Seasonal storage of CO_2 in aquifers

Technical and financial feasibility assessment

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Dit onderzoek is financieel ondersteund door Productschap Tuinbouw en het Ministerie van Landbouw, Natuur en Voedselkwaliteit in het kader van de Kas als Energiebron.

Uw sector investeert in dit project via het Productschap Tuinbouw

25.279/59513/NB
29 september 2011

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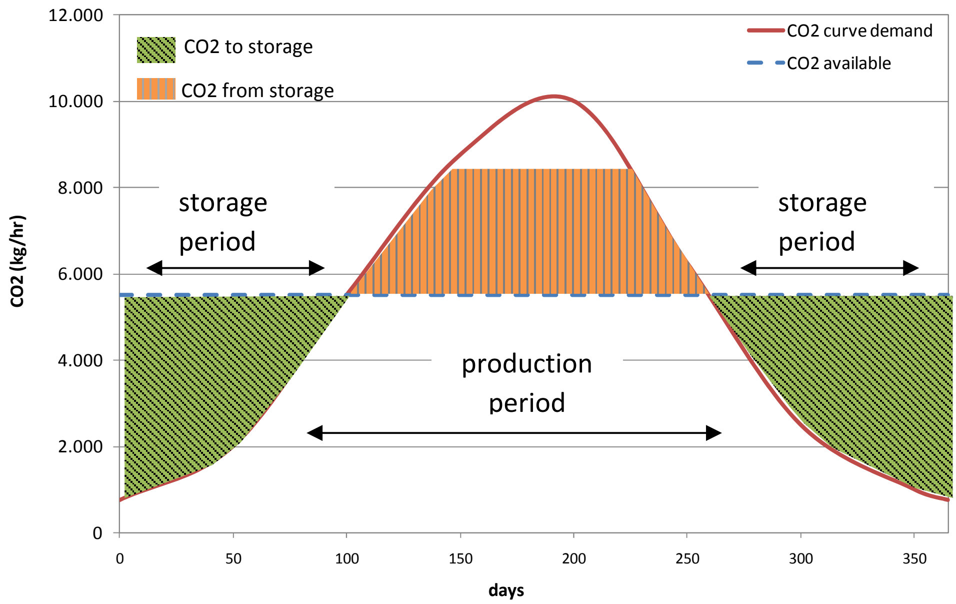
Samenvatting

In opdracht van het Ministerie van Landbouw, Natuur en Voedselkwaliteit en het Productschap Tuinbouw is een studie uitgevoerd naar het tijdelijk opslaan van CO_2 in de ondergrond. Deze studie past binnen het gezamenlijke energieonderzoek binnen het programma Kas als Energiebron. De studie is gebaseerd op de situatie van Lans in Rilland. De locatie van het glastuinbouwgebied is weergegeven in onderstaand Google Earth plaatje.

Op deze locatie wordt een biovergister geplaatst die het gehele jaar CO_2 produceert (50 miljoen kg/j). ‘s Winters is er echter geen vraag naar CO_2 terwijl de vergister ’s zomers niet voldoende CO_2 produceert om aan de vraag te voldoen. Tijdelijke opslag komt dan al snel in beeld. Gezien de grote hoeveelheden die opslagen moeten worden (variërend van 8 tot 20 miljoen kg) lijkt ondergrondse opslag interessant.

In figuur S1 is dit grafisch weergegeven.



Figuur S1 Grafische voorstelling CO_2 opslag en CO_2 productie.

Voor het onderzoek is een geologische inventarisatie uitgevoerd. Uit deze inventarisatie is gebleken dat een geschikte laag op opslag op een diepte tussen 320 en 420 m-mv aanwezig is. Op deze diepte heerst een druk tussen de 320 en 420 bar. Bij deze druk is de CO_2 gasvormig, hetgeen betekent dat de CO_2 als gas in deze laag opgeslagen wordt.

Vervolgens zijn simulaties uitgevoerd om het opslagrendement te bepalen. De berekeningen laten zijn dat een opslagrendement tussen 70 en 80% haalbaar is. Het opslagrendement is afhankelijk van de grootte van de opslag, de eigenschappen van de opslaglaag en de eigenschappen van de CO_2. Tevens blijkt uit de berekeningen dat de CO_2 nauwelijks beïnvloed wordt door de in de bodem en grondwater aanwezige stoffen. Het belangrijkste effect dat optreedt is dat het waterdampgehalte toeneemt van minder dan 100 ppm tot 1.000 ppm. Droging van de CO_2 na opslag is hierdoor noodzakelijk.

Op basis van de modelresultaten is een financiële analyse uitgevoerd. Deze analyse is uitgevoerd voor een tweetal situaties, zie tabel S1.

Tabel S1 Scenario's 50 ha en 75 ha

Onderdeel	**Eenheid**	**50 ha**	**75 ha**
Hoeveelheid beschikbaar	kg/h	5.500	5.500
Laad periode	dagen	200	150
Hoeveelheid op te slaan	kg	$21{,}6 \times 10^6$	$8{,}1 \times 10^6$
Productie periode	dagen	165	215
Max. hoeveelheid uit opslag	kg/h	4.360	1.250
Aantal benodigde bronnen	stuks	4	1
(gebaseerd op een debiet van 1.200 kg/h)			

Voor deze situaties zijn de volgende scenario's uitgewerkt:
1) Opslag zonder zuivering (afschrijving over 15 jaar)
2) Opslag zonder zuivering (afschrijving over 30 jaar)
3) Opslag met zuivering (afschrijving over 15 jaar)
4) Opslag met zuivering (afschrijving over 30 jaar)

De volgende uitgangspunten zijn gehanteerd voor de financiële analyse:
- Onderhoud en beheer bronnen 1,7% van de investering
- Beheer en onderhoud zuivering 5% van de investering
- Kosten zuivering 20 €/ton opgeslagen CO_2
- Rente 6%
- Elektra 0,06 €/kWh

Tabel S2 Investeringen en kosten per jaar

Scenario	Investering [M€]	Exploitatie [k€]	Rentelast 15 jaar [k€]	Rentelast 30 jaar [k€]
50 ha zonder zuivering	1,79	56	185	130
75 ha zonder zuivering	1,15	29	118	83
50 ha met zuivering	2,29	435	236	167
75 ha met zuivering	1,65	192	170	120

Tabel S3 Kostprijs opgeslagen CO_2 [€/kg]

Scenario	50 ha	75 ha
15 jaar zonder zuivering	0,01	0,02
30 jaar met zuivering	0,01	0,02
15 jaar zonder zuivering	0,04	0,06
30 jaar met zuivering	0,03	0,05

Bij de kostprijsberekening is ervan uit gegaan dat er niet betaalt hoeft te worden voor de CO_2 die opgeslagen wordt. Indien deze CO_2 wel een economische waarde vertegenwoordigt, verandert de kostprijs. Een deel van de opgeslagen CO_2 blijft immers achter in de bodem.

