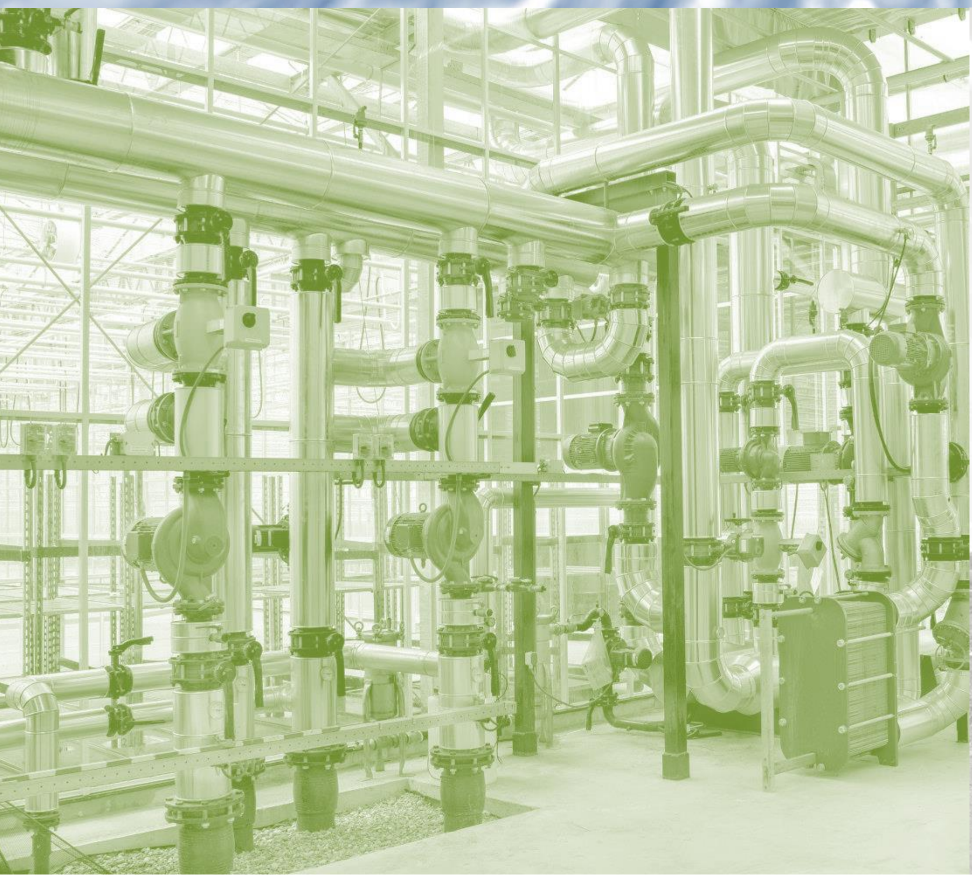
Sector Innovation Strategy

A secure and affordable CO_2 supply for the Dutch greenhouse sector



TNO innovation for life

LTO Glaskracht Nederland

Ministerie van Economische Zaken

KAS ALS ENERGIEBRON

Productschap Tuinbouw

TNO
Earth, Life & Social Sciences
Princetonlaan 6
3584 CB Utrecht
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 88 866 42 56
F +31 88 866 44 75

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Author(s)	Tom Mikunda, Filip Neele, Frank Wilschut, Maurice Hanegraaf
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Abbreviations

bcm	Billion cubic metres
BIA	Branche Innovation Agenda
CCS	Carbon capture and storage
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
ECN	Energy research Centre of the Netherlands
EU	European Union
EU ETS	European Union Emission Trading Scheme
H_2O	Water
H_2S	Hydrogen sulphide
Kt	Kilotonnes
mcm	Million cubic metres
MSW	Municipal solid waste
MSWC	Municipal solid waste combustion
Mt	Megatonnes
Mtoe	Megatonnes oil equivalent
MW	Megawatt
NGCC	Natural gas combined cycle
NH_3	Ammonia
OCAP	Organic Carbondioxide for Assimilation of Plants
PC	Pulverised coal
PSA	Pressure swing adsorption
PWS	Pressurised water scrubbing
ROAD	Rotterdam Opslag en Afvang Demonstratieproject
SDE+	Stimulering Duurzaam Energieproductie
TNO	Netherlands Organisation for Applied Scientific Research

Samenvatting

De Nederlands glastuinbouwsector is een wereldspeler in het produceren en exporteren van groenten, snijbloemen en bolgewassen. De beschikbaarheid en toevoer van extra CO_2 is een belangrijke randvoorwaarde om de productie van de gewassen te stimuleren. De meest voorkomende bron is de CO_2 die vrijkomt bij de verbranding van aardgas in een warmtekrachtinstallatie (WKK), of in een gasketel. Door stijgende aardgasprijzen en dalende elektriciteitsprijzen verslechtert de rendabiliteit van WKK's. Daarnaast heeft de sector afspraken gemaakt met de Nederlandse overheid over het terugdringen van de CO_2-uitstoot door energiebesparing, het gebruik van restwarmte en het toepassen van hernieuwbare energie. Echter, om de afhankelijkheid van WKK-installaties terug te dringen is een alternatieve, maar ook betrouwbare en betaalbare bron van CO_2 noodzakelijk.

Het huidige aanbod van 'extern' CO_2 is ongeveer 500 kiloton per jaar en wordt geleverd via een pijpleiding of per vrachtwagen. Deze hoeveelheid wordt niet beperkt door de vraag, maar door de beschikbaarheid van CO_2 tegen een acceptabele prijs. De marktprijs voor de levering van extern CO_2 is vaak te hoog (circa €90/ton - €100/ton) voor de meeste glastuinbouwers. Kwekers zijn daarom momenteel afhankelijk van aardgas om in hun CO_2-vraag te voldoen. Daardoor zijn de kashouders maar beperkt in staat te kiezen voor duurzame alternatieven voor het verbranden van aardgas om in de vraag naar warmte en elektriciteit te voorzien.
In de zomer wordt aardgas verbrand voor CO_2-productie, terwijl warmteproductie niet wordt benut. Het gebruik van aardgas in de zomer zou dus kunnen worden beperkt wanneer de tuinder toegang heeft tot goedkoop extern CO_2.

Schattingen voor de toekomstige vraag naar extern geleverde CO_2 zijn afhankelijk van veranderingen in de productiecapaciteit van de industrie, de trend in rendabiliteit van het gebruik van warmtekrachtinstallaties, de snelheid waarmee duurzame warmte en energie beschikbaar komen en de ontwikkelingen in de verbetering van CO_2-doseringstrategieën in de kassen. Experts binnen de glastuinbouwsector schatten dat de mogelijke maximum vraag naar externe CO_2 voor de gehele sector tussen de 1 en 2 megaton per jaar zal liggen.

Om deze patstelling te doorbreken heeft LTO Glaskracht Nederland TNO gevraagd een Branche Innovatie Agenda (BIA) op te stellen om de verschillende mogelijkheden voor CO_2-levering aan de Nederlandse glastuinbouwsector in kaart te brengen. Het doel hiervan is een overzicht te geven van mogelijke CO_2-bronnen en per bron de kansen en uitdagingen aan te geven.

Speciale aandacht gaat uit naar de mogelijkheid om CO_2 te gebruiken van het ROAD-project voor CO_2-afvang en -opslag in het Rotterdamse havengebied. Dit project zou in 2019 van start kunnen gaan, onder de voorwaarde dat begin 2016 een positieve investeringsbeslissing wordt genomen. Als dit project doorgaat is er voldoende CO_2 beschikbaar tegen acceptabele kosten om de gehele glastuinbouw in het Westland en Vierpolder van CO_2 te voorzien.

Tevens wordt in dit rapport aandacht besteed aan de mogelijkheden voor (seizoens)buffering van CO_2, CO_2-levering vanuit de productie van biomethaan en CO_2-afvang bij huisvuilverbrandingscentrales. Het resultaat van de BIA is een aantal aanbevelingen voor beleidsmakers en een overzicht van technische stappen die nodig zijn om de CO_2 tegen acceptabele kosten beschikbaar te krijgen. Voor de verduurzaming van de glastuinbouw is de levering van CO_2 van essentieel belang. Door de inzet van (duurzame) warmte en extern CO_2

kan de glastuinbouwsector, die momenteel circa 10% van het jaarlijkse Nederlandse aardgasverbruik voor zijn rekening neemt, onafhankelijk worden van het gebruik van aardgas.

CO_2-levering door ROAD
Het ROAD-project (Rotterdam Opslag en Afvang Demonstratie-project) behelst het afvangen van circa 1,1 megaton CO_2 per jaar van een kolencentrale op de Maasvlakte in het Rotterdamse havengebied, met aansluitend transport en (permanente) opslag van het CO_2 in een geologische formatie onder de zeebodem (een offshore gasveld). Het CO_2 van ROAD kan via de OCAP-pijpleiding naar kassen worden getransporteerd. De OCAP-pijpleiding levert momenteel ongeveer 400 kiloton aan zijn bestaande klanten. Via OCAP kan circa 100kt – 250kt CO_2 worden geleverd om aan de extra vraag naar externe CO_2 te voldoen. Hiervoor is een investering nodig om 25 kilometer extra pijpleiding aan te leggen tussen het ROAD-project en de bestaande OCAP-pijpleiding. De ROAD-partners hebben aangegeven om de levering van CO_2 aan de glastuinbouw verder te willen onderzoeken nadat een positieve investeringsbesluit is genomen.

Het ROAD-project is op dit moment de aantrekkelijkste route om op korte termijn de CO_2-levering naar de Nederlandse glastuinbouwsector in de provincie Zuid-Holland uit te breiden. De Europese commissie en de Nederlandse overheid dragen 330M€ bij aan de realisatie van dit project. De glastuinbouwsector kan van deze investering profiteren doordat er een grote hoeveelheid vrijwel zuiver CO_2 beschikbaar kan komen tegen relatief lage meerkosten. Begin 2016 nemen de ROAD-partners een definitieve ‘go/no go’-beslissing. Bij een positieve beslissing zal de bouw en ingebruikname ongeveer drie jaar later voltooid zijn, zodat in de zomer van 2019 extra CO_2 beschikbaar zou kunnen komen voor de glastuinbouw.

