M3
Materials/fuels		
Sand, at mine/CH U	4.40E+06	Kg
Diesel, burned in building machine/GLO U	3.31E+06	MJ
Steel, low-alloyed, at plant/RER U	2.70E+05	Kg
Drawing of pipes, steel/RER U	2.70E+05	Kg
Rock wool, packed, at plant/CH U	5119	Kg
Transport, helicopter/GLO U	26	hr
Transport, helicopter, LTO cycle/GLO U	10.4	p
Transport, lorry 32t/RER U	3.15E+05	tkm
Transport, freight, rail/RER U	5.51E+04	tkm
Waste to treatment		
Disposal, inert waste, 5% water, to inert material landfill/CH U	4.40E+06	kg
Disposal, steel, 0% water, to inert material landfill/CH U	1.35E+05	kg
Disposal, mineral wool, to final disposal/CH U	5.12E+03	kg

Transport, pipeline, supercritical CO$_2$

Resources		Unit/km
Pipeline, supercritical CO$_2$	6.34E-09	km
Emissions to air		
Carbon dioxide, fossil	2.60E-04	Kg

Storage, CO2, depleted gas field, 200 km pipeline transport, pipeline from (Wildbolz, 2007)

Resources		Per kg stored
well double, depleted gas field	2.54E-11	p
supercritical CO2, w/o recompression	0.2	tkm

Well double, depleted gas field from (Wildbolz, 2007)

Resources		Per unit
Occupation, industrial area	900	m2a
Occupation, industrial area, vegetation	8100	m2a
Transformation from unknown	600	m2
Transformation, to industrial area	60	m2
Transformation, to industrial area, vegetation	540	m2
Materials/fuels		
drilling, deep borehole for HDR	1.13E+04	m
Cement, unspecified, at plant/CH U	1.26E+05	kg
Gravel, unspecified, at mine/CH U	1.32E+06	kg
Transport, lorry 28t/CH U	2.89E+04	tkm
Transport, freight, rail/CH U	1.26E+04	tkm

Appendix B – Scenario analysis

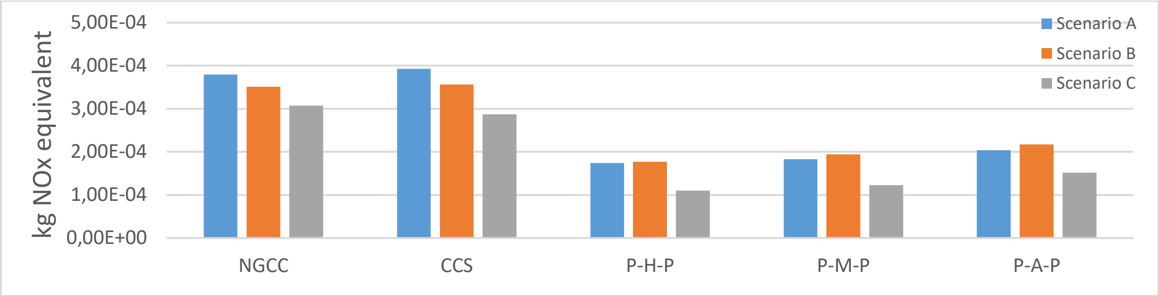

Figure 31: Ozone formation of the systems for the three different scenarios, expressed in kg NOx equivalent.

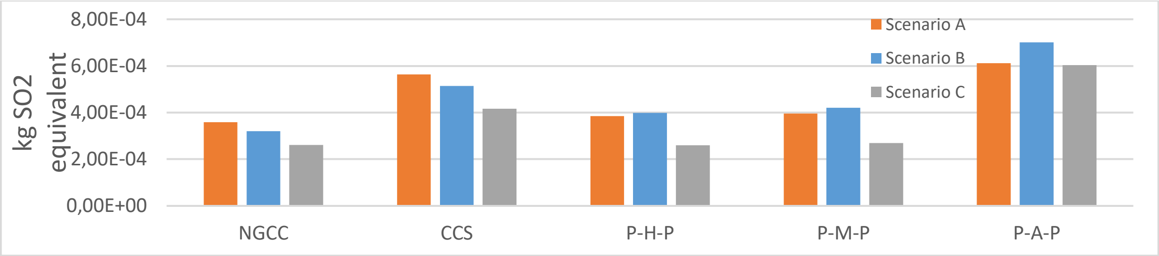

Figure 32: Terrestrial acidification of the systems for the three different scenarios, expressed in kg SO_2 equivalent.

