SCBA of CCU Smart Grid

A study on social welfare impacts

CE Delft

Committed to the Environment

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Authors:
Martijn Blom
Diederik Jaspers
Thomas Huigen

Reviewed by Geert Warringa and Frans Rooijers

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More information on this study is te available from project leader Martijn Blom (CE Delft)

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Preface

This study was performed at the request of a broad consortium of local and regional authorities, trade associations and companies under the guidance of BLOC. In the course of the project we exchanged knowledge with various stakeholders in the projected CCU Grid. To arrive at a workable methodology, the scope of the project alternatives and the study itself were defined in collaboration with these parties, with a draft of this report being presented to the core group, who provided useful comments. All of this took place in a very short time. At CE Delft a final draft was internally reviewed by Geert Warringa and Frans Rooijers.

We are extremely grateful to all those concerned for their remarks and for the openness with which they shared their knowledge. Without their support this project could not have been brought to fruition.

For the SCBA CCU Smart Grid project team,
Martijn Blom

Delft, 31 May, 2018

Summary

This Social Cost-Benefit Analysis (SCBA) of a projected CO_2 Smart Grid was undertaken at the request of 22 parties, supported by BLOC, with the aim of assessing the desirability of such a project from a social welfare perspective, i.e. based on the balance of its social costs and benefits. It is hoped that the understanding thus gained will provide stakeholders with sufficient information for decisions on strategy, investments and optimum design of the CO_2 Smart Grid.

Carbon Capture and Utilisation (CCU) can be seen as the recycling of CO_2 as a feedstock in production processes. For users it adds value, because of the positive properties of CO_2 for the product concerned (financial benefits), but it also benefits society at large (social benefits), because it helps tackle climate change. Carbon Capture and Storage (CCS), underground sequestration of CO_2, in contrast, is associated solely with social benefits.

Scope

The analysis presented here is concerned with the entire CO_2 chain from source through to utilisation, with the CO_2 Smart Grid linking sources and users. The net carbon footprint of the chain – the avoided CO_2 emissions per tonne of CO_2 captured – varies widely, depending on what CCU applications are involved. The costs of CO_2 capture (particularly energy costs) depend on the purity of the CO_2 source, moreover. For the social costs and benefits, then, it is of key importance what CCU route is adopted.

The SCBA was performed using the currently available data from the project feasibility phase. As the various business cases are elaborated in further detail, results may therefore change. Some of the impacts have not been quantified in this SCBA, key among which is the following. Without an external CO_2 supply, Dutch greenhouse horticulture will remain dependent on natural gas; off-site supply is thus essential for the sector to reduce its carbon footprint. Because this is partly included in the underlying scenarios, however, the impact of such a move does not show up in the ultimate SCBA balance.

Project alternatives

This SCBA examines two project alternatives for a Smart Grid transporting CO_2 from sources to users, one consisting solely of CCU, the other combined with underground CO_2 sequestration in depleted gas fields (CCU+CCS; see Table 1). The present analysis is concerned primarily with CCU. In the alternative including CCS, 40 Mt/a storage has been assumed, given the capacity of the existing CCS pipeline. In the future, though, far larger CCS volumes are envisaged following construction of new infrastructure.