Conclusies en aanbevelingen

Uit de uitgevoerde studie blijkt dat het tijdelijk opslaan van CO_2 in de ondergrond technisch zeer goed mogelijk is. Ook laten de modelresultaten zien dat een hoog opslagrendement haalbaar is. De kostprijs van een ton opgeslagen CO_2 kan concurreren met de kostprijs van een ton CO_2 van de OCAP. Hierbij moet wel opgemerkt worden dat bij het berekenen van de kostprijs van een eenheid opgeslagen CO_2 ervan uitgegaan is dat er niet betaald hoeft te worden voor de CO_2 die opgeslagen wordt.

De resultaten van de studie zijn dusdanig positief dat vervolgonderzoek naar de mogelijkheden van het tijdelijk opslaan van CO_2 in de ondergrond zin vol is.

Het vervolgonderzoek zou zich moeten richten op:

Contaminatie van de opgeslagen CO_2 met in de bodemaanwezige stoffen.
In het voorloggende onderzoek is met name gefocust op opslagrendementen en de technische haalbaarheid. De chemie is in de studie nog onderbelicht. Het wordt derhalve aanbevolen om een uitgebreide modelstudie uit te voeren om vast te stellen in hoeverre de CO_2 beïnvloed wordt door in de bodem aanwezige stoffen. Stoffen die hierbij een belangrijke rol spelen zijn: stikstof, methaan en waterstof.

Nader uitzoeken of zuivering noodzakelijk is.
Nadat de hier voorgaande stap uitgevoerd is, kan een betere inschatting gemaakt worden of zuivering van de opgeslagen CO_2 noodzakelijk, hoe deze eruitziet en wat het kost. De kwaliteit van de benodigde CO_2 zal in overleg met de eindgebruiker bepaald moeten worden.

Punten waarop in een vervolg nader aandacht aan geschonken moet worden zijn:

- Meest ideale (economisch en technisch) manier van zuiveren.
- Noodzaak droging van CO_2.
- Levensduur van de putten door de aantasting van de materialen door het CO_2.
- Verspreiding van de achtergebleven CO_2 in de bodem en gevolgen hiervan.
- Voor CO_2 opslag is een goed afsluitende (klei)laag noodzakelijk. Dit is een onderzoek dat locatie specifiek uitgezocht moet worden hoe afsluitend de aanwezige kleilagen zijn.
- Ontwerp van de bovengrondse infrastructuur.
- Optimalisatie putconfiguratie en putontwerp. Dit zodat hogere opslagrendementen haalbaar zijn en met minder putten volstaan kan worden.

Opslag rookgassen WKK

In deze studie is alleen gekeken naar de opslag van CO_2 uit een vergistinginstallatie. Deze CO_2 is zeer zuiver. Veel tuinders hebben echter niet de beschikking over CO_2 vanuit een dergelijke installatie. Voor hen is het wellicht interessanter om de CO_2 vanuit de wkk op te slaan. Uit een aantal oriënteerden gesprekken met tuinders blijkt dat dit inderdaad het geval is. Zij kunnen de wkk dan sturen op warmtevraag en het overschot aan CO_2 opslaan en deze op een ander moment gebruiken.

Het nadeel van de rookgassen uit een wkk is dat deze niet alleen uit CO_2 bestaan, maar dat er ook veel andere componenten in zitten. Het ongezuiverd opslaan van deze rookgassen kost veel energie (geld). Deze rookgassen zullen dus eerst gezuiverd moeten worden voordat ze opgeslagen worden. Deze zuivering kost echter ook geld. Er zijn reeds veel studies uitgevoerd naar het afvangen van CO_2 uit rookgassen. Dit betekent dat de technieken en de kosten redelijk inzichtelijk zijn. Onderhavige studie geeft inzicht in het opslagrendement en de kosten hiervan. Voor veel tuinders is het interessant om dit eens verder uit te werken. De beste aanpak is het uitwerken van een business case op basis van de beschikbare onderzoeken aangevuld met vraag een aanbod patroon (warmte, elektra en CO_2) van een tuinder.

1 Introduction

CO_2 is an essential nutrient for the crops grow. It has been shown that if the concentration of CO_2 is increased inside the greenhouse the growth and hence crop production is also substantially increased. However, the amount of CO_2 required is not constant throughout the year but varies seasonally. In the winter, when the days are shorter and less light is available, the crops will require also less CO_2 to grow. Whilst in the summer, when the days are longer and more light is available, the crops will grow faster if more CO_2 is supplied. The CO_2 demand in the greenhouses hence is low during the winter months and high during the summer months.

Greenhouse owners rely therefore on an external supply of CO_2. At Rilland, this supply comes from the flue gases produced in the CHP (combined heat and power) plant and boilers, and by the OCAP-piping line which delivers CO_2 coming from a Shell refinery located in the area around Botlek.

At present, the production of electricity and heat by the CHP plant is constant all year long and hence also the CO_2 gas production. However, during peak periods (summer months) the CO_2 produced is not currently enough to meet the demand whilst during the winter months there is surplus of CO_2. In addition to this seasonal variability, the CO_2 delivered by the OCAP-pipe may be sometimes shut down and leaving the greenhouses without CO_2. The consequences of such can be very damaging for the crops.

One possible solution to the CO_2 shortage is the temporal storage (buffering) of the CO_2 surplus that exist during the winter period for later re-use in the summer. Storage will take place in local aquifers and can therefore reduce the dependency from external CO_2 supply.

1.1 Main objectives

This project investigates the feasibility of seasonal CO_2 storage in local aquifers. The focus will be to store the CO_2 in aquifer layers occurring within the first 500 m. Following a geological inventory, the potential storage aquifers are selected and a site-specific numerical model is built. Based on the specifications at the Green Port, the behaviour of CO_2 in the aquifers is investigated and the storage efficiency is determined. Based on the results of the numerical study, a financial analysis will be carried out to assess the feasibility of applying seasonal storage at Rilland.

2 The Green Port in Rilland

The Groen Port (Green Port) in Rilland is a development cooperation between the greenhouse enterprise Lans B.V. and various other agricultural entrepreneurs. At the Green Port, three installations are being considered: a bio-ethanol installation, a biogas installation (digester) and a water purification installation. The biogas produced will be 'cleaned' from components such as siloxenes and sulphur acid and then supplied to the existing CHP (combined heat and power) plant of Lans or sold to the gas net.

