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

TNO report

Preliminary Technical Concept Assessment – The CO_2 Smart Grid

Version 1 – Q1 2018

Date	10 January 2018
Author(s)	Tom Mikunda, Filip Neele

Copy no.	1
No. of copies	1
Number of pages	19
Number of appendices	0
Customer	The CO_2 Smart Grid
Project name	The CO_2 Smart Grid
Project number	nvt

Contents

1 Introduction and objective

The CO_2 Smart Grid is a climate initiative of around 30 stakeholders from industry, provincial governments and authorities, supported by research institutes and national ministerial departments. The initiative aims to plan and realise a large-scale CO_2 transportation infrastructure across the Netherlands. The main goal of the CO_2 Smart Grid is to reduce the CO_2 emissions to the atmosphere, by linking emitters and users, both current and potential, through an optimised 'smart' CO_2 grid which provides demand-matching through a combination of temporary and permanent CO_2 storage solutions.

The initiative is currently embarking of the start of a pre-feasibility phase, which aims to address a series of key questions to determine the societal, economic, and most importantly, the environmental benefits of the potential infrastructure. Furthermore, the pre-feasibility study will assess the characteristics and availability of the key technical and engineering components required to develop such a plan. The latter will include the development status of current and potential CO_2 suppliers, temporary and permanent (geological) storage possibilities and an inventory of current and potential future CO_2 users, which together will ultimately define the physical extent and operation of the CO_2 pipeline network.

To contribute to the technical understanding at this pre-feasibility phase, TNO, in collaboration with a number of the CO_2 Smart Grid stakeholders, proposes to develop a 'Technical Concept Assessment' for the CO_2 Smart Grid. The objective of this document is to provide an overview of the expected physical extent of the CO_2 Smart Grid, based upon an assessment of the existing CO_2 pipeline infrastructure in the Netherlands (operated by OCAP), potential CO_2 suppliers (both current and expected), potential geological storage locations, current CO_2 demand by the horticultural industry, and where available, future CO_2 demand for innovative re-use technologies[1].

This is the first version of the Technical Concept Assessment, based on the currently available information of the intentions of various stakeholders within the Smart Grid consortium. It is possible that as more concrete information becomes available that this document will be updated.

1.1 Climate mitigation challenges in the Netherlands

By 2020, The Netherlands has committed to reduce its CO_2 emissions by 14-17% against 1990 levels, in order to comply with European climate legislation. Furthermore, the Dutch State currently have a legal obligation to reduce CO2 emissions to 25% against the same baseline as a result of the 'Urgenda' court case ruling in 2015. However, national CO_2 emissions have actually increased from 160Mt to 170Mt since 1990's [PBL], and recent data suggests that emissions are continuing to rise (CBS, 2017).

---

[1] The inclusion of future re-use options in the Netherlands is dependent on outcomes of another study to be conducted in parallel by consultancy firm, Ecofys, with initial results expected by the end of July 2017.

The Netherlands has a strong industrial base, which contributes considerable GDP to the economy, however at the price of high CO_2 emissions. Figure 1 shows that for a number of key industrial sectors in the Netherlands, CO_2 emissions have remained relatively stable since 1990. A slight downward trend is apparent for the chemical sector. Noteworthy though, is that all sectors covered have managed to greatly increase industrial productivity over the same period, without allowing CO_2 emissions to rise. It can be deducted, that energy efficiency measures have been effective in these sectors.

Emissions from waste-to-energy plants on the other hand have grown steadily over the same period. This increase can be attributed to landfill bans which were introduced in the Netherlands in the mid-1990s, but also more recently, the increase in waste imported for incineration from other European countries such as the United Kingdom, Ireland and Italy. It is understood that a number of initiatives are underway to reduce the CO_2 emissions from waste incineration, including the CO_2 Smart Grid initiative.