Table 1 - Project alternatives

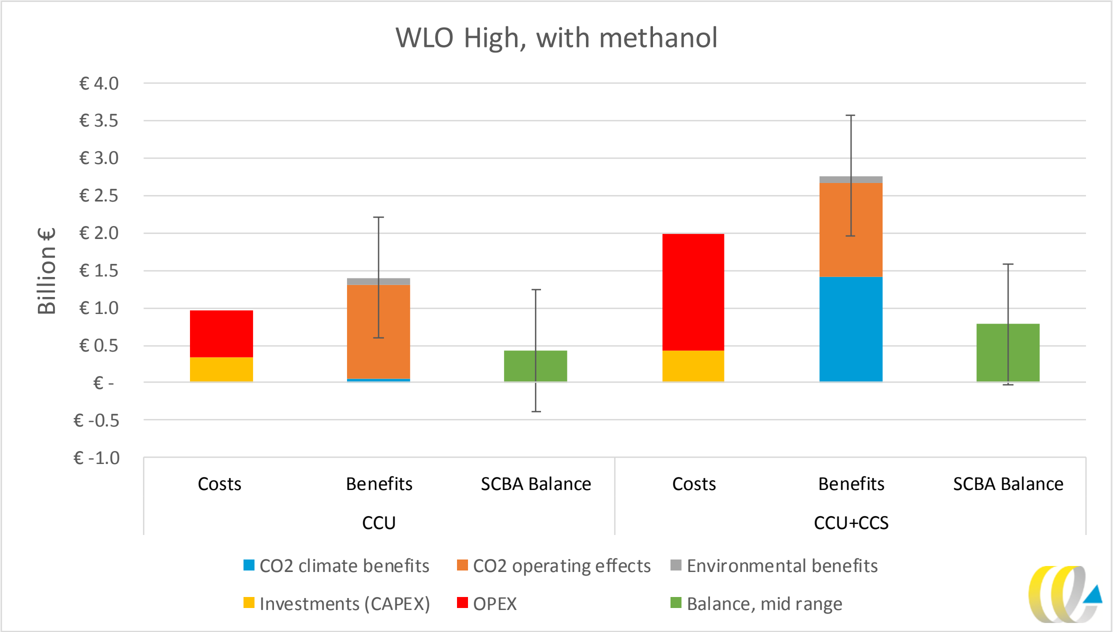
	Sources	Consumers	Grid
CCU project alternative	5 sources	Horticulture, building materials, methanol	Expansion around present grid
CCU+CCS project alternative	5 sources	Horticulture, building materials, methanol	Expansion around present grid, including connection to depleted gas fields (CCS)

Results

The net balance of the SCBA of a CO_2 Smart Grid depends very much on (avoided) CO_2 emissions being priced sufficiently high. Under the climate policy scenarios considered, the results are as follows:

- With a modest climate policy regime (the 'Low' WLO scenario) a positive outcome for the SCBA remains just out of reach. In the absence of vigorous climate policy, such a grid therefore creates little added value.
- With a more ambitious climate policy regime (the 'High' WLO scenario) the outcome of the SCBA is negative to slightly positive, with the balance being tipped by the availability of competitively priced renewable power for methanol production. Avoiding the uncertainty on this issue, i.e. if the CO_2 is used only in horticulture and building materials (mineral carbonation), the SCBA has a net positive outcome.
- With climate policy tightened further, in line with the targets agreed to in the 2015 Paris accord (sensitivity analysis), only biogenic CO_2 may be used and the business case and the SCBA are positive.

Figuur 1 - SCBA result in methanol variant, 2018-2068, High WLO scenario (NPV)



NPV = Net Present Value.

Conclusions

- CCU is a broad concept encompassing a range of potential applications in greenhouse horticulture (crop fertilisation), building materials (CO_2 binding via mineral carbonation) and the chemical industry (including fuels). It depends very much on the routes and applications adopted what net reduction in CO_2 emissions is achieved down the chain, whether there is a viable business case, and whether the SCBA is positively for the Netherlands from a social welfare perspective.
- There is major synergy between CCU and CCS. The combination CCU+CCS creates scope for transporting a greater volume of CO_2, improving security of supply through buffering and, overall, for successfully averting more CO_2 emissions.
- For CCU the financial balance for the grid operator is positive, while for CCU+CCS it is negative, because in that case the benefits are in the form of *social* climate benefits. Only if savings on

emission permits are multiplied by a sufficiently high ETS price will the business case for CO_2 sequestration under the North Sea be viable.