A further step is planned which consists of upgrading the cleaned biogas to Green Gas (gas of similar quality as natural gas). This upgrading process increases the methane concentration by separating the CO_2 contained in the biogas. This CO_2 comes out as a free by-product of the upgrading process. Depending on the upgrading technique used (i.e. gas cleaning, cryogen) the amount and physical properties (i.e. gas or liquid form) of the CO_2 will differ. However, and for either case, it is expected that the purity of the extracted CO_2 stream is of good enough quality for its direct transport and use in the greenhouses.

2.1 Specifications Green Port

The table below summarizes the potential production of CO_2 from biogas in kilo's. This is based on the assumption that 1,55 kg of CO_2 can be extracted for each m³ of biogas.

Table 2.1 Extraction of CO_2 from biogas

*	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec
Biogas*	2.625	2.625	2.625	2.625	2.625	2.625	2.625	2.625	2.625	2.625	2.625	2.625
CO_2 *	4.069	4.069	4.069	4.069	4.069	4.069	4.069	4.069	4.069	4.069	4.069	4.069

*Biogas given in m³ and CO_2 production in kg (x1000)

The total amount of produced biogas is approximately 31.500.000 m³/a from which 48.825.000 kg/a of CO_2 can be potentially extracted.

2.2 Project location

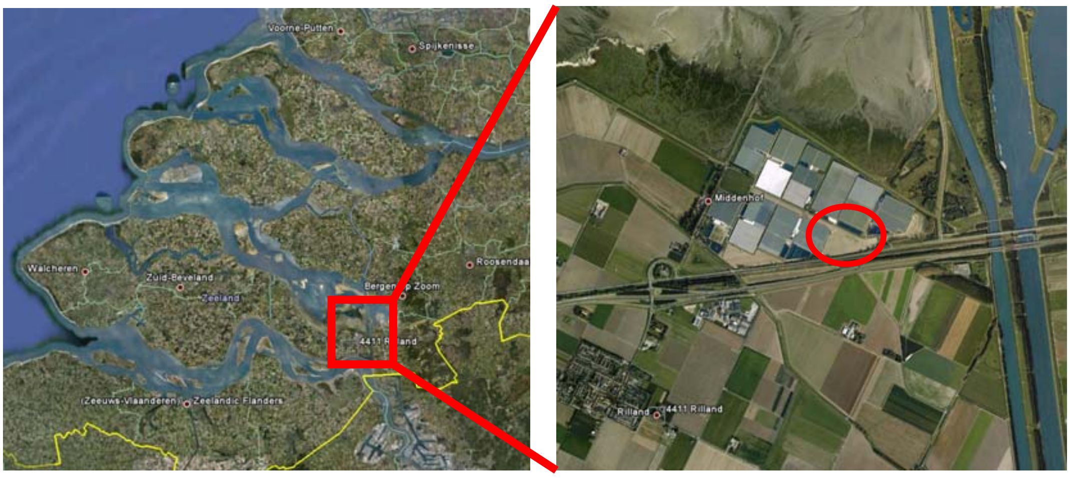


Figure 2.1 Aerial view of the project location and the Green Port in Rilland.

2.3 Geology

As above mentioned, the focus is to store CO_2 in the shallow aquifers occurring within the first 500 m. The estimated geological sequence at Rilland of the first 500 m is summarized in Table 2.1.The geological information was interpreted from:

- Well logs of boreholes located in the vicinity of Rilland. Obtained from the NLOG Oil and Gas Portal.
- Geological Atlas of the Subsurface of the Netherlands, maps sheets XII and XIII.

Two potential aquifers are selected: the aquifers the Ruisbroek sands, part of the Vessem Member and the Brussels Sands Member. Both aquifers are moderately permeable and are confined by thick layers of poorly permeable clay (the Rupel Clay and the Asse Member respectively), making them suitable as storage aquifers. An aquifer is suitable for storage if the permeability is not too high (< 15 m/d) and if there is a sealing (clay) layer on top. Aquifers with these properties can be found almost everywhere in the Netherlands. The thickness and depth of these aquifers will off course vary from location to location.

Table 2.1 Expected geology at Rilland

Depth [m-bgl]*	Formation	Geohydrology
0-40	Quaternary	aquifer /aquitards
40-80	Oosterhout	aquifer
80-120	Breda	confining layer
120- 200	Rupel clay (Boom clay)	confining layer
200-250	Vessem Member	aquifer/aquitard
250-320	Asse Member	confining layer
320-420	Brussels sand member	aquifer
420-470	Ieper Member	confining layer

* metres below ground level.

The Vessem Member is further subdivided into three different formations, from top to bottom the Ruisbroek Sand, Watervliet Clay and Bassevelde Sands. The Ruiskbroek Sands aquifer is located right below the Rupper Clay will be the choice of aquifer for this formation.

3 Numerical modelling

Numerical simulations are carried out with the purpose of investigating the behaviour of CO_2 during and after injection in the aquifer and the effects on the recovery efficiency. Some simplifications of the real system are introduced. However the CO_2 injection rates, system geometry and physical properties will correspond to those expected at Rilland.

3.1 Methodology

Numerical simulations are performed with the multiphase, multicomponent fluid and heat flow code TOUGH2 V2 [2] in combination with the fluid property module ECO2N. This property module describes the thermodynamic and thermo-physical properties of the H_2O-NaCl-CO_2 system [3]. The following processes are studied:
- Gravity-driven advection in respond to strong vertical and lateral density gradients as result of injection of CO_2 into a saline aquifer.
- Density, viscosity and solubility formulations of water and CO_2 as a function of pressure and temperature changes.
- The reactive chemistry assumed is dissolution of gaseous CO_2 in the formation water (aqueous phase) and dissolution of water into the CO_2 gas stream (equilibrium partitioning).
- Precipitation and dissolution of salt (NaCl).
- Processes are modelled isothermally.
- Chemical interactions with the formation minerals are not taken into account in the present simulations.

The current capabilities of the ECO2N module and the TOUGH2 simulator make possible modelling of the behaviour of CO_2 under sub- and super-critical conditions. However, under sub-critical conditions, the model has no provisions to treat separate liquid and/or gas CO_2 phases or transitions between them, should these occur. At sub-critical conditions, a gas-only phase will be modelled.

3.2 Problem definition and model geometry

A two-dimensional radial-vertical geometry (2-D R-Z) was chosen with radial extent of 10.000 m to ensure an infinite-acting system. The simulated time period is of 5 years. A refined grid is applied in regions where the gradients would be significant (i.e. near the well) with coarser gridding further away from the injection/extraction points. The aquifer system is assumed homogeneous with no-flow boundaries representing impermeable upper and lower layers. Injection and extraction take place in the first left-hand side block, with the injection well screen located in the lower-half of the aquifer and the extraction well screen located in the upper-half (see Figure 3.1). This injection/extraction configuration is desired due to the expected CO_2 buoyancy during the injection cycles.