CO_2-levering aan de glastuinbouw is een belangrijke randvoorwaarde voor de verduurzaming van de glastuinbouwsector en een versnelde uitrol van de opwekking van duurzame warmte en het realiseren van een warmterotonde in Zuid-Holland. Dit argument speelt echter geen doorslaggevende rol in de besluitvorming omtrent het ROAD-project. Daarom wordt aanbevolen dat de glastuinbouwsector het belang van CO_2-levering aan de glastuinbouw onder de aandacht moet brengen bij de Nederlandse overheid.

CO_2 van de productie van biomethaan
Biomethaan, ook wel ‘groen gas’ of ‘biogas’ genoemd, is een duurzame vorm van aardgas die wordt geproduceerd uit organisch materiaal. Biomethaan kan worden toegevoerd aan het bestaande gasnetwerk of worden gebruikt als transport-brandstof. In 2030 moet 3 bcm biomethaan worden geproduceerd volgens doelstellingen van de Nederlandse overheid. Door de productie van biomethaan wordt de afhankelijkheid van import van aardgas in de toekomst verkleind. Tijdens het opwerken van biogas naar de benodigde kwaliteit wordt een aanzienlijke hoeveelheid CO_2 verwijderd, die momenteel in de atmosfeer wordt uitgestoten. Het CO_2 kan worden verzameld, gecomprimeerd en getransporteerd, waarmee het een mogelijk bron van CO_2 voor de glastuinbouw is. Nieuwe faciliteiten voor de productie van biomethaan zijn voorzien op verschillende locaties in Nederlands, mogelijk ook op plaatsen dichtbij potentiële CO_2-afnemers.

De schaal waarop momenteel biomethaan wordt geproduceerd is beperkt; in termen van CO_2-levering bedraagt de hoeveelheid 30-40 kiloton per jaar. De productie van biomethaan wordt echter gestimuleerd door beleid van de Nederlandse overheid op het gebied van duurzame energie. Producenten kunnen aanspraak maken op een ‘feed-in’-tarief onder de SDE+-regeling. Afgaand op de huidige aanvragen voor dergelijke subsidie kan worden verwacht de jaarlijkse productie van biomethaan in 2020 is toegenomen tot 300 miljoen kubieke meter, waardoor 300 kiloton zuivere CO_2 beschikbaar kan komen. In hoeverre deze CO_2

getransporteerd kan worden hangt af van de opwerkingstechniek. Om CO_2 per vrachtwagen te vervoeren, wat gezien wordt als de meest haalbare oplossing, is het nodig om het CO_2 in zuivere en vloeibare vorm te krijgen. Dit vergt extra bewerking en daarmee extra investering door de operator.

Op basis van de bevindingen voor CO_2- afvang en gebruik afkomstig van de productie van biomethaan worden de volgende aanbevelingen gedaan:

- Gedetailleerder onderzoek is nodig om de kosten te bepalen voor het produceren van vloeibaar CO_2 met de productie van biomethaan. In de berekeningen moet een aantal belangrijke factoren worden meegenomen, zoals (de kosten voor) nieuw te bouwen installaties en het geschikt maken van cryogene distillatie-apparatuur, verschillende scenario's voor productiecapaciteit van biogas en kostenbesparing door schaalvergroting, de meeropbrengsten van marginale verbetering van methaanproductie en transportafstanden voor de CO_2.
- De kosten van het integreren van cryogene distillatie-apparatuur in het productieproces van biomethaan moeten nauwkeuriger worden ingeschat, zodat een betere beoordeling kan worden gemaakt van de economische haalbaarheid en mogelijke verdienmodellen. Dit is een eerste stap naar het verder ontwikkelen en demonstreren van installaties die productie van CO_2 en biomethaan combineren. Op deze manier wordt het bewustzijn van mogelijkheden bij de gasproducenten verhoogd.
- Bij het produceren van CO_2 bij biomethaanproductie wordt ook tegelijkertijd de uitstoot van methaan gereduceerd. De win-win situatie die kan ontstaan door het vergroten van de beschikbare hoeveelheid CO_2 voor de glastuinbouw en tegelijkertijd terugdringen van methaanemissies moet worden gecommuniceerd naar de Nederlandse overheid zodat duidelijk wordt hoeveel de totale afname in broeikasgasemissies kan bedragen.
- Afstemming van vraag en aanbod van bestaande en geplande productie-faciliteiten van biomethaan in Nederland (en mogelijk West-Duitsland) zou moeten worden uitgewerkt en jaarlijks bijgesteld om mogelijke transportroutes van CO_2 met een lage prijs te identificeren.

CO_2 uit afvalverbranding

Afvalverbrandingsinstallaties produceren grote hoeveelheden CO_2 in lage concentraties. Er zijn verbrandingsinstallatie op verschillende locaties in het land en sommige zijn dichtbij bestaande clusters van kassen. Omdat afvalverbrandings-installaties niet onder het EU 'Emission Trading Scheme' vallen, zal de prijs van CO_2-levering niet sterk worden beïnvloed door de prijs van CO_2-emissierechten. De prijs van CO_2-levering zal zo naar verwachting in de toekomst niet sterk stijgen. Een van de grootste installaties, AEB Amsterdam, bevindt zich op slechts 2 km van de OCAP-infrastructuur en zou een significante bijdrage kunnen leveren om aan de CO_2-vraag van de glastuinbouw te voorzien.

In een gedetailleerde studie over CO_2-afvang uit het rookgas van een afvalverbrandingsinstallatie, blijkt dat zeer zuiver CO_2 kan worden afgevangen tegen een prijs van €43 per ton[1]. Ondanks deze relatief hoge afvangkosten kunnen een aantal acties worden ondernomen om het concept verder te brengen:

- Verschillende technologieën voor CO_2-afvang kunnen worden onderzocht. De enige studie naar CO_2-afvang van AEB Amsterdam ging uit van afvang door een combinatie van membranen met cryogene distillatie, maar andere processen waaronder het gebruik van

[1] Deze prijs is exclusief transportkosten

CO_2-selectieve chemicaliën en/of restwarmte uit andere delen van de verbrandingsinstallatie zouden kunnen leiden tot lagere kosten.

- De glastuinbouwsector kan, via de brancheorganisatie, meer actief betrokken worden bij onderzoek en ontwikkeling van technologieën voor CO_2-afvang in Nederland. Grote onderzoeksinstellingen zoals TNO en ECN zetten bestaand onderzoek voort, onder andere in het CATO-TKI project, met als voornaamste doel weliswaar grootschalige CO_2-opslag, maar de principes voor CO_2-afvang zijn hetzelfde en kunnen op termijn tot kostenbesparingen leiden.
- Voor het hergebruiken van CO_2 uit AEB Amsterdam bestaat (momenteel) geen stimulerend beleid. Desalniettemin zou dit hergebruik het proces verduurzamen, mits aangetoond kan worden dat minder aardgas in de kassen wordt verbrand om in de CO_2-behoefte te voorzien. Vanuit een dergelijk initiatief kunnen mogelijk afspraken gemaakt worden over de verdeling van kosten tussen OCAP, AEB Amsterdam, de (lokale) overheden en de glastuinbouwsector.

Executive Summary

The Dutch greenhouse sector, or ‘horticulture under glass’, is a global leader in the production and export of vegetables, cut flowers and potted plants. The industry relies on supplying its greenhouses with elevated levels of CO_2 in order to support the growth of its products. The use of purified exhaust gases from the combustion of natural gas in combined heat and power (CHP) installations, is the most common route to achieve this. However the industry is under pressure, as steady gas prices and decreasing power prices are eating into the economic viability of using the CHP. Furthermore, the sector has agreed objectives with the Dutch government for reducing its overall CO_2 emissions through both energy efficiency, and by harnessing the considerable potential for waste heat utilisation and renewable energy technologies, particularly geothermal heat. Though in order to reduce the reliance on the CHP installations, a key precondition is access to dependable and affordable external sources of $CO_{2.}$

The current supply of external CO_2, delivered either by pipeline or by truck (tanker), is approximately 500 kilotonnes per year. However, this amount is not limited by demand, but by the availability of low-cost CO_2. CO_2 is available by commercial suppliers, however, the costs are too high for many growers and is thus restricting the potential to diversify from reliance on natural gas combustion to other forms of sustainable heat (i.e. industrial waste heat and geothermal) and renewable power. Estimates for future demand for external CO_2 are dependent on changes in the production capacity of the sector, the trend in economic viability of using CHP installations, the speed at which sustainable heat and renewable power opportunities become available, and the development of improved CO_2 dosing techniques in greenhouses. Experts close to the sector estimate potential demand for external CO_2 from the entire sector to be able to reach a maximum of between 1Mt to 2Mt.

In light of this problem, TNO has been asked by LTO Glaskracht Nederland to support them in the development of a Branch Innovation Agenda (BIA) for CO_2 supply for the Dutch greenhouse sector. The objective is to access the potential sources of CO_2 from across a limited number of industries in the Netherlands, and highlight the opportunities and challenges presented. Particular attention is provided to the possibility of using CO_2 from the planned CO_2 capture project, ‘ROAD’, located in the Rotterdam harbour. This project could commence operation in 2019, under the premise that a positive financial investment decision can be taken in 2016. In addition to the direct supply of CO_2 from ROAD, the possibility of CO_2 buffering in a natural gas field, CO_2 supply from biomethane production, and CO_2 capture from a municipal waste incinerator are evaluated. The outcomes of the BIA are a set of recommendations for policy and technical actions that the sector as a whole can consider.