Recommendations

- From a social welfare perspective, the most promising CCU applications are in greenhouse horticulture and building materials. If renewable electricity and CO_2 are both available in sufficient quantities, utilisation in the chemical/fuels sector also contributes to a positive SCBA balance.
- This leads to the key recommendation of this study: to gradually extend the (physical) CO_2 Smart Grid using today's supply to horticulture as a backbone, developing viable business cases for other applications from there on.
- Concrete investment decisions on both the source and demand side can be based on uniformly designed micro-SCBAs and mini-LCAs. The CO_2 impact and social impact both need to be unambiguously established.
- Under a climate policy regime in line with the Paris target, it is essential that renewable energy and biogenic CO_2 sources are employed for the CCU grid. To this end, criteria can be drawn up for certifying CO_2 sources and for steering sustainability policy in this area.

1 Introduction

1.1 Background

One year ago the feasibility phase of the CO_2 Smart Grid was initiated by a consortium of 22 public and private parties in the Netherlands (companies, knowledge institutes, local and regional authorities), supported by BLOC. On commissions from and in collaboration with the consortium, several elements of this phase have now been completed: a feasibility study, a technology assessment and LCA studies to estimate net CO_2 emission reductions. The next step in the feasibility phase is a social cost-benefit analysis (SCBA) to assess the impact of the CO_2 Smart Grid from a social welfare perspective, i.e. how the social costs and benefits weigh up. To judge the project's feasibility and legitimacy for society as a whole, proper understanding of these costs and benefits is essential.

1.2 Aim

The key question addressed in this study is:

What are the financial and non-financial (social) costs and benefits of the envisaged CO_2 Smart Grid?

An understanding of these issues should provide the consortium and principal stakeholders sufficient information to make investment decisions, to assess the value of their potential financial contribution to the project, and to evaluate the project alternatives.

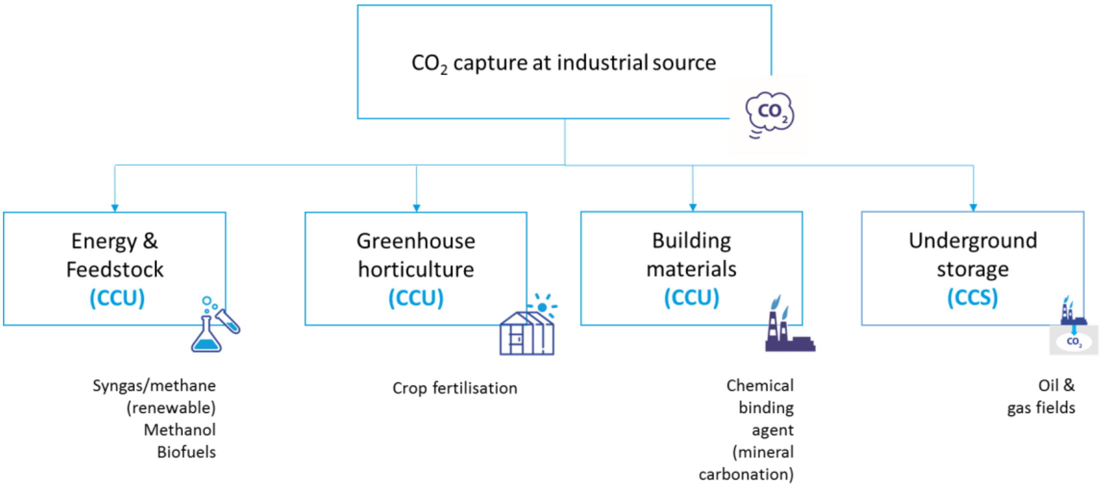
1.3 What are CCU and CCS?

This study considers the costs and benefits of two project alternatives. In the first, CO_2 is used as a feedstock in production processes. This is generally referred to as Carbon Capture and Utilization (CCU) or sometimes Carbon Capture and Recycling (CCR). Whether this leads to a net reduction in atmospheric CO_2 emissions depends on how the product or alternative production route is used.

The second project alternative combines CCU with capture and subterranean storage of the CO_2 gases in depleted oil and gas fields in the North Sea: Carbon Capture and Storage (CCS). Such storage is currently regarded as providing permanent removal of the captured CO_2 from the atmosphere.