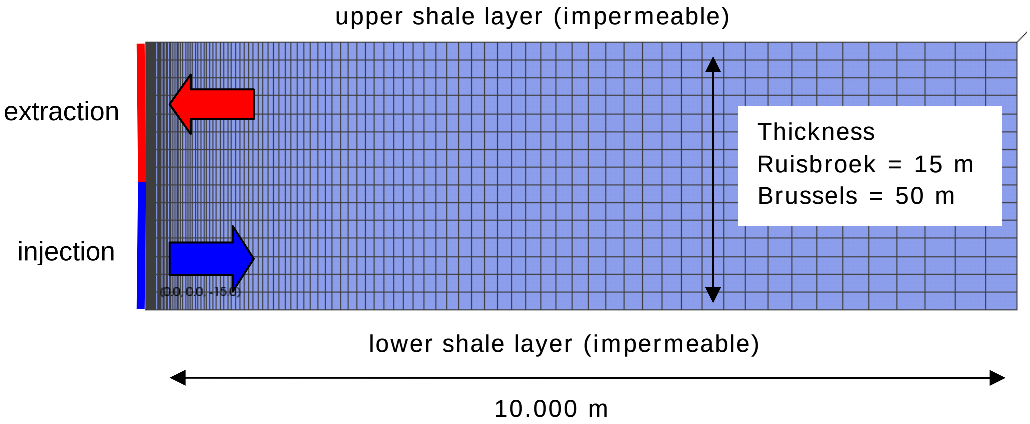


Figure 3.1 Schematic representation and model grid.

Model initial and boundary conditions
Table 3.1 summarises the intial conditions for the Ruisbroek Sands and Brussels Sands models respectively. The physical properties and composition of the aquifer water were taken from [1]. Pressure distribution is initially hydrostatic and will be fixed at the far-right end of the model allowing flow in and out of the model and avoiding over pressuring of the aquifer. All the simulations are carried out isothermally (i.e. CO_2 temperature is similar to the aquifer temperature) and for a period of 5 years total.

The boundary conditions for the injection and production wells are set to constant rate and both set to 5.500 kg/hr (~1,53 kg/s)

Table 3.1 Characteristics of selected storage aquifers and initial conditions

Parameter	**Ruisbroek Sand (Vessem member)**	**Brussels Sand**
depth to top [mbgl]	200	320
thickness [m]	15	50
permeability [mD]	400	900
porosity [-]	0.25	0.25
initial pressure [bar]	20	35
initial temperature [°C]	18	23
salt content [mg/l]	0.07	0.1
CO_2 injection/extraction rate [kg/hr]	5.500	5.500

The storage/production scheme consists of 4 cycles a year, 3 months of CO_2 storage, a rest period, 3 months of extraction and 3 months of rest period.

CO_2 phase conditions
Figure 3.2 shows the CO_2 phase diagram. Based on the temperature and pressure at which CO_2 will be injected, sub-critical conditions and gas phase will prevail.

As mentioned in section 3.1, the current model capabilities allow to model sub-critical CO_2 conditions but no distinctions can be made between liquid or gas phases (and transitions) during the modelling. This implies that the model considers all sub-critical CO_2 as a single, gas-only phase. Figure 3.2 also shows that for the range of expected working conditions CO_2 will stay in the gas phase and the assumption of modelling a gaseous phase will apply and the results will be representative of a gaseous phase.

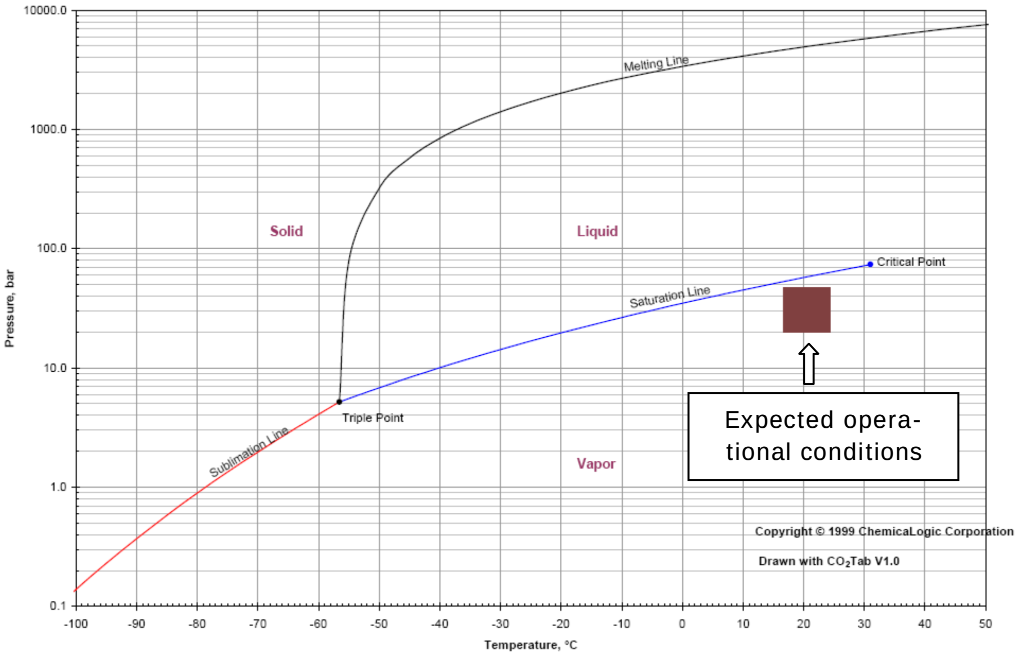


Figure 3.2 Carbon dioxide temperature-pressure diagram showing the expected range of operational conditions for seasonal CO_2 storage at Rilland.
[Modified from http://www.chemicalogic.com]

4 Results

Modelling results are shown below for the two models reported in Section 3.3

4.1 CO_2 behaviour in the aquifer

The behavior of CO_2 in the aquifer is controlled by a complex interaction between two-phase flow dynamics (CO_2 gas phase + H_2O liquid phase), density effects (CO_2 is less dense than water and tend to be very buoyant) and mutual dissolution of CO_2 and H_2O (CO_2 dissolving into the liquid phase and H_2O evaporating into the CO_2 gas stream) which is also dependent on the salinity content of the aquifer water. A fraction of the of the CO_2 will remain in the aquifer in residual form and due to hysteresis phenomena (due to reversibility of the flow as result of injection/extraction cycles). Calculations show that approximately 10% of the CO_2 stream may not be recovered due to these two processes.