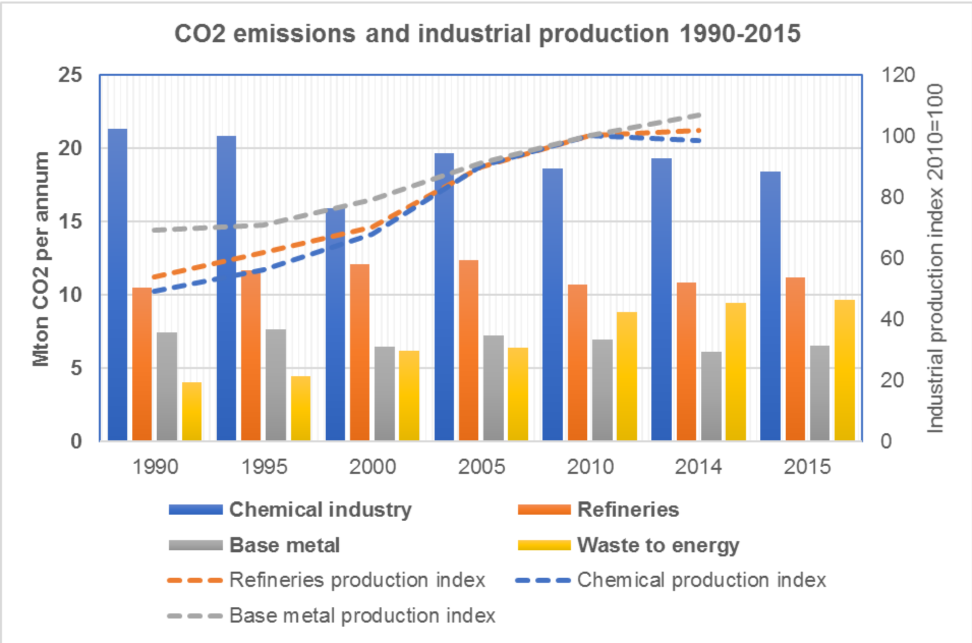

Figure 1 CO_2 emissions and industrial production in the Dutch chemical, refining and base metal sectors between 1990 and 2015.

In October 2017, the newly formed cabinet of the Dutch political parties VVD, CDA, D66 and the ChristenUnie, released the long-awaited coalition agreement, a document outlining the key policies of the Dutch government for the period of 2017-2021. The plans include an ambitious acceleration in national climate policy to contribute in reaching the goals of the Paris Climate Agreement. The agreement highlighted that CO_2 capture and storage (CCS) must play a central role in decarbonizing Dutch heavy industry.

The main target of the coalition government is a 49% reduction in CO_2 emissions from 1990 levels by 2030, equating to an annual reduction of 56 Mt CO_2. The emission reduction targets will be formalized in a new climate law. Based on scenarios from the Netherlands Environmental Assessment Agency (PBL), an overview of the foreseen reductions per sector and associated measures have been included (see Table below). Noteworthy is the contribution of CCUS towards the overall target, with an 18 Mt reduction from the industrial sector, and a 2 Mt reduction from the waste incineration sector foreseen.

Table 1 Indicative share of CO_2 emission reductions per sector in the Dutch coalition agreement

Indicative share per sector of 49% emission reduction plan for 2030		
Sector	Reduction in 2030 (Mt)	Measures
Industry	1 3 18	Recycling Process efficiency CO_2 capture and storage
Transport	1.5 2	Efficient tyres, European standards, electric cars Biofuels and urban initiatives
Built environment	3 2 2	Optimum energy use in office buildings Insultation of residential buildings, heat networks and heat pumps Energy efficient housing developments
Power production	1 12 2 4 1	Efficient lighting Closure of coal-fired power stations CO_2 capture and storage from waste incineration plants Extra offshore wind developments Extra solar energy developments
Land use and agriculture	1.5 1 1	Intelligent land-use planning Reduction in methane emissions Energy production from greenhouse sector

Furthermore, the document also highlighted that the industrial clusters of both Rotterdam and Amsterdam must be supported in realizing the deployment of CCUS.

1.2 Potential impact of the CO_2 Smart Grid concept

The need for Dutch industry to reduce emissions is all too evident. The CO_2 Smart Grid could play an important role in kick starting an infrastructure for the reuse and permanent storage of CO_2. The CO_2 Smart Grid concept is particularly suited to the Netherlands for a number of reasons, many of which are fully unique to the Dutch economy:

Geographical factors

- A considerable amount of Dutch CO_2 emissions are located within a radius of 100 km. For example, the industrialised harbours of Rotterdam and Amsterdam, and the integrated steel mill in Ijmuiden contribute approximately 1/3 of total Dutch CO_2 emissions (this figure would be much higher if one considers point sources alone).
- There is ample potential CO_2 storage capacity on the Dutch continental shelf, sufficient for an estimated 1000 Mt of CO_2 storage.

Knowledge and experience

- There is an existing CO_2 transportation network which have been operating successfully for a number of years, which runs between the harbours of Rotterdam and Amsterdam (OCAP).
- There is considerable knowledge on CCS, and a growing body of knowledge on CO_2 utilisation which Dutch universities, research institutes and the private sector.

Industry and economy

- There is existing demand for CO_2 from the Dutch horticultural sector, of between 0.8 to 1.2 Mt CO_2, of which only half is currently met through the OCAP system. If more CO_2 can be provided this sector can further reduce its reliance on natural gas combustion and invest further in waste heat and renewable energy technologies. Reducing energy and nutrient costs for this sector can help it to become more sustainable and compete with growing competition from European and non-European producers.
- The Netherlands has a large and innovative petrochemical and chemical sector where opportunities lie for the reuse of CO_2 for polymer production and synthesis of cleaner burner transportation fuels.
- There are opportunities in the concrete manufacturing industry for CO_2 storage through carbonate mineralisation.

1.3 Foreseen benefits of the CO_2 Smart Grid initiative

Beyond the potential for reduced CO_2 emissions, a coordinated initiative, such as the CO_2 Smart Grid, has a number of foreseen advantages. For example, potential economies of scale can be taken advantage of, making sure new CO_2 transportation and storage infrastructure is developed to allow potential third-party users to gain access, without having to construct separate costly point to point pipelines. Approximately 70% of the construction costs for CO_2 pipelines in the Netherlands are associated with engineering and construction, rather than materials (pers. comm. J. Limbeek).