1 Introduction

The Netherlands greenhouse sector, or ‘horticulture under glass’, is a global leader in the production and export of vegetables, cut flowers and pot plants. In 2014, the production of these three groups of crops had a total added value of €5.2 billion (LEI, 2015), representing approximately 10% of the total economic output of the entire Dutch agricultural sector. As roughly three-quarters of the total produce is exported, the sector plays an important role in the balance of trade in the Netherlands. However, since 2000, the sector has been facing increasing global competition and increasing energy prices, which has contributed to a reduction in the total greenhouse area from 10.500 ha to 9.500 ha (CBS, 2015).

Sufficient warmth, light and enhanced CO_2 levels in a greenhouse are essential for creating the optimal growing conditions for all commercial crops. The combustion of natural gas in combined heat and power (CHP) installations, is the most common route to create such an environment[2]. The replacement of conventional natural gas boilers with CHP units has been a key contributor to a 57% energy efficiency improvement in the sector since 1990, which also provides 10% of the electricity consumed in the Netherlands through the sale of excess power to the transmission grid. Nevertheless, through the considerable consumption of natural gas, the greenhouse sector remains an energy intensive sector, with CO_2 emissions remaining relatively stable since 1990 at around 7 $MtCO_2$/year, close to 4% of the total national CO_2 inventory of the Netherlands.

Steadily increasing natural gas prices, and decreasing electricity prices are having a negative impact on the economic viability of CHP installations. In addition, both through sector-wide agreements with the Dutch government to achieve CO_2 reductions by 2020, and the possibility of subsidised sustainable energy sources such as geothermal power, many stakeholders are looking to reduce the reliance on CHP installations, reducing energy costs to ultimately improve market competitiveness. However, the majority of growers use purified exhaust streams from such installations as the primary source of CO_2 to optimise the development of their crops. Pure CO_2 is commercially available, however expensive. Therefore, identifying sources of suitable and affordable CO_2 for the sector can be beneficial both to reduce dependence on natural gas and accelerate the uptake of sustainable energy sources in the sector.

“…many stakeholders are looking to reduce the reliance on CHP installations, reducing energy costs to ultimately improve market competitiveness.”

1.1 Current CO_2 demand by the greenhouse sector

Generally speaking, CO_2 concentrations in a greenhouse are normally increased to 600-1000ppm, whereby 400ppm represents atmospheric conditions. The exact usage of CO_2 in a greenhouse is dependent on a number of factors: the type of crop, ventilation in the greenhouse, the level of lighting and the cost of CO_2. CO_2 delivery to the greenhouses are measured in kilograms of CO_2 per hectare per hour (kg/ha/hr), and delivery ranges from 100 – 300 kg CO_2 per hectare per hour depending on the type of crop. Demand for CO_2 in greenhouses is considerably higher during the summer months, when the production rate is at its highest, with little or no CO_2 needed in the winter months.

[2] Approximately 70% of the total greenhouse area is equipped with a CHP installation.

In the Netherlands, it is estimated that on average, 60% of the CO_2 demand for greenhouses is met using the exhaust gases of CHP installations (Smit, 2010). In some cases, growers may purchase pure CO_2 from external sources, which is either delivered by pipeline or by trucks. The demand for external CO_2 could occur when there is no heat demand from the CHP, or an alternative source of heat is available (such as waste heat or geothermal heat), or if a high level of CO_2 purity is required in the greenhouse for specific crops. Figure 1 below displays the consumption of external CO_2 (not from CHP exhaust gases) by the Dutch greenhouse sector between 2006 to 2013.

"…it is estimated that on average, 60% of the CO_2 demand for greenhouses is met using the exhaust gases of CHP installations"

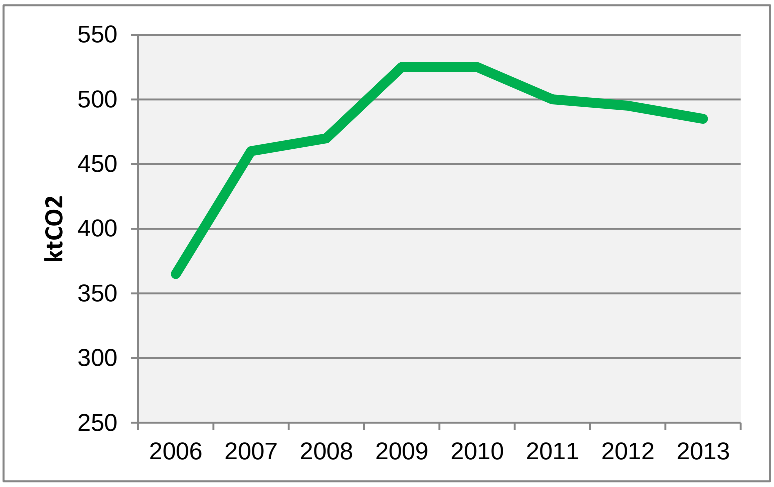


Figure 1: External CO_2 consumption in the Dutch horticultural sectors 2006-2013 (after van der Velden & Smit, 2013)

With reference to Figure 1 above, the reason for the levelling off of CO_2 consumption after 2009 is not because demand has stabilised, however that the availability of affordable CO_2 has been expended.

1.2 Future trends in CO_2 demand

The future demand for external CO_2 sources in the coming 15 years from the Dutch greenhouse sector is dependent on three key factors:

1) **The development of the sector as a whole in terms of production area (total hectares) -** this depends on demand of horticultural produce from domestic and large European consumers such as the United Kingdom and Germany, and the market share held by the sector in light of from European and global competitors. Since 2000, the production area has reduced by approximately 10%, but it remains unclear whether this trend will continue (CBS, 2015).

2) **The usage level of CHPs –** can be influenced by a further three factors:

   a) *CHP spark spread* - the margin between natural gas prices and revenue from power sales, commonly called the 'spark spread'. The CHP sector has seen a reduction in the spark spread in recent years, with low power prices and stable gas prices reducing the profitability of CHPs. It is expected the spark prices will remain low in the coming years, as subsidised renewable electricity will increase (Energymatters, 2014).

b) *Energy efficiency savings* – reduced demand for heat and power from the CHPs through, for example, optimal lighting strategies, the use of energy efficient lighting systems and improved insulation in greenhouses.

c) *Alternative sources of heat* – An increase in alternative sources of heat for greenhouses would place less reliance on CHPs, particularly if the private power demand of a CHP operator is low. Advanced feasibility studies have been completed to transport waste heat from the Rotterdam industrial port area, both to residential areas and to the Westland Greenport horticultural area (BLOC, 2014). The implementation of geothermal projects in the sector is also increasing, and the sector has agreed with the Dutch government to use geothermal energy to reduce the sector's CO_2 emissions by 0.3 Mt per year by 2020 (Kas als Energiebron, 2013).

3) **The development of optimised CO_2 use strategies in greenhouses** – Advanced CO_2 dosage strategies and improved greenhouse concepts are currently being developed, and can lead to a reduction in the overall CO_2 demand for the sector. The potential impact of these strategies on the overall demand of CO_2 in the sector is unclear.

Of the three factors highlighted above, the second factor regarding the level of usage of CHP installations will have the most pertinent effect on future external CO_2 demand. Both the economic pressures through the narrowing spark spread, and the opportunities and commitments to improve the sustainability of the sector by developing alternative heat sources, can have significant depressing effect on the usage of the CHP installations. However, any reduction in the use of CHP installations by growers can only take place under the condition that sufficient, affordable CO_2 is available from external sources.

There have been a number of studies, both regional and national, that provide estimates on the future demand for external CO_2 by the greenhouse sector in the future. For example, external CO_2 demand from the growers located in the Greenport[3] Venlo in the south-east of the Netherlands with a cultivating area of 850 ha in total has been estimated to increase from 120 kt to 220 ktCO_2 between 2012 and 2028 (DWA, 2013). The external CO_2 demand of the growers in the Greenport Westland, an area of 2000 ha, has been estimated to increase from 243 ktCO_2 in 2014, to 394 ktCO_2 in 2018, with the possibility to increase to 439 ktCO_2 by 2028 if waste heat from local industries could reduce the use of CHP installations for heat provision (Prins et al., 2014).

Smit (2010) calculated that in 2008, the entire Dutch greenhouse sector burned 2.65 billion m^3 of natural gas in boilers, to provide 3.7 MtCO_2 for assimilation in crops. Based on a target of the sector using 20% energy from renewable sources (primarily geothermal and heat from biomass), 680 million m^3 less natural gas would be combusted leading to an additional external CO_2 demand by 2020 of 1.2 Mt. Although the target of 20% renewable energy has since been revised to an overall CO_2 reduction target for the sector of 6.2 Mt per year by 2020 (from 6.8 Mt in 2013), this exercise

"…estimates suggest that national external CO_2 demand could reach a maximum of 1.5Mt to 2Mt of CO_2"

[3] 'Greenport' is the official administrative name given to clusters of greenhouse in the Netherlands, there are six nationally. The companies in each Greenport cooperate on development issues in the region.

highlights the issue that if more geothermal and renewable heat are to be used in the sector, the demand for external CO_2 by growers will rise substantially. Other estimates suggest that national external CO_2 demand could reach a maximum of 1.5 Mt to 2Mt of CO_2 by 2020 (Smit, 2012). However, there is no agreed figure for future CO_2 demand that takes into account the wide range of variables which can influence this.

1.3 Current and future CO_2 sources for Dutch greenhouses

Approximately 80% of the total external CO_2 demand is provided by OCAP[4] CO_2 B.V., a company that supplies CO_2 at a high concentration of 99%, to greenhouses via pipeline from two petrochemical sources in the Rotterdam industrial area. One of these CO_2 sources comes from a hydrogen production facility which is part of the Shell Pernis Oil Refinery, and emits a pure stream of CO_2 as a by-product of the hydrogen production process. The other source, the Abengoa Bioenergy plant, also produces CO_2 as a by-product through the production of bioethanol. Figure 2 highlights the location of the OCAP pipeline, the CO_2 sources and the existing and planned delivery areas for the greenhouses.