In addition to these 'losses', a small portion of CO_2 will dissolve in the aquifer water. The total amount depends on the prevailing temperature and pressures. For the range of working conditions used here, about 2% of CO_2 will be lost due to dissolution. Therefore, a cumulative irrecoverable CO_2 during seasonal storage is expected to be between 10 and 20%.

4.2 Ruisbroek Sands Model

Figure 4.1 depicts the pressure evolution in the injection and extraction wells for the Ruisbroek Sands model.

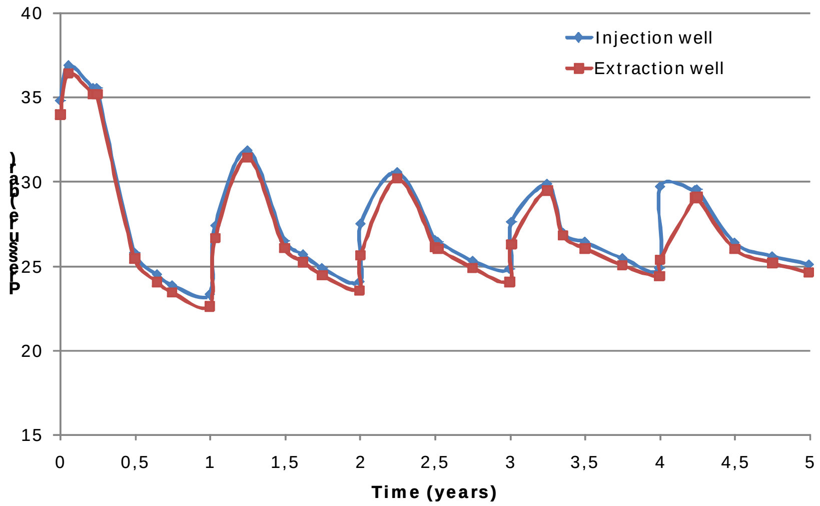


Figure 4.1 Pressure response in the injection and extraction wells for the Ruisbroek Sands model.

Startup injection of CO_2 causes pressure to rise initially. The response trend is similar in both wells but slightly lower in magnitude for the extraction block. This is because the aquifer has a relatively small thickness and the pressure field will quickly distribute equally across the injection/extraction blocks. Pressures decline with time and reach quasi-stable values after a period of 4 storage cycles. The lowering in pressure is related to an increase in the CO_2 saturation (gas saturation) which reduces the initial aquifer permeability (liquid permeability) and increases the gas permeability as more water is displaced further away from the well blocks.

Figure 4.2 shows the gas saturation distribution at the end of year 5 during storage (top panel) and extraction (bottom panel). Close to the wells, the CO_2 gas plume is distributed almost through the entire thickness of the aquifer. However, due to its lower density compared to water, it is more bouyant and tends to saty below the upper confining layer. This behaviour favours production to take place in the upper half of the aquifer. The extendt of the CO_2 plume after 5 years of operation has reached almost 1 km away from the injection point.

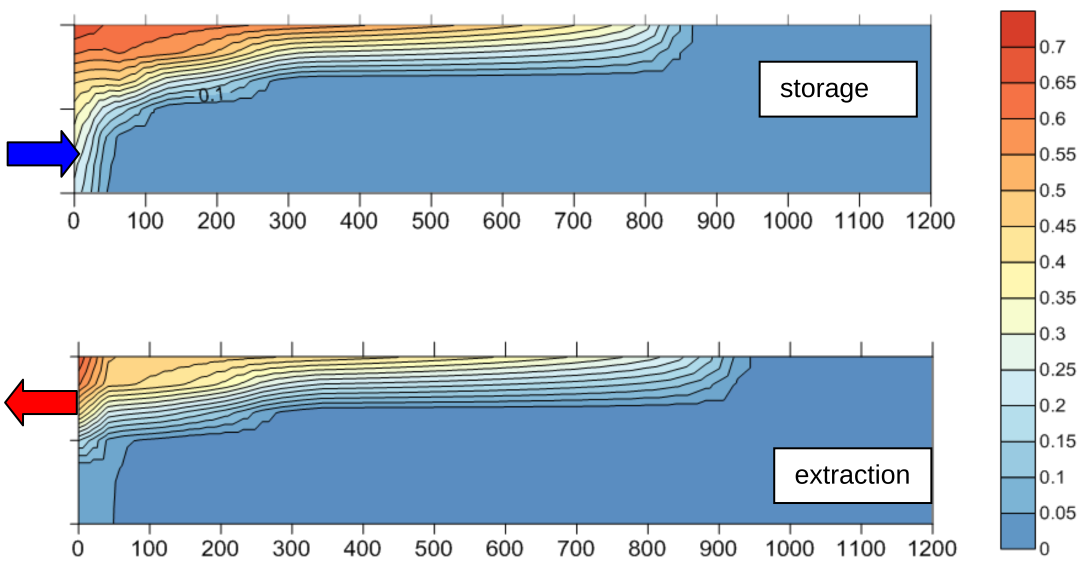


Figure 4.2 CO_2 distribution in the Ruisbroek Sands model at the end of year 5.

CO_2 properties and optimised extraction rate

Table 4.1 outlines the average properties of CO_2 at the injection and extraction well. During extraction, there is a lowering in the pressure which reduces the CO_2 density by approximately 40% compared to the initial density at which CO_2 enters the aquifer. If the extraction rate is kept constant (in volume) the amount of CO_2 (in mass) will be reduced.

The calculated extraction rate listed in table 4.1 corresponds to the extraction rate at which the production well can work extracting a 'gas-only' phase. In practice, higher extraction rates will be possible but may warrant the extraction of two fluids, water and gaseous CO_2.
It is noted that the optimised rate reported here is obtained after 4 periods of injection/extraction cycles and a somewhat larger rate may be possible after a langer number of storage/extraction cycles.

Assuming that about 12% of the CO_2 that is stored in the aquifer is irrecoverable, and considering a feasible extraction rate of 300 kg/hr, the total number of needed extraction wells will be 16 to produced the stored CO_2

Table 4.1 CO_2 properties for Ruisbroek Sands aquifer

Storage (CO_2 gas)	Extraction (CO_2 gas)
Dry CO_2	'wet' CO_2 (<0,1 % H_20)
T = 18°C (isothermal)	T = 18°C (isothermal)
P = 30 bar	P = 25 bar
Density = 90 kg/m³	Density = 55 kg/m³
Injection rate = 5.500 kg/hr	Extraction rate = 300 kg/hr
1 injection well	16 production wells

4.3 Brussels Sands Model

The pressure responsed obtained for the Brussels Sands model is shown in Figure 4.3. Both injection and extraction wells, respond qualitatively the same. Pressures decline slighlty with time and reach quasi steady values after a period of 3 storage/extraction cycles. However, the thickness of the aquifer is greater compared to the Ruiskbroek Sands model and the CO_2 distribution in the aquifer will concentrate in the upper meters of the formation (Figure 4.4).