Having multiple parties in an initiative such as the CO_2 Smart Grid, can also reduce the financial risks to individual parties. Shared investment across a number of development phases of the project could help overcome financial barriers to the project moving forward.

Finally, the establishment of a CO_2 Smart grid can lay the foundations for a CCU R&D hub in the Netherlands, attracting international companies and start-ups, strengthening the knowledge position of the Netherlands and boosting export potential of both CCU knowledge and products.

2 Current and future CO_2 projects in the Netherlands

2.1 Existing sources

2.1.1 CO_2 from hydrogen production and bio-refineries

There are currently a number of existing industrial installations in the Netherlands which have to remove CO_2 as an inherent part of the production process. These processes are generally related to the production of hydrogen, from either steam-methane reforming, the gasification of liquid fossil fuels or the fermentation of biogenic material. Hydrogen is produced at a number of places around the Netherlands, such as Geleen (Chemelot), Sluiskil (Yara), and in the Rotterdam harbour (Shell, Air Products, Air Liquid, Linde Gas etc). A number of these companies sell CO_2 in liquid form to a ranges of users, however only the Shell Pernis refinery and the Alco biorefinery are connected to the OCAP CO_2 network. These two sources deliver approximately 450 kt CO_2 per year to the OCAP network.

2.2 Potential future sources

2.2.1 TATA Steel HIsarna production process

Process: TATA Steel in Ijmuiden are developing a new innovative technology for the production of primary steel. The technology, which could replace the use of the conventional blast furnace, and can directly use raw materials (iron ore and coal) without the need for agglomeration or coking. This new process can reduce emission of primary steel production by 20% compared to a conventional blast furnace route. However, the exhaust stream of the HIsarna process in rich in CO_2, and it's expected that this CO_2 can be removed at a relatively low cost, compared to for example coal and gas-fired power plants.

Status: Currently testing a pilot facility. If successful a CO_2 capture unit could be built by 2020. A full-scale HIsarna plant, producing 1 million tonnes of primary steel per year could be built by 2024 if pilot testing is successful.

CO_2 availability: 2020 – 100 kt, 2024 – 1 Mt.

2.2.2 AEB Amsterdam

Process: AEB Amsterdam is a large waste-to-energy plant in the harbour of Amsterdam. The company joined a 'Green Deal' initiative with the Dutch Ministry of Economic Affairs to develop a CO_2 capture facility at the plant, and deliver the CO_2 to the Horticultural sector in the region. It is understood that the company has the ambition to capture 450 kt CO_2 per year (pers. comm. J. Limbeek). The capture costs of CO_2 capture from waste incineration are however higher (€40-50/tonneCO_2) than for example hydrogen production and fermentation processes (€5-15/tonneCO_2).

Status: FEED study – ambition start capture 2020

CO_2 availability: 450 kt CO_2/yr

2.2.3 *AVR Rotterdam*

AVR is a waste-to-energy installation in the Rotterdam harbour. CO_2 capture is one of the potential routes that the company is developing to reduce its overall environmental impact. AVR has a CO_2 capture installed at a waste incineration plant in Arnhem.

Status: Design phase, ambition to deliver by 2020/21

CO_2 availability: 250 – 300 kt CO_2/yr

2.3 Development of foreseen CO_2 supply to Smart Grid 2020-2030.

Based on the current availability of CO_2 from existing sources linked to the OCAP network, and from the ambitions of a number of Smart Grid partners, and visualisation of the potential CO_2 supply to the Smart Grid is provided below (Figure 2). With CO_2 becoming available from the HIsarna demonstration plant in 2020, combined with considerable CO_2 from the waste to energy plants of AEB and AVR, the total CO_2 to be transported could reach 1.25 Mt/year by 2021. It is not clear if the waste incinerators will capture CO_2 during the entire year, as there is currently little demand for CO_2 from the horticultural sector in the winter months.

If the HIsarna pilot plant and CO_2 capture facility is successfully demonstrated, a full-size industrial plant could be realised by 2024. In this case, total potential CO_2 supply to the Smart Grid could reach 2.15 Mt/year by this time. It is highly likely that should this supply be realised, the CO_2 Smart Grid would need to be connected to additional transportation infrastructure to access geological CO_2 storage locations in the North Sea.