The two approaches are summarized schematically in Figure 2.

Figure 2 - Schematic representation of CCU and CCS



In Chapter 2 we discuss the project alternatives in more detail and assess how they can contribute to reducing atmospheric CO_2 emissions.

1.4 Scope

The present report is an SCBA based on the currently available project information, derived from the feasibility phase. Further engineering of the CO_2 grid and elaboration of the business cases for CO_2 delivery via the grid may alter the results reported here.

The following scope was adopted:
- The basic premise of this SCBA is that it should encompass all relevant welfare impacts, with direct and indirect impacts being distinguished.
- Costs and benefits have been estimated on the basis of existing studies, with no new cost studies being undertaken.
- The CCU routes are the same as those covered in an earlier Life Cycle Assessment (CE Delft, 2018).
- The volume involved in the CCS route differs from that considered in the study by Gasunie and EBN (Gasunie and EBN, 2018). It has been assumed that the CCU+CCS project alternative shoulders a proportional share of the infrastructure costs. This alternative is thus always part of a larger CCS infrastructure.
- Finally, price paths (for CO_2 in particular) have been calculated for several different scenarios (‘High’ and ‘Low’, ‘two-degree sensitivity’) and are international (see Section 3.5).

1.5 Impacts distinguished

Table 2 shows the impacts distinguished in this SCBA. With respect to greenhouse horticulture, a few remarks are in order. We expect greenhouse operators to save out on gas costs, because in the project alternatives he will need to fire up his boiler less often in the summer for the purpose of CO_2 enrichment. We assume, though, that the current market situation will move the grid operator to opt for a contract price that at the margin is advantageous for horticulturalists to switch to the CCU grid. At the moment there is a latent demand for CO_2 from greenhouse operators who want to switch to

alternative heat sources (waste heat, geothermal), and this demand is set to grow given the sector's sustainability ambitions for 2040.
What this in fact means is that the horticulturalists' surplus is skimmed off and that these benefits are thus already included in the revenue from sales of off-site CO_2 to horticulture.

Table 2 - Impacts distinguished

Type of impact	Impact	Value
Direct	One-off investment costs (CAPEX)	€
	Reinvestment	€
	Operating costs (OPEX)	€
Indirect	Employment	Qualitative
External	Climate benefits	€
	Environmental benefits (other emission cuts)	€

Crop productivity and growth

Carbon dioxide is essential for crop growth and adding extra CO_2 to greenhouse air makes crops grow not only faster but also better. Today, this CO_2 is obtained from the fuel gases of heating boilers or combined heat-and-power plant (CHP). This is done in summer, too, when there is less need for extra heating, but CO_2 requirements are higher. Use of externally sourced CO_2 has a number of benefits for horticulturalists:

- **Production optimisation**: At certain times in the crop cycle, additional CO_2 can improve quality and/or yields.
- **Better-quality greenhouse air:** Flue gases fed into greenhouses may contain unwanted contaminants that may accumulate with insufficient venting. To reduce risks for crops and output, horticulturalists prefer to use pure CO_2.
- **Security of CO_2 supply:** Multiple CO_2 sources can be used. Some horticulturalists already have several sources available on-site to minimise the risk of being without CO_2 (due to technical failure or incidents).
- **Environmental certification:** Many 'green product' certificates attach a value to use of externally sourced CO_2. A certificate allows entrepreneurs to distinguish themselves and gain a competitive edge (as a preferred supplier, or via a higher product price).

These benefits are internal, i.e. they are also inherent in the contract price the horticulturalist is willing to pay for the off-site CO_2. If they were separately valued, this might lead to double-counting. Put differently, the better the quality and security of supply of off-site CO_2, the higher its sales price – or, with a fixed price, the greater the latent demand that can be met by the supplier. The approach adopted here is a pragmatic one, thus yielding a conservative estimate of project impacts.