Figure 2: The OCAP pipeline, CO_2 sources (red arrows) with current (green) and planned (blue) CO_2 delivery areas

The current OCAP infrastructure delivers approximately 400 kilotonnes of CO_2 to around 500 greenhouses annually, representing approximately 2,000 hectares of production area (20% of total national production area). However the demand for CO_2 from greenhouses within the technically feasible delivery range of the pipeline is assumed to be close to double the current delivery rate (pers. comm. Limbeek). By connecting the OCAP infrastructure to other

[4] Organic Carbondioxide for Assimilation of Plants

greenhouse areas (see areas highlighted blue in Figure 2), OCAP could supply close to half of the national greenhouse production area.

Demand for CO_2 from the OCAP pipeline is high, because the cost per ton of CO_2 is understood to be considerably lower than purchasing liquid CO_2 from other commercial suppliers which are delivered by truck. The availability of pure CO_2 from industrial sources is the limiting factor in OCAP's operations, and the company is currently exploring alternative sources of CO_2 to meet demand.

1.4 Identification of three 'innovation areas' for CO_2 supply

In combination with an assessment of current and future demand of CO_2 by the greenhouse, the first phase of the development of the BIA involved a scoping study of a broad range of possibilities for additional CO_2 supply, and a number of CO_2 management options. CO_2 management options focus, for example, on ways to balance the seasonal CO_2 demand by storing large amounts of available CO_2 during winter months, to then be able to expand the coverage of demand during the peak growing months in the summer. The range of options were comparatively compared using a simple multi-criteria analysis which draws from existing literature and interviews with experts. Each option was assessed for potential coverage (i.e. national or local), short term availability, relative cost per ton CO_2, security of supply, technical feasibility and innovation potential (i.e. the potential for further research and development to reduce costs and/or improve the technical feasibility). The full multi-criteria analysis is presented in Annex I – with an overview of options considered in Table 1.

Table 1: CO_2 supply and CO_2 management options assessed in the BIA (options highlighted bold were selected for further investigation in this report)

CO_2 supply options	CO_2 management options
CO_2 supply from large scale CO_2 capture project 'ROAD'	**Geological CO_2 buffering**
CO_2 from biomethane production	Surface CO_2 buffering (tanks)
CO_2 capture from municipal solid waste incinerator	CO_2 shipping by inland water ways
CO_2 capture from air	
Natural geological sources of CO_2	
CO_2 capture from other industrial sources	

Based on the outcomes, of the comparative analysis, a smaller number of options were selected for further investigation, which are covered in the following sections. The detailed analysis focuses on the nature and current status of the potential source, the technical feasibility of supplying greenhouses, and an initial figure(s) of existing available cost data or indication of expected costs by expert interview.

2 Innovation area 1: Large scale CO_2 capture and storage combined with CO_2 buffering

Carbon capture and storage (CCS) involves the removal of CO_2 from the flue gases of large combustion installations and then transporting the CO_2 for indefinite storage in suitable geological formations found at least one kilometre deep below the earth's surface. CCS allows the CO_2 to be isolated from the atmosphere indefinitely thereby prevent dangerous climate change, however the investment and operating costs of CCS are considerable, and a full-scale demonstration plant has yet to be realised in Europe. One of the most advanced planned CCS demonstration project, the Rotterdam Opslag en Afvang Demonstratieproject 'ROAD' CCS Project in Rotterdam, is currently on hold, and awaiting a final investment decision.

2.1 Large scale CO_2 capture and storage technology

The European Union, and therefore the Netherlands, has committed itself to 30% reduction of greenhouse gas emissions (against 1990 levels) by 2030. To achieve these goals, each Member State has implemented specific targets to improve energy efficiency and support the broad deployment of renewable energy technologies. Many Member States, such as the UK and the Netherlands, are also exploring the use of CCS to allow fossil-fuel based power and industrial installations to reduce CO_2 emissions. The Dutch government is supporting CCS through funding research programmes and demonstration projects to try and reduce the long-term costs of the technology.

Although there is no legal standard for the specification of CO_2 that would be captured in CCS projects, many of the proposed demonstration projects would result in a captured gas with a composition of between 95-99% CO_2, dependent on restrictions with the pipeline and storage systems. CCS projects are also most economically feasible when capturing large volumes of CO_2, at least upwards of 500 ktCO_2 per year. It is therefore technically feasible that a small proportion of the captured CO_2 could be diverted from long-term geological storage and reused as a feedstock in the chemical industry, or for fertilisation of crops in a greenhouse. It must be pointed out, however, that the CO_2 diverted to the greenhouse would be considered as emitted, as once the biomass is oxidised the CO_2 will be released into the atmosphere.

The following sections provide further details on the proposed ROAD CCS project, and in addition to long-term storage, introduces a feasibility study for the utilization of CO_2 for enhanced oil recovery and delivery of an additional 100 ktCO_2 per year to greenhouses through the OCAP pipeline.

2.2 The ROAD project: additional supply of CO_2

Initiated by E.ON Benelux and GDF SUEZ Energy Netherlands, the Rotterdam ROAD project plans to develop a post-combustion CO_2 capture facility at a coal-fired power plant, producing CO_2 at a rate of about 1.5 Mt/yr (due to assumed plant down time, on a yearly basis 1.1 Mt will be captured). The capture unit uses post-combustion, amine-based technology to remove approximately one-quarter of the CO_2 produced from a 1070 MWe coal-fired power plant in the Rotterdam Maasvlakte.[5] The CO_2 is planned to be transported with a 25-km pipeline to the P18-4 offshore depleted gas field, however, the CO_2 will be of a specification that could be transported and used directly by greenhouses. The existing OCAP pipeline extends to

[5] See http://road2020.nl/en for more information.

approximately 20km east of the proposed ROAD project, and a linking pipeline to carry CO_2 through Rotterdam harbour area could enable OCAP to expand its planned distribution capacity to many greenhouse areas in the west of the Netherlands (see Figure 2).

According to current planning, the plant should commence operation by 2019. Despite funding support of €180 million pledged by the European Commission, and up to €150 million by the Dutch government, the lack of a long term business case for reducing CO_2 emissions means that the project is on hold indefinitely. The current and projected prices for emission allowances under the EU Emission Trading Scheme are too low to incentivise capturing CO_2 from coal-fired power plants.

2.3 CO_2 buffering in Q16-Maas: a potential solution to increase OCAP capacity

Although the long-term storage of CO_2 for climate purposes is novel, the concept of injecting CO_2 into the deep sub-surface (e.g. at depths lower than 1.5km), is not a new concept, and has been used to enhance the production of oil in the United States since the 1980's. Recently, using CO_2 to enhance hydrocarbon production is being considered by European countries, including Denmark and the Netherlands. It is technically feasible, as it is with natural gas, to temporarily store or 'buffer' CO_2 in geological formations in order to balance seasonal demand fluctuations. Case in point, the prospect of large scale CO_2 storage developments in the Netherlands could also be interesting for the Dutch horticultural sector.

During the peak demand for CO_2 in the summer period (April through to September), all the CO_2 supplied from the Shell Pernis and Abengoa bioethanol plants is used. Demand is low during winter and therefore this results in most of the CO_2 (in a very pure form) being emitted, rather than utilised. However, the demand for CO_2 during summer is larger than what currently can be delivered. Seasonal storage (buffering) of the CO_2 from Shell Pernis and Abengoa (and other future sources if available), for example in active or expended gas reservoirs could help match demand and supply, potentially doubling the number of greenhouses that can be supplied with OCAP CO_2, and reducing the CO_2 emitted by industry and through the combustion of natural gas in CHP installations.

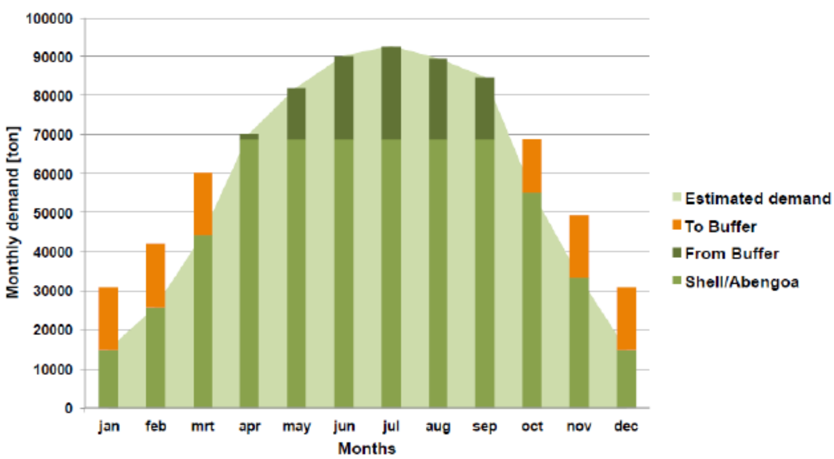


Figure 3: Potential future monthly supply and demand of CO_2 if a buffer facility is connected to the OCAP system.

Currently, an interesting option presents itself in the Q16-Maas field. The Q16-Maas field is located just offshore of the recently extended Maasvlakte and is produced from a site on the

Maasvlakte. The OCAP pipeline ends at a distance of about 20 km from the site (see Figure 4 for a more detailed map of the area). A 20 km transport line from the Abengoa plant, at the current end point of the OCAP pipeline, to the second Maasvlakte is being considered. This pipeline would link the Rotterdam Maasvlakte CCS project (ROAD) to the OCAP system. A further extension of about 5 km would connect the Q16-Maas site to the system (at '4' in Figure 4).