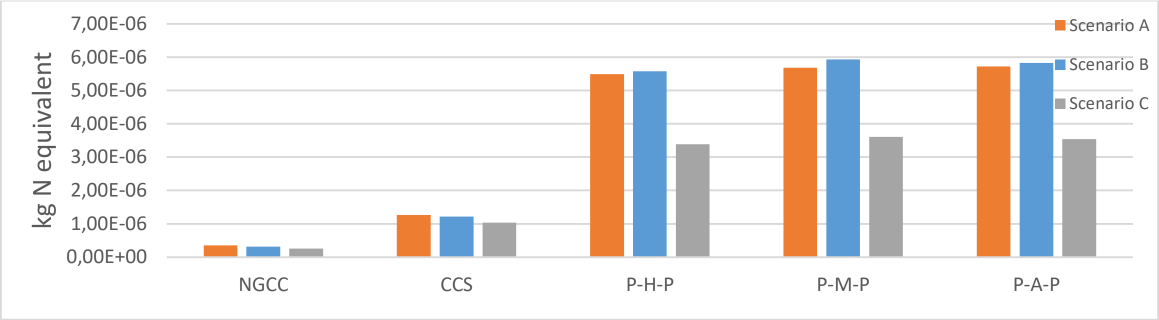

Figure 33: Marine eutrophication of the systems for the three different scenarios, expressed in kg N equivalent.

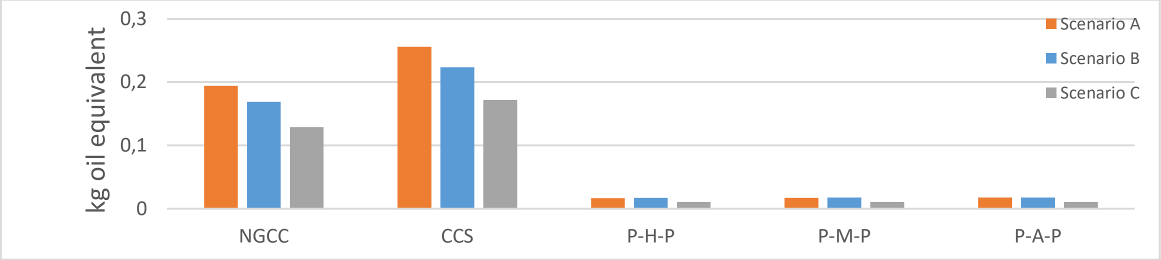

Figure 33: Fossil resource scarcity of the systems for the three different scenarios, expressed in kg oil equivalent.

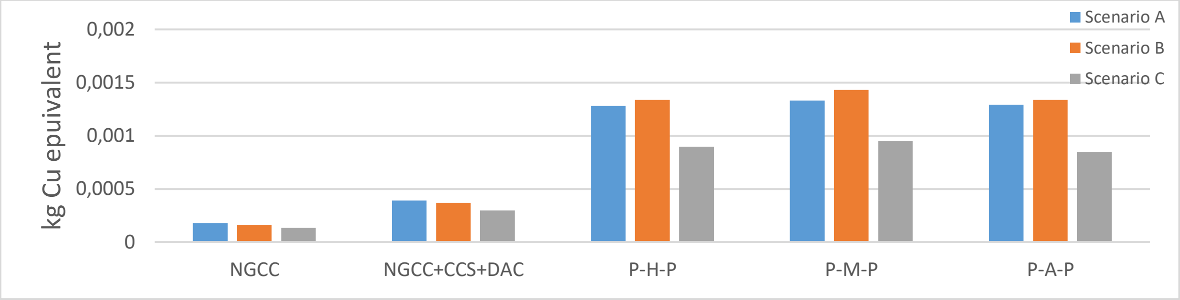

Figure 34: Mineral resource scarcity of the systems for the three different scenarios, expressed in kg Cu equivalent.