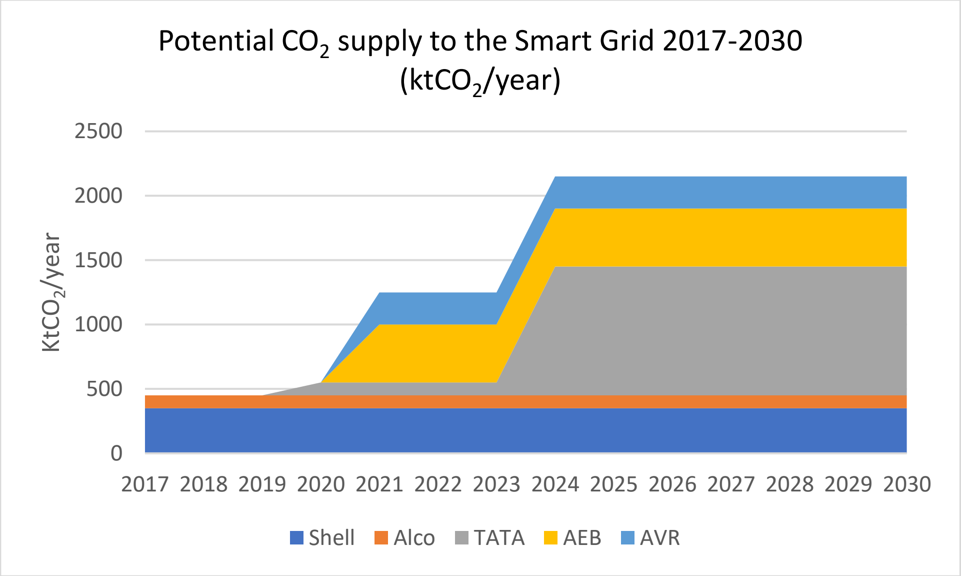

Figure 2: Potential CO_2 supply to the Smart Grid 2017-2030 (ktCO_2/year)

3 Geological CO_2 storage locations in the North Sea

The CO_2 Smart Grid Feasibility Study identified 3 strategies for a Smart Grid to develop, namely; (1) a CCU grid, (2) a demonstration-size CCUS grid and, (3) a large-scale CCUS grid. Whereas the first option of a market-driven CCU grid could be developed in the near term with limited public subsidies, the maximum societal value good be achieved by incorporating the initially CCU focused Smart Grid into a large scale CO_2 transportation and geological storage network. The latter development would require much greater intervention by the Dutch government in the form of subsidies and policy mechanisms to address the current market failures.

Should an initial CCU grid become part of a large CCUS infrastructure, there is considerable offshore CO_2 storage capacity available in either soon to be decommissioned natural gas production fields, or known saline aquifer formations in the North Sea. A number of potentially interesting fields and formations, both in terms of locations, geological suitability and storage capacity are outline below.

3.1 Q16-Maas

The Q16-Maas field is located just offshore of the Maasvlakte, and is actually produced from an onshore installation operated by Oranje Nassau Energie. The production of gas and condensates from the Q16-Maas field commenced in 2014, and is expected to continue to 2020 and perhaps later. Given the close proximity of the field to the OCAP pipeline, TNO was asked to conduct a pre-feasibility study for using the field as dual-purpose CO_2 storage, but also as a CO_2 buffering location. During periods of low demand of CO_2 from the horticultural sector in the winter, surplus CO_2 would be injected into the Q16-Maas and then re-produced once demand increased in the busier spring/summer seasons. 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. However further research is ongoing regarding potential reaction of the CO_2 with the geology, and the extent of gas cleaning necessary prior to delivery to the OCAP network after (re)production.

Storage capacity: ~ 2 Mt (high confidence)

Theoretical availability: 2017 (as dual-purpose buffer)
~ 2021 (as standalone storage site)

3.2 P18-4 gas field

The P18-4 field is a near-depleted gas field at a depth of 3.5 km under the seabed, located approximately 20 km off the Dutch coast in the North Sea. P18-4 is one of a number of gas fields in the P18 and P15 licensing blocks on the Dutch continental shelf of which TAQA Off-shore B.V. holds the production licenses. The gas production has reduced the field pressure from 340 bar to 20 bar, and the field has since been identified as a highly suitable CO_2 storage formation, with an approximate capacity of 8 $MtCO_2$. TAQA received an irrevocable CO_2 storage permit under the EU Directive on the geological storage of CO_2 (2009/31/EC) for P18-4 in September 2013.

Storage capacity: ~ 8 Mt (high confidence)

Theoretical availability: 2017

3.3 P18-2 gas field

The P18-2 gas field is the largest field in the P18 block, located near the P18-4 field. The P18-2 gas field is also connected to the P18-A platform. The gas field has been producing since 1992, and the original amount of gas in place is estimated at 13.4 bcm. The gas field is expected to cease production in 2018. As part of the EIA of the ROAD project conducted in 2011, an initial risk assessment for CO_2 storage in the P18-2 field has been completed. The field is expected to have much the same geological characteristics as P18-4, and therefore be very suitable for CO_2 storage. Prior to any storage permit application, the condition of a number of suspended and abandoned wells needs to be re-assessed. Based on the amount of gas originally in place, the fields has a theoretical CO_2 storage capacity of 32 $MtCO_2$.