The average pressure in the extraction well is lower than the pressure in the injection well. Although the plume rises and reaches the production well, it is not equally distributed across the whole extraction lenght. The upper part of the extraction well has a higher gas saturation and consequentely a lower pressure (due to a higher gas permeability) whereas the bottom part of the extraction well exhibits a higher pressure. In the injection well, the gas saturation is almost the same across the injection lenght.

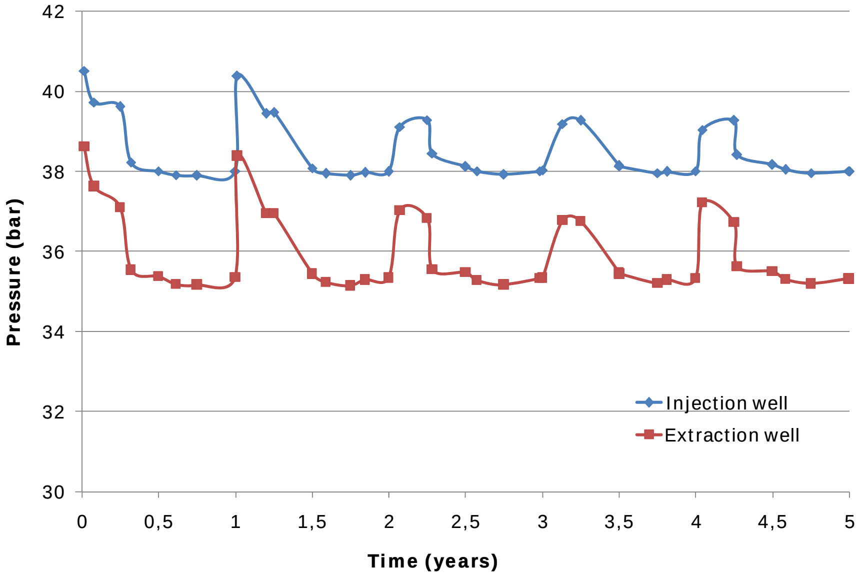


Figure 4.3 Pressure response in the injection and extraction wells for the Brussels Sands model.

A thicker aquifer (and higher permeability) favours the buoyancy effects of the CO_2 plume and therefore limits the vertical extend, concentrating must of the plume below the upper confining layer. Compared to the Ruisbroek model, and considering that the same amount of CO_2 has been injected after 5 years, the CO_2 plume in the Brussels Sand model is somewhat shorter laterally.

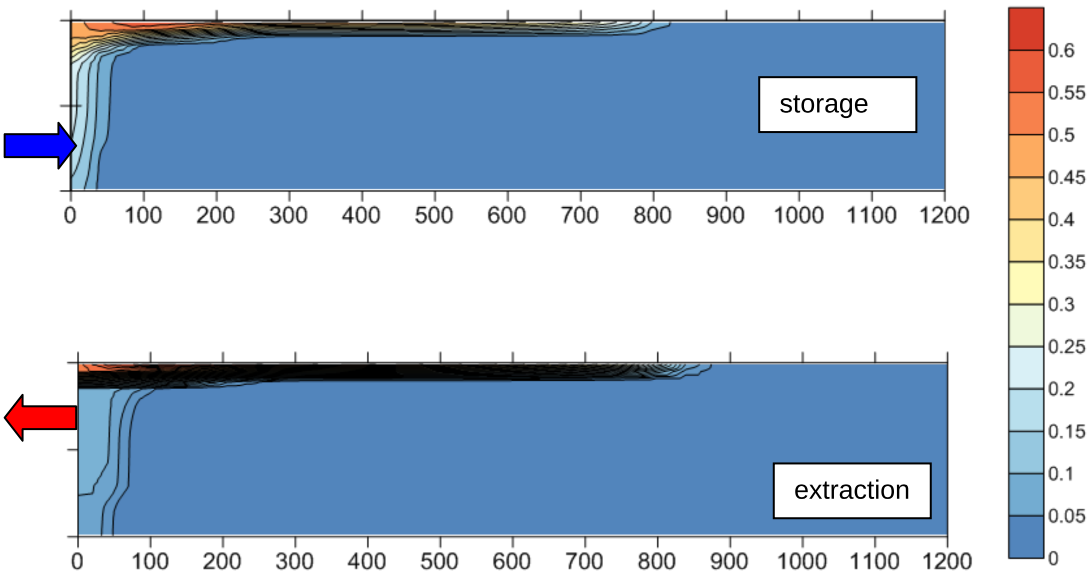


Figure 4.4 CO_2 distribution in the Brussels Sands model at the end of year 5.

CO_2 properties and calculated extraction rate

Table 4.2 outlines the average properties of CO_2 at the injection and extraction well. . Similar to what is observed for the Ruisbroek Sands model, a lowering in the pressure during production reduces the CO_2 density. However, for the range of conditions (pressure and temperature) in the Brussels Sands aquifer, changes in CO_2 density are not so significant and around 15% compared to the initial values. The amount of CO_2 (in mass) that can be extracted at a constant rate (in volume) is nevertheless reduced.r

The calculated extraction rate for the production well is lower than the injection well. The optimised value (listed in table 4.2) corresponds to the extraction rate at which a'gas-only' phase will be produced. Taking into account that 12% of the CO_2 that is injected (at a rate of 5.500 kg/h) cannot be recovered, and considering an optimsed extraction rate of 1.200 kg/hr, the total number of extraction wells will be 4 to produced the stored CO_2.

Table 4.2 CO_2 properties for Brussels Sands aquifer

Storage (CO_2 gas)	Extraction (CO_2 gas)
Dry CO_2	'wet' CO_2 (<0,1 % H_20)
T = 23°C (isothermal)	T = 23°C (isothermal)
P = 40 bar	P = 35 bar
Density = 95 kg/m³	Density = 80 kg/m³
Injection rate = 5.500 kg/hr	Extraction rate = 1.200 kg/hr
1 injection well	4 production wells

Current limitations
The present simulations consider the interaction of a three-components system CO_2-H_2O-NaCl. In a real system, other components such as CH_4 and H_2S may be present in the gas stream and/or in the aquifer water and could alter the chemical composition of the extracted CO_2. At this moment it is not known how large the impact on the chemical composition of the groundwater will be. The chemical effects where beyond the scope of this study. In a next phase more attention should be paid on these chemical effects.