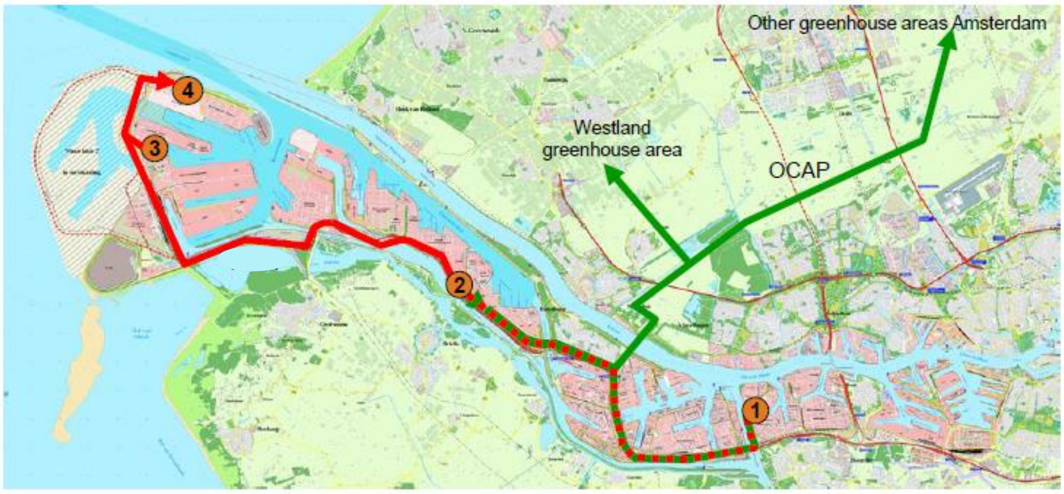


Figure 4: Location of the existing OCAP pipeline (green) and delivery areas, the Shell Pernis Refinery (1), Abengoa bioethanol plant (2), the proposed ROAD project (3), the ONE Q16-Maas surface facility (4), and the route of a possible new CO_2 pipeline (red).

2.4 Technical feasibility

In 2015, a project concept was developed in collaboration with the potential operators of the ROAD project - the Maasvlakte CCS Project C.V.[6], the operator of the Q16-Maas field - Oranje Nassau Energie (ONE) and OCAP, with the advisory services of TNO. To improve the business case for the ROAD project, it was investigated whether the CO_2 could be stored in the nearby Q16-Maas field, rather than the P18 field located 25km offshore. This option could reduce the capital and operational costs of the ROAD project associated with transporting CO_2 offshore, which could allow the CCS demonstration to proceed. This concept is financially interesting for ONE, as the CO_2 injected could increase the maximum amount hydrocarbon condensates recoverable from the field. The production of gas and condensates from the Q16-Maas field commenced in 2014.

TNO conducted a showstopper study for the concept, which also included both the connection of the ROAD CO_2 capture facility to the existing OCAP pipeline, and the use of a the Q16-Maas as both a permanent CO_2 storage location for the ROAD project, but also as a temporary CO_2 buffer to balance the seasonal CO_2 demands of the greenhouse industry. The feasibility study conducted by TNO covered, *inter alia*, the suitability of the geology for CO_2 injection at Q16-Maas, the integrity of the injection well, interaction of CO_2 with the reservoir, reservoir modelling for condensate production, separation requirements of the production stream, pipeline transport routes and requirements, and legal aspects.

[6] ROAD is a joint project initiated by E.ON Benelux N.V. and Electrabel Nederland N.V. (GDF SUEZ Group). Together they constitute the limited partnership Maasvlakte CCS Project C.V.

As part of the feasibility study, the fundamental engineering components and gas transportation requirements for the concept were identified. Figure 5 provides a basic sketch of a potential layout and specifications of the transport connections between the existing OCAP pipeline (lower left), the ROAD project facilities (top left) and the Q16-Maas field (right). The main investments, in addition to the costs of the CO_2 capture unit at ROAD, include a low-pressure 18 km pipeline to the existing OCAP pipeline, a 5 km low-pressure pipeline to ONE's Q16-Maas surface facility, and a compressor and well to allow the high-pressure injection of CO_2 into the Q16-Maas field.

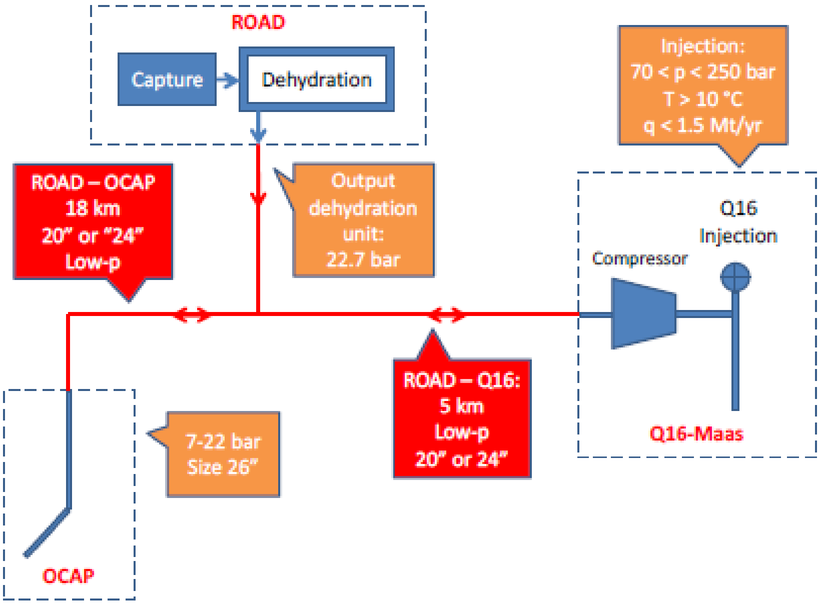


Figure 5: . A basic sketch of a potential layout and specifications of the transport connections for the ROAD-ONE-OCAP project.

No technical or engineering showstoppers were identified for the use of the Q16-Maas field as either a permanent CO_2 storage location, or as a dual-purpose CO_2 storage/buffer system. Furthermore, the storage/buffer system also facilitates the enhanced recovery of condensates from the field. The quality of the CO_2 to be captured from the ROAD facility is also suitable to be transported by pipe for use in supporting crop development in nearby greenhouses. The total CO_2 storage capacity of the field was calculated as being between 1.9 to 2.3 $MtCO_2$ (based on a range of scenarios) allowing the ROAD project to initially operate for 2 years and also meets the minimum storage requirements to secure funding from the European Commission. The feasibility study also confirmed that injection of CO_2 is expected to improve the total volume of condensates recoverable, and was assessed for potential coverage (i.e. national or local), short term availability, relative cost per ton CO_2, security of supply, technical feasibility and innovation potential.

"No technical or engineering showstoppers were identified for the use for the use of the Q16-Maas field as a CO_2 buffer"

Using the Q16-Maas field as a CO_2 buffer could help balance supply and demand over the year to OCAP customers, however further research is necessary on the potential reaction of the CO_2 with the geology, and the extent of gas cleaning necessary prior to delivery to the OCAP network. In addition, using the Q16-Maas as a buffer only for the seasonal surplus CO_2 already supplied to OCAP from Shell and Abengoa is not considered technically (or financially) feasible, at least in the short term, as the amount supplied would be insufficient to enhance the recovery of condensates. Geological CO_2 buffering may however be feasible in other expended gas fields across the Netherlands and remain an interesting option for balancing demand in greenhouses, should additional CO_2 supply become available.

2.5 **Financial aspects**

Capturing CO_2 from the outlet gas of a power station, with an initial concentration of between 10-15% by volume, and concentrating it to the high purity of >98% needed to supply the greenhouses requires considerable energy. Comparable to the existing sources of CO_2 for the OCAP pipeline system, which have pure CO_2 streams as the by-products of hydrogen (Shell refinery) and bioethanol (Abengoa) production, capturing CO_2 from large industrial installations, such as a coal-fired power plant, involves substantial capital and investment requirements.

Despite the costs of CO_2 capture, the ROAD project is currently the most promising near-term opportunity to considerably expand the CO_2 supply to parts of the Dutch horticultural sector. The project, if it proceeds, will receive grants by the European (~180 M€) and Dutch (~150 M€) governments to contribute to the capital investment costs. The government grants are available only because the capturing and long-term storage of CO_2 has the potential to be an important and efficient means of reducing European (and global) greenhouse gas emission and to prevent (or slow) the effects of dangerous climate changes. This means that costs for supplying CO_2 to OCAP, and then to customers, could also benefit by this cost-sharing agreement.

“the most promising near-term opportunity to expand CO_2 supply to parts of the Dutch horticultural sector”

This is a highly unique situation of a CCS demonstration project located close a CO_2 pipeline which supplies CO_2 to greenhouses. Capturing CO_2 from the coal-fired power plant solely for the purposes of supplying greenhouses with CO_2 is not financially feasible, as only approximately 100 ktCO_2/yr is needed in additional demand by OCAP, with demand also fluctuating seasonally. The sole use of the Q16-Maas as a CO_2 buffer is not financially feasible given the high investment costs required for the pipeline, compression and injection facilities, and possibly an additional well in the field. Should the three activities of CO_2 storage, CO_2 enhanced hydrocarbon recovery and CO_2 buffering be combined, the costs of the necessary infrastructure can be shared between multiple parties. Once the infrastructure is in place, the CO_2 buffering system could continue to be used for balancing seasonal CO_2 demand after the demonstration period of the ROAD project (should this be restricted to a 2 year demonstration period).

If the ROAD project proceeds, it will be important to address the risk of CO_2 prices fluctuating in the future. The ROAD project is dependent on a business case built on the incentive of reducing emissions under the EU ETS. Assuming the ROAD project proceeds, each ton of CO_2 sold to OCAP will be considered as emitted under the scheme, and therefore must be paid for. At the current prices of €7, this may still represent an small portion of cost to be built into the CO_2 tariff charged by the operators of ROAD, however if the EU ETS price increases as it is generally expected to do so (and will have to if ROAD is to keep capturing CO_2 affordably after the two year demonstration phase), one would expect the costs of purchasing CO_2 to also increase.

3 Innovation area 2: CO_2 from biomethane installations

Biomethane, which is referred to as 'groen gas', or green gas, in the Netherlands, is a sustainable form of natural gas which is produced from organic material. Biomethane can be injected into the existing natural gas grid and, therefore, can support energy security by reducing the reliance on foreign imports of natural gas. During the upgrading of raw biogas to biomethane, a considerable amount of CO_2 must be removed and is conventionally released to the atmosphere. This CO_2 can be accumulated, compressed and transported, representing a possible low-cost supply of CO_2 to the horticultural industry.