Storage capacity: ~ 32 Mt (theoretical)

Theoretical availability: 2020 (end production +2 years for characterisation / permitting)

3.4 P15 Complex

The P15 complex is a cluster of gas fields together with the Rijn oil field located approximately 20km north-west from the P18 fields. The gas fields are connected to the P15-D platform, where the gas is processed to sales specification and exported through a 40 km 26" pipeline to the Maasvlakte, near Rotterdam. A number of gas fields, specifically the P15-9, P15-11 and P15-13 are expended but are highly suitable for CO_2 storage. An approximate total CO_2 storage capacity of 34 $MtCO_2$ is theoretically available. An initial storage assessment of the above fields concluded that the containment characteristics of the field are good and that risks for CO_2 storage are minimal (Neele, et al., 2011). The depleted gas fields of the P15 complex are considered as logical follow-on storage sites after P18-4 and P18-2.

Storage capacity: ~ 34 Mt (theoretical)

Theoretical availability: 2020 (end production +2 years for characterisation / permitting)

3.5 Q1 saline formation

The saline formation in the Q1 block that contains the Q1 oil fields could become the prime storage location for CO_2 captured in the Amsterdam and Rotterdam regions. The oil fields in the Q1 block, located at about 40 km west of Den Helder, are close to the end of production, producing both water and oil. Water has been injected to optimize production from the fields. The water has been drawn from the saline formation in the crests of which are located the oil fields. As a result of these production activities, the pressure in the saline formation is now well below the hydrostatic (original) pressure. The voidage created by the production of water and oil can be used for CO_2 storage. A preliminary estimate of the storage capacity of the saline formation is in the order of 100 Mt CO_2 (Neele, et al., 2011). Continuing production of saline formation water is also an option, which could further increase the field's storage potential significantly. In addition to the significant storage capacity, the saline formation can potentially accommodate high to very high injection rates (several megatonnes per well per year).

Storage capacity: ~ 100 Mt + (theoretical)

Theoretical availability: 2024 (needs further site characterisation and test injection, plus permitting)

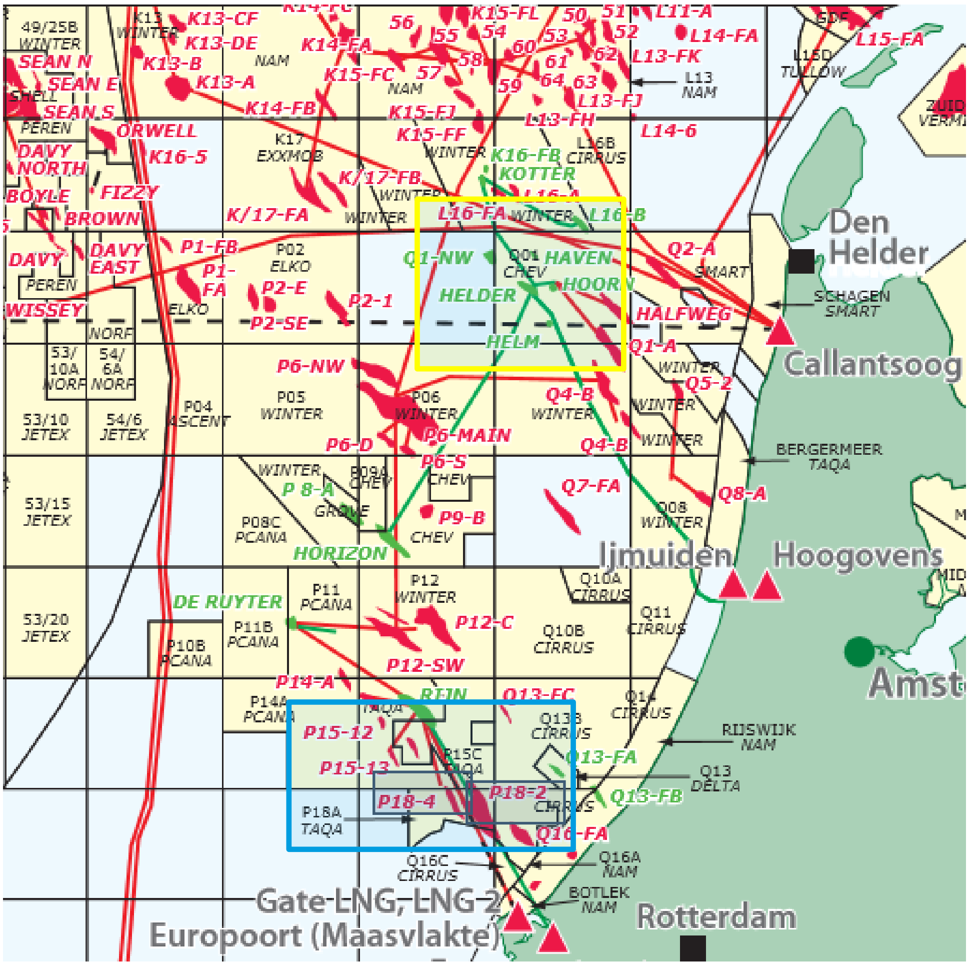

Figure 3: Locations of P18 and P15 gas fields (blue outline), and the Q1 saline formation (yellow outline)

4 Current and future CO_2 users

4.1 Demand from the horticultural sector

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.