4.4 Reliability of the model results

A model is always a simplification of the reality. Not all the processes that occur can be taken into account and also not all the properties of the underground are exactly known. The performed model study is based on all the data that is available and also are all the relations used in the model verified by measurements. However the in this study performed calculations are the first for this kind of storage. The results couldn't therefore be compared with real measured data because at the moment no seasonal CO_2 storage systems exists. The feeling is that the calculations give a good representation of what will happen. But how accurate they are cannot be quantified at this moment. A field test is necessary to calibrate the model.

5 Technical feasibility

The technical feasibility of seasonal CO_2 storage in shallow aquifers has been investigated with a numerical study. Based on the geological conditions at Rilland, two aquifer layers were selected as suitable for storage. These are the aquifers of the Vessem and Brussels Member. Both are located within the first 500 m and are overlain by a thick confining layer.

Some of the main findings are listed below:
- For the operational conditions assumed in the present study, CO_2 stays in the gas form (during injection and extraction) which would allows direct use in the greenhouses after extraction.
- CO_2 is very buoyant in the aquifer and therefore extraction wells should be located in the upper part of the aquifer.
- A portion equivalent to 10 - 20% of the stored CO_2 may be irrecoverable due to residual saturation and hysteresis phenomena and CO_2 dissolution in the aquifer water.
- Only a small percentage (> 0,1%) of water evaporates into the CO_2 stream.
- For the injection rates here considered (1,5 kg/s) it is possible to use only 1 injection well. However, results show that the extraction rate at which a gas-only stream is produced, will be lower and limited by the aquifer and CO_2 initial conditions. In practice, higher extraction rates may be imposed in the production well. However, the extracted fluid may be a combination of water and CO_2 and may not necessarily increases the amount of CO_2 that can be extracted.
- Deeper aquifers (i.e. Brussels Sands) seem to favor higher extraction rates (per well) due to more favorable ranges in the CO_2 physical properties.

5.1 Future considerations

The results presented here, make a number of simplifying assumptions with respect to the processes influencing the CO_2 behavior during seasonal storage. In addition, the storage/extraction scheme was set to 4 annual cycles (1 storage period, 2 rest periods and 1 production period) using one injection and one production well configuration. Consideration of the following processes may lead to a more accurate prediction of the CO_2 performance and an optimized storage efficiency:
- Include non-isothermal and geochemical processes.
- Optimisation of injection/extraction schemes and well configuration (e.g. longer injection screens, smaller extraction screens).

6 Financial Analysis

To determined if seasonal CO_2 storage is financially an interesting option at Rilland, a financial analysis is carried out using the results from the Brussels Sands model. The costs of the main system components are taken into account in order to determine the cost-price per kg of CO_2 coming from the storage. As shown in previous section, the storage variant will provide the possibility of not only delivering more CO_2 but also the investments costs per CO_2 amount may be reduced. Figure 6.1 shows the schematic principle of seasonal storage at Rilland. The need of the intermediate purification step is related to the possibility of other gases (naturally existing in groundwater or coming out from the biogas) may be present in the produced CO_2. This topic remains an uncertainty as it was not investigated in this study but will be considered for the financial analysis.

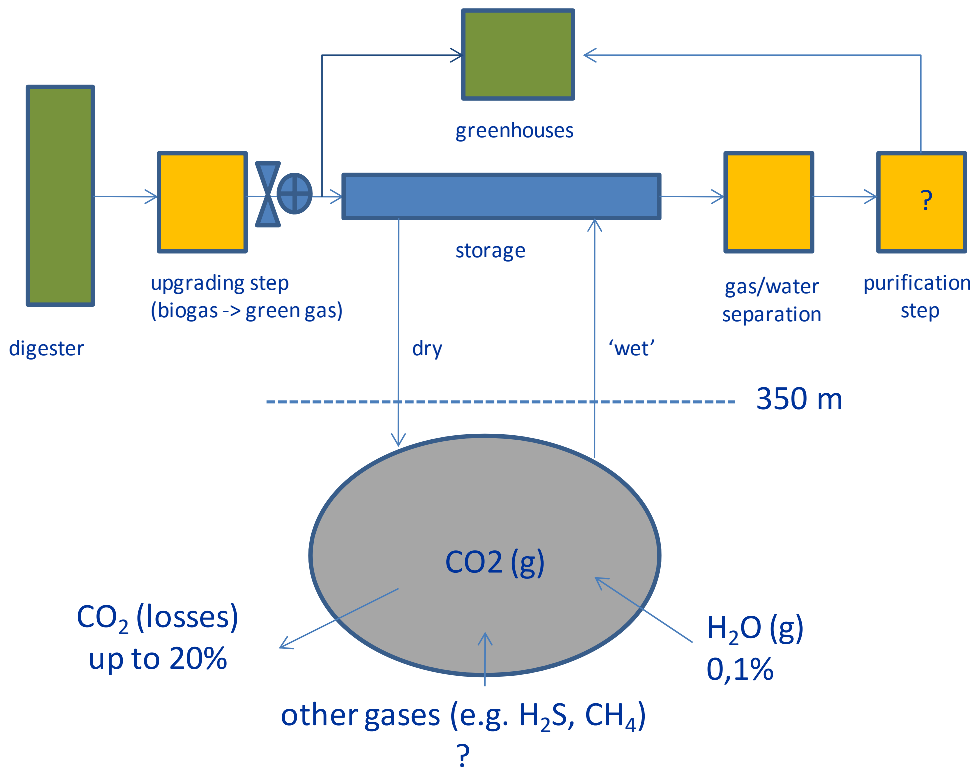


Figure 6.1 Schematic principle of seasonal storage at Rilland.

6.1 CO_2 demand and supply

TheCO_2 demand peaks during the summer periods while is limited during the winter months. Figure 6.1 shows a typical CO_2 demand curve for a greenhouse. The CO_2 demand is shown in kg/hr per hectares.