3.1 Biomethane production

The precursor to biomethane is called biogas, which can be produced from many different kinds of organic materials via either a chemical process (anaerobic digestion) or a thermal process (gasification). The gasification of biogas is still in the research and development phase, and the anaerobic digestion of biomass (i.e. food waste, sewage, agricultural waste) is currently the primary route for biogas production across Europe. Biogas is composed on average of 60% methane (CH_4), 35% CO_2, together with smaller amounts (0-2%) of hydrogen sulphide (H_2S), ammonia (NH_3) and water (H_2O). Biogas can also be directly combusted for local heat, or also combusted in a combined heat and power boiler.

Figure 6: An overview of the biomethane from biogas route (Greengasgrids, 2015)

To produce biomethane (the sustainable equivalent of natural gas), the calorific value of the biogas must be increased, or 'upgraded' (see Figure 6). The Netherlands has strict regulations on the quality of gas that can be injected into the grid. To meet the required specifications, the level of methane in the biogas must be increased to at least 88%, meaning that a considerable amount of CO_2 must be removed from the gas stream. In addition the H_2S must be removed, and the gas must be dried to prevent corrosion to pipelines and other steel components. There are several well-established processes for removing CO_2 from gas, which are used across many industries, including oil and gas, chemical and also beverage industries.

There are four fundamentally different processes that CO_2 removal technologies are designed around, namely CO_2 absorption, adsorption, cryogenic distillation or the use of CO_2 selective membranes. It is also possible that a combination of

"Dependent on the CO_2 removal technology, the CO_2 off-stream can meet the required specifications for customers"

processes are used, particularly if the CO_2 is to be used as a by-product. The selection of CO_2 removal technology is dependent on the composition of the biogas, scale of operation, and an economic balance between methane production efficiency, capital and operational costs.

Large biomethane production plants can therefore produce considerable amounts of CO_2 as a by-product. Dependent on the CO_2 removal technology, the CO_2 off-stream can meet the required specifications for customers in the beverage and greenhouse sectors.

Box 1: Biomethane projects with pure CO_2 supply in the Netherlands

The opportunity of supplying CO_2 from biomethane plants to customers in the horticultural and beverage production sector has been recognized by some technology suppliers, and there are already examples of biomethane plants in the Netherlands that sell CO_2 as a useful byproduct. A company called Ecofuels B.V. in the Netherlands produces biogas from vegetable-based material. The company produces 2.2 million m^3 of biomethane annually, while recovering 2500 tons of food-grade carbon dioxide per year. Agricultural company Kloosterman B.V. has a 6000 m^3 fermentation plant which can produce 500 m^3 of biomethane per hour, which also results in approximately 4000 tons of food grade CO_2 per year (Peeters, 2012).

Both of the above examples utilize a technology developed by engineering firm Pentair Haffmans, also located in the Netherlands. Their biomethane production system combines membrane separation with cryogenic distillation, which allows 100% recovery of methane (no methane slip), and a food-grade stream of liquid CO_2.

The captured CO_2 is stored onsite at the biomethane plant in a large buffer tank and then transported by truck to customers in the greenhouse sector. The sale of CO_2 adds an additional income stream for the biomethane producer.

3.2 Technical potential for CO_2 supply

Biomethane is produced in 11 European countries and injected into the gas grid in 9 countries. Although in most countries the contribution of biomethane to the total volume of gas consumed is still marginal, both the production of biogas and biomethane are accelerating rapidly in many European countries. Germany, the largest producer of biogas in Europe, produces 6.87 Mtoe (~8.27 bcm) from 7000 operating biogas plants. As of 2014 Germany had 151 biomethane plants, and injection of biomethane into the national gas grid has increased from 275 mcm in 2011 to 520 mcm in 2013 (EurObservER, 2014).

In the Netherlands, there are currently 12 existing biomethane installations, with a total production capacity of between 15 and 20 mcm annually (van Foreest, 2012). It has been calculated that existing biomethane installations remove approximately 36 $ktCO_2$ per year (Peeters et al., 2013). However, there are ambitious plans to accelerate the development of biomethane production in the Netherlands with feed-in tariffs for biomethane available under the Dutch SDE+ policy. Biomethane projects received feed-in tariffs per m^3 for a period of 12 years. A goal has been set by the Dutch government in collaboration with stakeholders in the biomethane industry to reach annual production levels of 700 mcm by 2020, and 3 bcm by 2030 (van Foreest, 2012), with the latter figure representing approximately 9% of total domestic natural gas consumption in the Netherlands.

As of December 2014, under the Dutch SDE+ scheme, subsidies have been granted for a number of biomethane production plants which together would have total production capacity of approximately 300 mcm per year. Assuming that 300 mcm biomethane would be derived from 475 mcm of biogas (with a methane content of 63%, and CO_2 of 35%), if realized these plants would produce a theoretical amount of 0.31 Mt of CO_2 per year by 2020, around 60% of current external CO_2 demand by Dutch greenhouses. Of course, the amount of biomethane that can be produced is also dependent on the availability of organic matter to produce the biogas. The Energy research Centre of the Netherlands (ECN) has made estimations that based on biomass availability in the Netherlands, biomethane production could reach a theoretical maximum of 600 mcm by 2020, and up to 3.5 bcm by 2030 (Lensink, 2013). Using the same calculation, realization of such biomethane production would involve the removal of 0.39 $MtCO_2$ in 2020, and 2.3 $MtCO_2$ by 2030.

"…if realized these plants would produce a theoretical amount of 0.31 Mt of CO_2 by 2020, equivalent to 60% of current external CO_2 supply to Dutch greenhouses"

3.3 Technical feasibility

Based therefore on the theoretical potential of biomethane production in the Netherlands, the amount of CO_2 that must be removed during the process looks like an important future source of industrial 'waste'-derived CO_2 for the Dutch horticultural sector. However, caution must be used in the interpretation of the above calculations. Even if considerable biomethane production is realized in the Netherlands, there are a number of technical and economic barriers that could prohibit the suitability of the CO_2 for use in greenhouses.

The suitability of the CO_2 is dependent on the type of CO_2 removal process that is selected. Few CO_2 removal technologies that are currently utilized in the biomethane industry have been designed to result in 'food-grade'[7] CO_2 that can be used directly in greenhouses. For all operators, the primary goal is to produce biomethane that meets grid specifications at the lowest cost possible. Many CO_2 removal technologies are not 100% efficient, and some methane can remain in the offgas together with CO_2, which is often referred to as 'methane slip'. Therefore many biomethane production facilities don't result in food grade CO_2 and therefore it cannot be marketed as such.

"…biomethane projects applying for subsidies in Germany must comply with a maximum methane slip of just 0.2%"

Methane is a powerful greenhouse gas, and the impact on global warming or 'global warming potential' of one tonne of methane is 25 times greater than one tonne of CO_2 over a 100 year period. Presumably for this reason, and in the interests of energy efficiency, some European countries have introduced regulation that sets limits on the amount of methane slip permitted during the upgrading of raw biogas to biomethane. Since April 1st 2012, the biomethane projects applying for subsidies in Germany must comply with a maximum methane slip of just 0.2%, supporting investment in biogas

[7] Food-grade CO_2 must have a purity of at least 99.9% CO_2

upgrading technology that produces very pure streams of both methane and CO_2. Based on information from the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland), there are no plans currently to introduce regulation on limiting methane slip in biogas-upgrading in the Netherlands, as the government expects the revenue from maximizing methane production from biogas to be the overwhelming factor in investment decisions (pers. comm. Dumont).

Table 2 below provides an overview of the different CO_2 removal techniques used in biomethane projects in Germany and their reported operating parameters. Pressure swing adsorption (PSA) and pressurized water scrubbing (PWS) have previously been widely deployed in for biogas upgrading when the resulting methane rich gas stream was used directly in combined heat and power installations. These techniques also result in a higher methane slip. Membrane filtration has previously been associated with higher methane loss, however, new membrane technologies are able to reduce such loss considerably. Importantly for the greenhouse sector, the combination of membranes with cryogenic separation (far right column), whereby the gas stream after membrane filtration is cooled and compressed, results in an ‘food grade’ CO_2 stream which surpasses the OCAP pipeline specifications and 0% methane slip.

Table 2: Reported operating parameters of different CO_2 removal techniques in Germany (Biogaspartner, 2014)

Criteria	PSA	PWS	Polyglycol	Amine	Membrane technology	Membrane/cryo hybrid technology
Rawgas desulphurisation neccessary	Yes	No	Yes	Yes[1]	Yes	Yes
Methane loss[2]	<3%	1-2%	1-2%	<0.1%	0.6-3%	0.004%
Required pressure (bar)	4-7	5-10	4-7	0-5	5-16	membrane: 6-10 cryo: 17
Consumption of electricity (kWh/Nm³ RGB)[3]	0.19-0.26[4]	0.2-0.25[4]	0.24-0.33	<0.09	0.2-0.3	0.35-0.37[5]
Required heat (temperature level)	No	No	55-80 °C	110-160 °C[4]	No	No
Chemicals	No	No	Yes	Yes	No	No
References in Germany	31	39	12	39	3	0

According to GroenGas Nederland, the biomethane association of the Netherlands, many of the recent applications for the SDE+ subsidy have chosen membrane separation as the CO_2 removal technique. For potential biomethane operators, the key priority is developing a business case for biomethane production with respect to the subsidies available, and CO_2 supply is not considered a priority (pers. comm. Voshaar).

3.4 Economic aspects

The cost of liquid CO_2 from biomethane production are related to the capital investment for the additional cooling and compression equipment, a CO_2 buffer tank(s)[8], and the associated installation and engineering costs. Operational costs are related to the additional power to run CO_2 liquefaction system, CO_2 quality control testing, and, most importantly, the transportation costs. CO_2 transportation tanks have a capacity of approximately 20-25 tons of CO_2, and the costs for the transportation service including a quality control check are estimated at between €650-800 per delivery, dependent on the distance between source and customer and the size of tanker (pers. comm. Den Heijer; Limbeek). The transport costs alone therefore already

[8] A 50-ton buffer tank would be able to hold approximately 2 trucks loads of liquid CO_2.

price the CO_2 at between €25 and €40 per ton delivered. For particularly small distances between the CO_2 producer and consumer, the transport costs may be slightly lower.