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]. Generally speaking, CO_2 concentrations in a greenhouse are normally increased to 600-1000ppm, whereby 400ppm represents atmospheric conditions.

However, steadily increasing natural gas prices, and decreasing electricity prices are having a negative impact on the economic viability of CHP installations. Growers are looking for alternative, more sustainable ways to heat, power and provide CO_2 at their facilities. The use of external CO_2, without the combustion of natural gas is growing in the Netherlands. 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.

The current OCAP infrastructure delivers approximately 450 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 much higher, at approximately 900 ktonnes per annum. It is further expected that demand for CO_2 in the provinces of North and South Holland could reach 1.2 Mt within 10 years (Ecofys, 2017). Figure 4 below shows the current extent of the OCAP pipeline, possible extensions, current and potential delivery areas and the estimated associated demand.

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

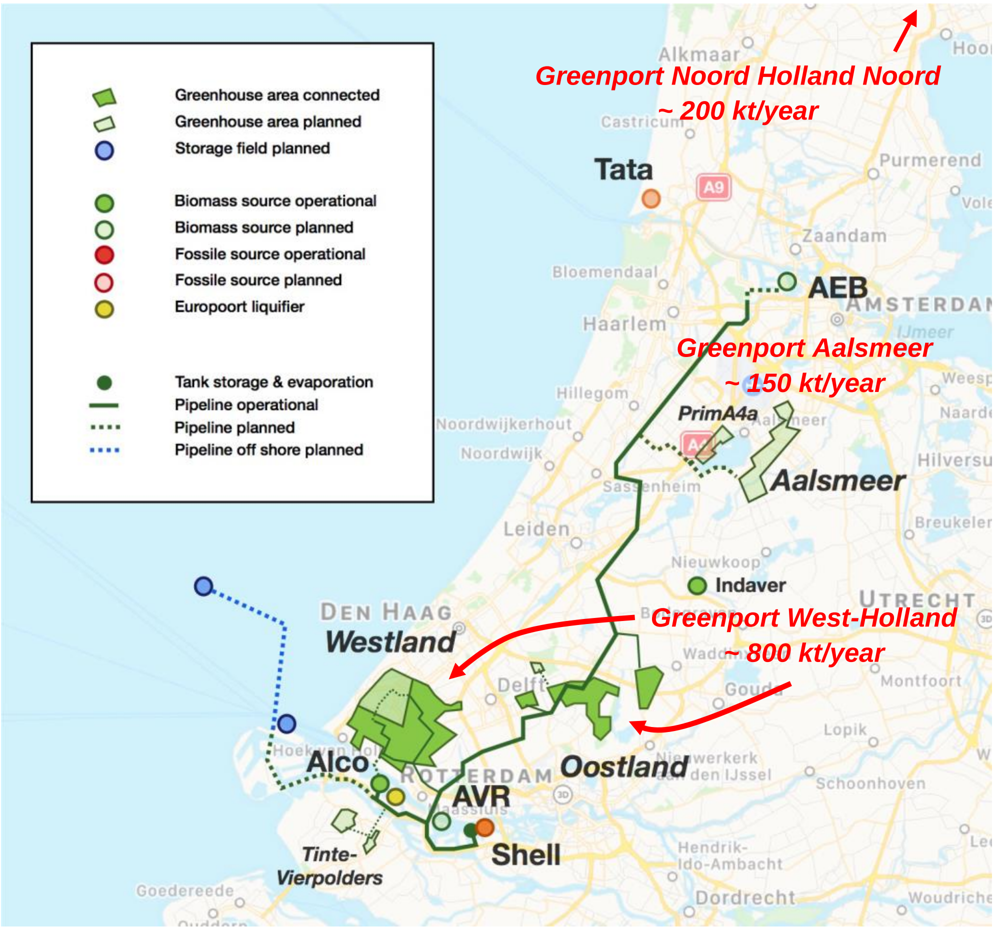

Figure 4 Current OCAP pipeline, potential expansion routes, delivery areas and associated demand Courtesy of OCAP).

4.2 Future CO_2 users

The future demand for CO_2 has been extensively assessed in the CO_2 Smart Grid Pre-feasibility Assessment (Ecofys, 2017). The report identifies a number of potential process that could require demand for CO_2 in the future (see Table 2). Although additional demand could arise, it's impossible to identify in which locations the demand will occur. With regards to polymer process and methanol production, it would be sensible to assume that such activities may occur within the considerable chemical complex situated around the Rotterdam harbour. Given that the OCAP pipeline is also situated in this region, supplying these new process with CO_2 from the Smart Grid is unlikely to warrant major investments. For carbonate mineralisation, which is generally associated with cement and concrete production, the potential location for such new processes are far less certain, as these activities are not currently found within the vicinity of the OCAP pipeline.