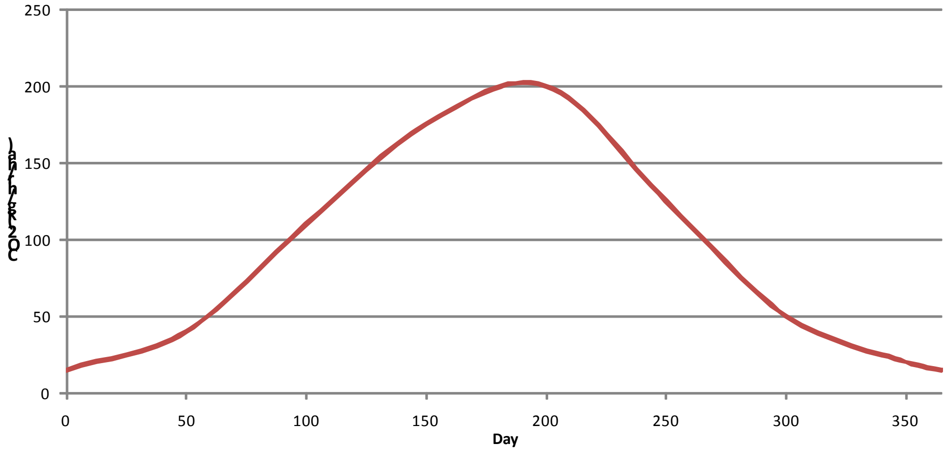


Figure 6.2 Typical CO_2 demand per year in a greenhouse.

In figure 6.3 the CO_2 demand and supply curve assuming storage is presented. The CO_2 availability from the biogas production is constant throughout the year and about 5.500 kg/hr. However, based on the CO_2 yearly demand, during the winter months there would be an excess of CO_2 which could be temporally stored for later re-use (green shaded areas).

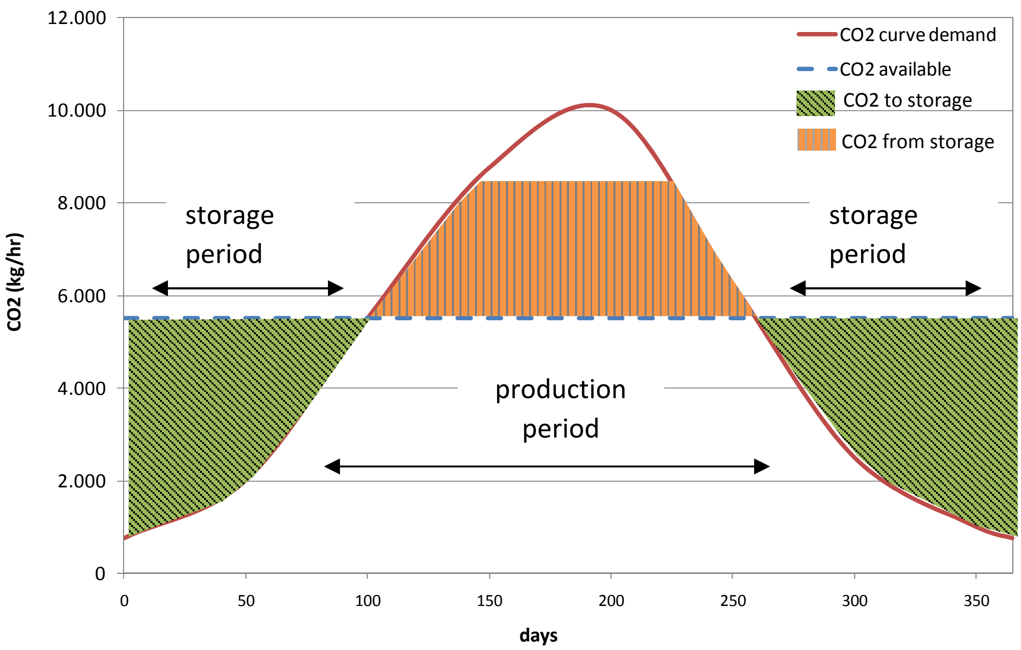


Figure 6.3 CO_2 demand and supply with storage variant

The additional CO_2 supply coming from the storage (orange shaded area) will not be equivalent to the initial CO_2 stored as a portion of the CO_2 would be irrecoverable after storage (up to 20%). The equivalent production and storage periods (in days) will depend on the intended amount of hectares to provide with CO_2. Based on two polder sizes of 50 and 75 hectares each. Two different polder sizes are taken to show the difference between a base load (75 ha) and peak load (50 ha). 75 ha is the total area and by 50 ha there enough CO_2 is being stored to deliver the complete demand. Table 6.1 summarises the expected conditions.

Table 6.1 Conditions based on 50 ha and 75 ha

	50 ha	**75 ha**
Current available supply	5.500	5.500
Storage period	200 days	150 days
Yearly CO_2 to storage	21,6 x10^6 kg CO_2	8,1 x10^6 kg CO_2
Production period	165 days	215 days
Max. additional supply from storage	4.361 kg/hr	1.250 kg/hr
Number of wells needed (based on well rate of 1.200 kg/h)	4	1

6.2 Cost price analysis

The cost-price of the kg of CO_2 from the storage will de dependent on a variety of factors. In addition, these resulting costs have to be compared to alternative scenarios to decide if seasonal storage is an interesting option. The following scenarios are evaluated:

1. Seasonal storage without purification step (15 years payback time)
2. Seasonal storage without purification step (30 years payback time)
3. Seasonal storage with purification step (15 years payback time)
4. Seasonal storage with purification step (30 years payback time)

The main investments and costs taken into account for the analysis are outlined below and listed in table 6.2

- Investments cost related to the aquifer storage system
- Investments costs using purification
- Exploitation costs, including monitoring and maintenance
- Payback time and interest rate

The following starting-points are taken for the financial analysis:

- Maintenance and administration 1,7% of the total investment
- Maintenance of the purification installation 5% of the total investment
- Costs of purification 20 €/ton
- Interest 6%
- Electricity 0,06 €/kWh

Table 6.2 Investments type and costs levels [€]

Scenario	**Investering [M€]**	**Exploitatie [k€]**	**Rentelast 15 jaar [k€]**	**Rentelast 30 jaar [k€]**
50 ha zonder zuivering	1,79	56	185	130
75 ha zonder zuivering	1,15	29	118	83
50 ha met zuivering	2,29	435	236	167
75 ha met zuivering	1,65	192	170	120

The investments and costs in table 6.2 are based on budget calculations and prices from manufactures. They should give a good impression of the real costs.

It is noted that the costs level related to the storage system are higher for a smaller polder (50 ha) compared to a larger area of 75 ha. This is to do with the fact that more wells are needed to provide the additional CO_2 demand. However, for a smaller polder area, the additional CO_2 supply from storage will cover almost the entire CO_2 demand, limiting the use of other CO_2 external sources.

The technical lifetime of the storage is 30 years. In table 6.3 the cost price of a kg CO_2 is calculated by this life time. Normally investments should be paid back in a shorter period of time (15 years). To show the difference both periods have been used to calculate the cost price of a kg CO_2, see table 6.3

Table 6.3 Costs price (€) of kg of CO_2 from storage

Scenario	50 ha	75 ha
No purification (15 year)	0,01	0,02
No purification (30 years)	0,01	0,02
With purification (15 years)	0,04	0,06
With purification (30 years)	0,03	0,05

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