Impacts of further greening of greenhouse horticulture

Delivery of off-site CO_2 by pipeline or tanker is a *sine qua non* for further greening of greenhouse horticulture. Only with a secure supply of CO_2 for crop fertilisation can horticulturalists make moves to green their heat (and power) supply. For this sector, then, timely guarantee of such a supply is an essential condition for a smooth energy transition. The WLO scenarios used as a background for the present study embody a transition path towards more climate-neutral greenhouse heating at a reasonably fast ('High' scenario) and a slow rate ('Low' scenario).

For practical reasons, we have opted **not** to allocate the social costs and benefits of this heat transition in greenhouse horticulture to the CCU Smart Grid. The CO_2 and other environmental benefits arising in the reference scenario in association with the gas consumption that can be specifically ascribed to the *production of (purified) CO_2 for greenhouses* have been included in this SCBA, however. This said, though, the future greening of the horticultural sector is still inextricably linked with the issue of CO_2 supply.

The same holds for the origin of the CO_2: biogenic or not. The pace at which such greening takes place will depend largely on the tempo achieved by industry on its own transition path. In addition, the grid operator can also incentivise biogenic CO_2 sourcing by means of quality criteria and prioritisation of biogenic sources. This issue is considered further in the sensitivity analysis.

1.6 Reading guide

This report is structured as follows. *Chapter 2* provides an extensive description of the CCU and CCU+CCS project alternatives.

Chapter 3 explains the SCBA method and discusses the main assumptions adopted here.

Chapter 4 then runs through the costs and benefits of each project alternative and compares them with those of the reference scenario. The various cost and benefit items are presented in terms of net present value (NPV). The figures used in each alternative to arrive at the total sum are also reported.

The net SCBA balance for the project alternatives is presented in *Chapter 5.* In this chapter we also look more closely at the sensitivity of the results to specific assumptions. Readers with time constraints can jump immediately to this chapter.

Finally, our conclusions and recommendations are presented in *Chapter 6*.

2 Project alternatives

2.1 Introduction

This chapter considers the following issues in more detail:
- the technical scope of the project (Section 2.2);
- the project alternatives (Section 2.3);
- the reference scenario (Section 2.4).

2.2 Technical scope of the project

In the provinces of Noord-Holland and Zuid-Holland a consortium comprising over 20 public and private parties is working on an initiative - the CO_2 Smart Grid – aimed at useful application of captured CO_2 as a feedstock for use in the circular economy: Carbon Capture and Utilisation, or CCU. To this end, in the years ahead a grid needs to be developed for feeding CO_2 from various sources to a range of different users. The envisaged backbone of this grid is the existing OCAP pipeline that is currently used to supply CO_2 from Shell Pernis and ethanol producer Alco at Pernis to greenhouse horticulturalists in the Westland region for promoting the growth of their crops. This system is set for expansion in the coming years, with a number of supply contracts already finalised (for the PrimAviera, Aalsmeer and Monster areas).