Table 2 CCU technologies potential for the Netherlands between 2017 and 2027 (Ecofys, 2017)

CCU technology	TRL	Current 2017 kt CO_2	Near term (5 years) kt CO_2	Long term (10 years) kt CO_2
Horticulture	9	400-500	850-1000	1200
Carbonate mineralization	4-8	0	100-200	100-300
Polymer processing	8	-	12-23	30-45
Concrete curing	7-8	-	-	30
Synthetic methanol (including methane)[3]	8	-	-	220
Methanol yield boosting[4]	9	630	900	1250
Rounded total[5]		**~400**	**~1000**	**~1700**

1: See appendix C for a discussion on biogenic CO_2
2: These estimates are produced keeping the UK market potential as reference from an earlier Ecofys study for BEIS UK (Not published yet).
3: Potential of synthetic methanol is highly uncertain, see appendix B
4: This potential usually represents on-site captive CO2 from flue gases of reformer, percentage of non-captive CO_2 is very small. If CO_2 is used through an external CO_2 source then high volumes of CO2 can be supplied as indicated.
5: Excluding methanol yield boosting, as these CO_2 can be recycled in internal methanol production processes.

5 Physical extent and requirements of the CO_2 Smart Grid

5.1 The role and basic operating principles of the CO_2 Smart Grid

During an expert workshop as part of the development of this technical assessment, a number of key operating principles of the CO_2 Smart Grid were discussed and agreed upon. These key principles are outlined below:

- The CO_2 smart grid should be designed to link current and future CO_2 emitters, with current and future CO_2 users.
- The current demand for CO_2 from the horticultural sector should be a catalyst for broader deployment of a CO_2 delivery grid for future applications.
- A ‘smart grid’ should have the capability to balance supply and demand.
- The smart grid should be able to manage daily demand, as well as seasonal demand.
- The smart grid should be able to improve the security of supply for CO_2 users, but also open new markets for CO_2 suppliers.
- Geological CO_2 storage/buffering should be used when CO_2 demand is low.

5.2 Current extent and capabilities of the OCAP CO_2 Network

The OCAP pipeline is expected to be the foundation, or ‘backbone’, for the future development of the CO_2 Smart Grid. The OCAP pipeline has a total annual transport capacity of 3-3.5 $MtCO_2$ at the standard operation pressure of 21 bar, and therefore sufficient to transport the amounts of CO_2 potentially becoming available for the Smart Grid towards 2030.

The OCAP pipeline is in good condition and can certainly operate for a further 20 years without significant renovation work. The pipeline could operate at higher pressures of up to 60 bar, which would increase the total capacity, however this would require additional investment to allow the infrastructure to operate at higher pressures.

5.3 Basic planning and identification of required extensions to supply and demand

In the phase towards 2024, there are three potential extensions of the OCAP pipeline to establish the CO_2 Smart Grid:

Pipeline connection	Length	To be realised by
OCAP pipeline Amsterdam Westpoort to TATA Steel – Velsen-Noord	~ 30 km	2020
OCAP pipeline Amsterdam Westpoort to AEB Amsterdam	~ 1.5 km	2020
OCAP pipeline inlet station in Botlek Rotterdam to AVR Botlek	< 1 km	2021

It important to note that there is also an existing disused oil pipeline that has been used to transport oil from the Q1 field in the North Sea to the Amsterdam oil terminals in Amsterdam Westpoort. The pipeline section near the oil terminals is within 2 km of the current OCAP pipeline. On it way to the coast, the trajectory of the pipeline passes to the East of the town of Beverwijk, which is within approximately 5 km of the TATA Steel site in Velsen-Noord. OCAP have investigated the suitability of reusing this pipeline for the purposes of transporting CO_2 and have found limited technical barriers for doing so. Therefore although the distance between the OCAP end station in Amsterdam Westpoort and TATA Steel in Velsen-Noord is approximately 30 km, the bulk of this distance for the transportation of CO_2 could be bridged by the reuse of this existing pipeline. This opportunity can therefore reduce the costs of extending the OCAP pipeline to TATA Steel considerably.

With regards to the supply of CO_2, particularly for the horticultural sector in Greenport West-Holland, the infrastructure is largely in place to supply the approximate 800 kt CO_2 needed per year. OCAP is also expanding its distribution network to Greenport Aalsmeer, and expects to be able to start delivering CO_2 to part of the area by 2018, with further expansion in the area by 2020 (Goedemorgentomaat, 2018). Beyond the horticultural sector, it is too early and uncertain to pinpoint where potential pipeline extensions may be needed to reach future CO_2 users.