Peeters et al. (2013) calculate the cost of cryogenic distillation of CO_2 at approximately €65 per ton, based on a 700 m^3/hour biogas plant, producing around 3000 tons of CO_2 per year, of which 60% is liquefied. In the above example, the additional revenue from additional methane recovery from the liquefaction process does not appear to be accounted for, which will be dependent on the efficiency of a biomethane plant without the additional liquefaction equipment. A greater incremental recovery of methane would mean that the additional revenue reduces the cost per ton of CO_2. According to biomethane technology provider Pentair Haffmans, the additional investment needed for cryogenic distillation to produce food grade CO_2, particularly in larger biomethane plants, can almost entirely be offset by the 100% methane recovery that results (pers. comm. Den Heijer). Another estimate for liquid CO_2 production as biomethane plants in the Netherlands is likely to be between €30-45 (pers. comm. Limbeek).

Therefore, based on the best available information available and expert opinion, the costs of delivering liquid CO_2 from biomethane production can be achieved at costs between €55-105 per ton of CO_2 delivered (excluding additional service costs to any third party CO_2 company e.g. OCAP), which is competitive with market prices of liquid CO_2. Market prices of purchasing liquid CO_2 from a chemical producer are understood to be between €80-150 per ton CO_2 dependent on capacity and distance. CO_2 delivered via the OCAP pipeline to growers has a market cost of between €50-80 per ton CO_2, also dependent on distance and capacity. Dependent on whether heat can be used efficiently, CO_2 produced from CHP has a cost of between €5-75 (Peeters et al., 2013). The latter option however, even if competitive, is less desirable given the contribution of CO_2 emissions from natural gas-fired CHPs in the sector.

" … biomethane production can be achieved at costs which are competitive with market prices of liquid CO_2."

4 Innovation area 3: CO_2 capture from municipal waste incinerators

4.1 Waste incineration in the Netherlands

Since the early 1990s, the incineration of waste in the Netherlands has become the primary route for waste management. As of the end of 2013, there were 13 municipal waste incinerators operating in the Netherlands, with a total waste processing capacity of 7.7 Mt of waste per year. There are incinerators located close to large towns across the Netherlands, with considerable capacity around the cities of Amsterdam and Rotterdam. Similar to other large combustion installations, such as coal and gas-fired power plants, significant amounts of CO_2 are released through the flue gases of waste incinerators. It is technically feasible therefore, to use CO_2 separation technology to isolate the CO_2 from flue gases, which represents another potential source of CO_2 for the horticultural sector.

4.2 Technical feasibility

Table 3 below provides an indication of the concentration of CO_2 in the flue gas of a municipal solid waste incinerator. At 8.5 Mol%, the concentration of CO_2 from incinerators is lower than expected from a coal-fired power plant, but higher than a natural gas-fired power plant. From a scientific perspective, the higher the concentration of the inflow gas to a CO_2 removal plant, the more efficient the removal process will be, which translates directly to the operational costs of the system. The same principals of post-combustion CO_2 capture, as being developed for other fossil-fuel combustion installations in the power and industrial sectors, can therefore be applied to incinerators (van Loo et al., 2014).

Table 3: Average CO_2 concentrations in the flue gases of a municipal waste incinerator (MSWC), a natural gas combined cycle plant (NGCC), and a pulverized coal-fired power plant (PC).

Plant	MSWC	NGCC	PC
Component	Mol%	Mol%	Mol%
CO_2	8.5	5.0	14.0
H_2O	12.8	11.0	6.4
O_2	8.8	9.7	3.8
N_2	69.1	74.3	75.6

No officially reported figure could be found regarding the total CO_2 emissions attributable to waste incinerators in the Netherlands. However, Vroonhof and Croezen (2006), calculated that based on an estimated composition of Dutch municipal waste, each ton of waste incinerated released 1.06 ton of CO_2. Using the figure of municipal waste incinerated in 2013, an annual emission of 8.16 $MtCO_2$ can be attributed to the sector. The abundancy of CO_2 from incineration is therefore not a limiting factor for considering it as a source for the horticultural sector.

4.3 Financial aspects

Unlike the power and certain industrial processes, there is generally no financial incentives to capture CO_2 from waste incinerators, as they are not included under the European Union Emissions Trading Scheme. Despite this, there has been a government supported initiative to explore the possibility of using CO_2 from a large waste incinerator in Amsterdam, using it to supply the OCAP pipeline which extends to approximately 2 km to the potential source (AEB Amsterdam, 2014).

A detailed techno-economic assessment has been conducted to calculate the costs of using CO_2-selective membranes to separate the CO_2 from the flue gases of the AEB waste incinerator (Huibers et al., 2013). In order to increase the CO_2 concentration from an initial 9% to the CO_2 purity levels of 99% required by the OCAP network, a combination of membranes and cryogenic distillation was selected for the evaluation. Based on an annual production of 37 ktCO_2 at 99% concentration and compressed to 21 bar (operating pressure of the OCAP network), the lowest cost per tonne of CO_2 captured was calculated to be €43. Although based on a preliminary modelling study, raise attention to what could be a potentially competitive, abundant and reliable source of CO_2 for the greenhouse sector.

5 Summary and potential actions

There is currently no single solution that can provide a dependable supply of CO_2 at below-current market prices, to the entire Dutch horticultural sector. However, in the current review, three potential future sources of CO_2 have been assessed and the opportunities and possible barriers have been presented. Recommendations are provided below on actions that the horticultural sector could take to develop these options further.

5.1 CO_2 from the ROAD Project and CO_2 buffering

The ROAD-ONE-OCAP concept can be completed with existing technology, and from the preliminary feasibility study completed by TNO, no technical showstoppers have been identified.

The key barrier to the project moving forward is primarily related to current European policy on incentivising the reduction of CO_2 from large combustion installations. As of spring 2015, the price for emitting one ton of CO_2 into the atmosphere under the European Union Emissions Trading Scheme is approximately €7 (European Energy Exchange, 2015). The costs of capturing CO_2 from ultra-supercritical coal-fired power plants using post combustion capture technology as proposed at the ROAD project is expected to be between €40 and €47 per ton of CO_2 (Finkenrath, 2011)[9], excluding transport and storage. Therefore, at present there is no business case to invest in large scale CO_2 capture for the Maasvlakte CCS Project. The pledged financial support both from the European Commission and the Dutch governments of a total of €330 million, can help offset the initial investment costs, however the ongoing operational costs of the project may still outweigh the current EU ETS price, which can force the plant to close and disrupt the supply of CO_2 both to ONE and OCAP.

The ROAD project is fully contingent on the ambitiousness of European climate policy. Despite the considerable potential, and lack of technical barriers, until the current price of EU ETS credits increases substantially to encourage companies to invest in low carbon technologies such as CCS, it is highly unlikely that any large scale CCS projects will be realised beyond an initial demonstration phase.

If the ROAD project proceeds, it will be important to address the risk of CO_2 prices fluctuating in the future. The ROAD project is dependent on a business case built on the incentive of reducing emissions under the EU ETS. Assuming the ROAD project proceeds, each ton of CO_2 sold to OCAP will be considered as emitted under the scheme, and therefore must be paid for. At the current prices of €7, this may still represent an small portion of cost to be built into the CO_2 tariff charged by the operators of ROAD, however, if the EU ETS price increases as it is generally expected to do (and will have to if ROAD is to keep capturing CO_2 affordably after the two-year demonstration phase), one would expect the costs of purchasing CO_2 to also increase.

There could be contractual or technical solutions that could be used to overcome this issue. A long-term contract for a fixed price per ton of CO_2 could mitigate the financial risk to OCAP of fluctuating ETS prices. The technical solution would be if the ROAD project co-fires coal with a percentage (i.e. 10-20%) of sustainable biomass, in which case the CO_2 emissions

[9] The range of figures is dependent on the type of coal used. Figures converted from EUR to USD using an historical exchange rate of 1.3 (2011). The actual predicted costs of the ROAD project are not known.

associated with the biomass portion are considered as CO_2-neutral and therefore insulated from ETS price fluctuations.

One area, however, that would require further scientific research, is the interaction of the CO_2 with the reservoir during the temporary storage (buffering). OCAP has strict specifications for the purity of CO_2 delivered to greenhouses, which are based on the limit values for impurities that are potentially harmful to greenhouse products. For a large number of components which could be present in the CO_2 after it is reproduced from the Q16-Maas field, no threshold values are defined, and hence, knowledge is currently lacking whether the organic species, i.e. methane, ethane, and butane, are potentially harmful to greenhouse crops. This issue is not considered a showstopper, however, the results of further research can allow for the more accurate identification of the most suitable gas-cleaning equipment.

The developers of the project, E.ON Benelux and GDF SUEZ Energy Netherlands, are expected to make a Final Investment Decision in early 2016, and if positive, construction and commissioning would take around two years to complete with additional CO_2 supply for greenhouse available by 2019. At present, the demand for CO_2 delivery to the greenhouse is not an overwhelming factor in the decision being made by the initiators of ROAD. In light of this, it is highly recommended that:

- The sector must highlight the importance of the external CO_2 supply to the greenhouses to the Dutch government, providing the foreseen demand for external CO_2 from the entire greenhouse sector in the Netherlands, developing scenarios for production capacity of the sector, the trend in economic viability of using CHP installations, the potential influx of renewable power and heat, and the development of improved CO_2 dosing techniques in greenhouses.

- Efforts should be made to quantify the potential net emission reductions through the greater use of sustainable heat and renewable power, and the employment opportunities that could be created through the increased competitiveness of the sector.