5.4 Identification of engineering works that could be necessary

Based on the potential connections to future CO_2 suppliers, and assuming the OCAP pipeline would be extended towards TATA Steel partially using an existing pipeline, the following engineering works can be foreseen:

- **Pipelines**
  - Approximate 1.5 km pipeline connection from OCAP pipeline segment in Amsterdam Westpoort to AEB Amsterdam.
  - Approximate 0.5 km pipeline connection from OCAP pipeline inlet station in Botlek Rotterdam to AVR Botlek
  - Approximate 2 km pipeline connection from OCAP pipeline segment in Amsterdam Westpoort to the disused Q1 pipeline.
  - Pipeline connection from Q1 pipeline segment to the East of Beverwijk, to the TATA Steel premises in Velsen Noord (distance may be between ~5-15 km dependent on route of new pipeline)
- **Other equipment**
  - Compressor stations may be need at the new CO_2 sources of AVR, AEB and TATA Steel. The size and type of compression units will be dependent on the amount of CO_2 to be captured, but also the type of CO_2 capture unit chosen at each site. Some capture units result in high pressure CO_2 streams.
  - There is also an opportunity to supply the Greenpoort NoordHollandNoord in the Dutch province of West Friesland, with CO_2 from the Smart Grid. However a pipeline will be too costly, to in this instance, a CO_2 liquefaction installation with buffering tanks would be needed to facilitate CO_2 transport by truck and trailer.
- **Geological storage**

- Suitable CO_2 storage sites can be identified for the advanced stages of the CO_2 Smart Grid, should it become part of a national CCUS infrastructure in the Netherlands.

In realising the above engineering works, no technical showstoppers have been identified. All technology needed to expand the OCAP pipeline to a CO_2 Smart Grid is commercially available from companies operating in the Netherlands.

5.5 Provide high-level estimates of investment requirements for the infrastructure development

Its currently not feasible to provide investment costs for the necessary infrastructure development. Such cost estimates are dependent on, amongst other things, pipeline routing, pipeline dimensioning, material use, operating pressures and capacity utilisation. The potential reuse of an existing pipeline further complicates matters.

However from the infrastructure needed to realise the initial phase of the Smart Grid, it can be confirmed that the largest investment is related to the realisation of the pipeline link between the OCAP pipeline in Amsterdam, and the TATA Steel plant in Velsen-Noord. The two shorter pipelines to AEB and AVR from the OCAP pipeline are not expected to incur high investment costs.

Once more information can be made available by the CO_2 Smart Grid Steering Committee regarding some of the issues listed above, cost estimates be derived.

6 Conclusions

From this initial Technical Concept Assessment of the CO_2 Smart Grid, a number of key conclusions can be drawn:

- The development of a CO_2 Smart Grid is technically feasible and no engineering showstoppers have been identified. All technology to realise the infrastructure needed for the concept is commercially available.
- The greatest technical challenges are associated with the emergence of new and innovative processes to valorise CO_2 to produce low-carbon, market-driven products.
- Should the CO_2 Smart Grid expand to include geological CO_2 storage, effort will be needed to identify the most suitable and efficient CO_2 storage sites in the North Sea.
- The greatest investment cost of realising the initial phase of the CO_2 Smart Grid are associated with the realisation of the pipeline link between the OCAP pipeline in Amsterdam, and the TATA Steel plant in Velsen-Noord. This conclusion is valid regardless of the re-use of existing pipeline infrastructure.
- The two shorter pipelines to AEB and AVR from the OCAP pipeline are not expected to incur high investment costs.

6.1 Recommendations

It is recommended that within the CO_2 Smart Grid consortium, an engineering working group is established to further discuss the required infrastructure needed to realise the initial phase of the project. In particular, the link between the OCAP pipeline and TATA Steel will require frequent dialogue given the technical, spatial, societal and economic aspects of this piece of infrastructure. It is recommended that this group meets on a quarterly basis.

More generally, it is also recommended that this document is used as a basis for discussion in identifying concrete plans for the realisation of a CO_2 Smart Grid, and once further details are made available to TNO by consortium members, the document can be supplemented with further technical analysis and cost estimates.

7 Referenced material

CBS, 2017. Uitstoot broeikasgassen in 2016 licht gestegen. Accessed (10/11/2017): https://www.cbs.nl/nl-nl/nieuws/2017/36/uitstoot-broeikasgassen-in-2016-licht-gestegen.

Ecofys, 2017. Prefeasibility study CO_2 Smart Grid – The potential of carbon capture, transport, usage and storage. July 2017. Ecofys.

Goedenmorgentomaat, 2018. Dit jaar OCAP-CO2 PrimA4a, omgeving volgt later. Available (18-01-2018): http://www.goedemorgentomaat.nl/tomaten/nieuws/prima4a-dit-jaar-ocap-co2-de-rest-later/

LEI Wageningen UR, 2015. BINternet: Bedrijfsresultaten en inkomens van land- en tuinbouwbedrijven. Available (4-11-2017): http://www3.lei.wur.nl/BIN_ASP/show.exe

Neele, F., Hofstee, C., Dillen, M. & Nepveu, M., 2011. Independent storage assessment of offshore CO2 storage options for Rotterdam - Summary report, Utrecht: TNO.

Velden, N.J.A. van der, P.X. Smit, 2014. Energiemonitor van de Nederlandse glastuinbouw 2013; Wageningen, LEI Wageningen UR (University & Research centre), LEI Report 2014-025.