5.2 Biomethane production

Technology for the production of biomethane from biogas has been considerably optimised in recent years. Whereas it is expected that advances in membrane separation technology for CO_2 removal will be improved in the future, the costs of cryogenic distillation equipment to produce fluid CO_2 necessary for transportation are not expected to drop considerably. Given the best information available, the costs of producing liquid CO_2 from biomethane installations are comparable with those of commercial CO_2 suppliers which deliver CO_2 to greenhouses by truck. However, the uncertainty of the cost of CO_2 from biomethane is considerable, and clarification of the costs under a range of scenarios and locations would be useful.

One concept that could offer scope for cost reductions is the development of biomethane hubs or clusters, whereby biogas from multiple producers are gathered into a pipeline that leads to a central biomethane production facility. There are currently plans to develop five biomethane hubs or ‘green gas hubs’, with a project total biomethane production capacity of 200 mcm per year (Energy Valley, 2010). Such hubs can greatly improve the economies of scale both for biomethane production, but also for the recovery of CO_2. Although the proposed sites for the green gas hubs are too far to connect with the existing OCAP infrastructure by pipeline, a central CO_2 recovery location could also offer possibilities for improved logistical coordination to reduce transportation costs.

In summary, in a number of actions are recommended in order to better assess the suitability of biomethane production to provide an affordable and sustainable supply of CO_2 to the Dutch greenhouse sector:

- Further and more detailed investigation is necessary to determine the costs of liquid CO_2 production from biomethane production. Calculations should incorporate a range of scenarios such as new build installations and retrofitting of cryogenic distillation equipment, different biogas capacities (economies of scale), the revenue from incremental methane recovery improvements and delivery distance ranges.

- Improved costing of cryogenic distillation equipment integration in biomethane production will allow a better assessment of economic feasibility, and hypothetical business cases (assuming they exist) which combine biomethane and CO_2-production can be developed and showcased to the Dutch biomethane association in order to raise awareness of the opportunities to gas producers.

- The co-benefits of methane slip reduction and the availability of CO_2 delivery to the greenhouses, which in turn can allow the reduced reliance on the combustion of natural gas, should be communicated to Dutch policy makers to highlight the net emission reduction potential.

- A ‘source-sinking’ matching exercise of existing and planned biomethane plants in the Netherlands (and potentially in the West of Germany) can be completed and annually updated in order to identify low-cost CO_2 delivery routes and to inventories availability and capacity.

5.3 Waste incinerators

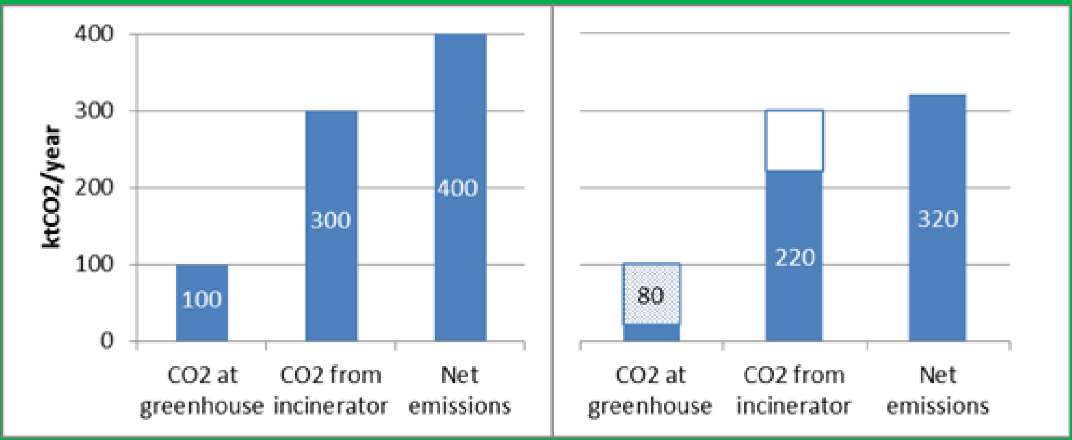
Municipal waste incinerators produce an abundant supply of CO_2 in low concentrations. Incinerators are present in many parts of the country and some are located close to greenhouse clusters. Waste incinerators are not covered by the EU ETS and therefore the price of CO_2 is not expected to increase in the future. One of the largest incinerators in the Netherlands, AEB Amsterdam, is located just 2 km from the existing OCAP infrastructure, and could provide a significant amount of the additional CO_2 demand from growers.

A detailed engineering study of CO_2 capture from a waste incinerator has calculated a cost of €43 per ton of CO_2 captured, to reach the specifications of the OCAP infrastructure, excluding any additional transportation costs. The costs associated with removing CO_2 from diffuse point sources are relatively high, and currently above current OCAP market prices. Despite the economic challenges with this option, a number of actions could be considered to further the concept:

- The reuse of CO_2 from AEB Amsterdam has no direct policy incentive, however it could improve the sustainability of the incineration process, as long as it can be demonstrated that less natural gas is consumed by growers due to the availability of additional external CO_2. With careful accounting, such an initiative could lead to net emissions reductions, with growers agreeing to invest in sustainable heat and power projects, in order to receive an affordable external CO_2 supply. Under this concept, there could be some incentive for a cost-sharing cooperative agreement between OCAP, AEB Amsterdam and the local municipal government, which could support the project moving forward.

Box 2: Potential for net emissions savings through CO_2 reuse

The availability of affordable external CO_2 can support the transition to a sustainable horticultural sector. A number of growers are already investing in geothermal heat projects, and further opportunities exist for the use of waste industrial heat and generating electricity through solar photovoltaic power, however, external CO_2 is a clear condition to allow such opportunities to flourish. External CO_2 capture from industrial sources such as incinerators can reduce the reliance on CHP exhaust gases for CO_2 supply, enabling heat and power to be provided without the need to combust natural gas, thereby leading to net emission savings. With careful carbon accounting, joint initiatives could support the environmental performance of waste incinerators and greenhouses, as part of a low-carbon regional development strategy, moving towards a competitive and sustainable horticultural sector.



* Numbers used are for illustrative purposes only

- Different types of CO_2 capture processes could be explored. The only study of CO_2 capture from AEB Amsterdam included a combination of membranes with cryogenic distillation, but other capture processes including the use of CO_2 selective chemicals which could incorporate waste heat from parts of the incinerator, may offer scope for moderate cost reductions, if compatible.

- The greenhouse sector, via the branch organization, could become more actively engaged in research and development projects for CO_2 capture technologies in the Netherlands. Large research institutions TNO and ECN, through for example the CATO-TKI project, continue to further the efficiency of capture technologies primarily for the purposes of carbon capture and storage (CCS), but the principles of CO_2 capture are identical and could deliver cost savings in the long-term.

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Annex I – Analysis of CO_2 supply and management options

CO_2 supply solutions	**Analysis criteria**						
	Potential coverage*	Short term availability**	Cost per ton CO_2***	Security of supply	Technical feasibility	Innovation potential	Comment
CO_2 from ROAD	+	++	++	-	++	**Low**	• CO_2 capture plant in planning phase • Close to CO_2 demand • Existing transportation infrastructure • Investment costs covered by third parties and government (low CO_2 cost) • Risk of project completion • Risk of long-term supply • Cost of CO_2 may fluctuate (EU ETS)
CO_2 from biomethane	++	-	0	++	++	**Low**	• High concentration CO_2 available as byproduct (low capture costs) • Potential sources across country • Secure supply, steady price • Green CO_2 (CO_2 neutral) • High transportation costs • Insufficient supply short term • CO_2 quality/suitability may vary
CO_2 capture from waste incinerators	++	+	-	++	+	**Medium**	• Existing sources across country • Project can be realized in short term • Secure supply, steady price • High capture cost (not byproduct) • Transportation infrastructure necessary

CO_2 supply solutions	**Analysis criteria**						
	*Potential coverage**	*Short term availability***	*Cost per ton CO_2****	*Security of supply*	*Technical feasibility*	*Innovation potential*	*Comment*
CO_2 capture from air	+	--	--	+	-	**High**	• Secure supply, steady price • Units can be installed in all regions • No transport necessary • Not proven at pilot scale • High/unknown capture costs • Heat source is necessary in many cases • Additional liquid CO_2 may be necessary during peak
Natural CO_2 source	++	?	?	++	+	**Low**	• Steady, stable supply • Controllable • Possible gas revenue • Public acceptance • Sustainability (Carbon +) • Transport costs • Investment cost (well)
Other industrial sources (Hydrogen, Steel etc)	+	+	+	-	+	**Medium**	• Large point sources • Relatively low carbon costs • Local coverage • Supply risk (dependent on operation) • Cost risk (EU ETS) • Transport infrastructure necessary

Analysis criteria

CO_2 management	Potential coverage*	Short term availability**	Cost per ton CO_2	Security of supply	Technical feasibility	Innovation potential	Comment
Surface CO_2 buffer	-	++	n/a	n/a	++	**Low**	• Project can be realized in short term • Integrated with existing infrastructure • Can balance seasonal demand • Existing source necessary • Limited additional coverage • Investment in land and equipment necessary
Geological CO_2 buffer	+	+	n/a	n/a	+	**Medium**	• Integrated with existing infrastructure • Can balance seasonal demand • Minimal surface footprint • Existing source necessary • High planning and development costs • Uncertainty regarding CO_2 quality
CO_2 shipping by sea/inland waters	+	-	n/a	n/a	-	**Medium**	• Potential to reduce bulk CO_2 transport costs • Improve CO_2 supply corridors nationally/internationally • Limited experience with CO_2 transport by ship in the Netherlands • Requires loading/offloading infrastructure

* Regional coverage of Dutch greenhouse that could potentially be supplied by source
** Possibility for CO_2 supply to greenhouses prior to 2020
*** Based on current costs estimates

Key

++	Clearly positive attribute	-	Negative attribute
+	Positive attribute	--	Clearly negative attribute
0	Neutral	n/a	Not applicable

Notes

TNO
Earth, Life & Social Sciences
Princetonlaan 6
3584 CB Utrecht
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 88 866 42 56
F +31 88 866 44 75