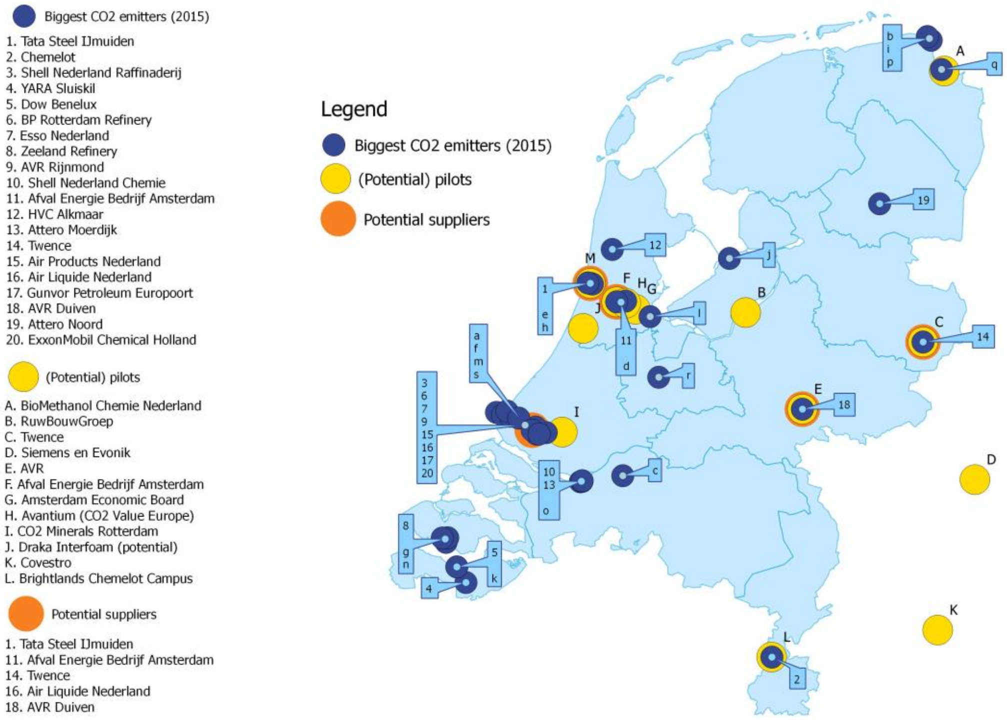
Potential sources

There are a number of CO_2 sources in Zuid-Holland that could potentially feed into a CO_2 grid: the steam methane reformers (SMRs) operated by Air Liquide, Air Products, the BP, Gunvor and Esso refineries and the AVR Rijnmond waste incineration plant. In Noord-Holland there are AEB, Tata Steel and HVC. Figure 3 provides a map showing the 20 largest CO_2 sources in the Netherlands.
This provisional survey makes no allowance for the present OCAP pipeline, however. Hooking up peripheral CO_2 sources holds no immediate appeal, given the high cost of laying the required additional pipelines.

Consumers

Besides greenhouse horticulturalists, building material producers are also expected to be interested in buying CO_2, which can be ‘fixed’ in stone-like building materials in a process known as mineral carbonation. The resultant materials have exactly the same structural properties as their traditional counterparts. Other CCU routes are also conceivable in the future: for producing formic acid, methanol and polyols for polyurethanes, for example, as well as downstream processes from methanol to olefins (MTO) and petrol/gasoline (MTG). These are expected to materialise once the price of (wind) power is low enough for hydrogen production via electrolysis. Potential consumers of pipeline CO_2 supply are in various phases of innovation.

Figuur 3 - Potential suppliers to the CO_2 grid



What would the CO_2 Smart Grid look like?

As envisaged by the consortium, the CO_2 Smart Grid will be built around concentrations of CO_2-producing industries located near the Noord-Holland and Zuid-Holland coast with a view to potential connections to depleted North Sea oil and gas fields, into which the conditioned CO_2 can possibly be injected at a later stage. The CO_2 Smart Grid will ultimately comprise both existing and yet to be constructed elements. A logical approach is to build it around the existing grid and to identify additional viable building blocks to steadily work towards ever greater volumes.

CO_2 can be delivered by pipeline (e.g. OCAP), by truck or directly on-site, through exchange with a different process emitting CO_2 (meeting relevant criteria). While truck-transported liquid CO_2 is an option, it will be more expensive than piped CO_2 if users are clustered in a particular area. If liquid CO_2 is delivered by truck, on the other hand, the area supplied can be far greater than that presently served by OCAP. Combinations are therefore entirely feasible.

The CO_2 can in principle also be made available at-source, obviating the need for an extensive pipeline grid. A major drawback of such an approach, however, is long-term dependence on a single party. If a pipeline grid is opted for, it is important that CO_2 sources be diversified and that there is long-term security of supply.

Premises of the CO_2 Smart Grid

OCAP currently supplies (almost) 0.5 Mt of pure CO_2 to greenhouse horticulturalists in the OCAP supply area, mainly to the Westland, Lansingerland and Delfgauw areas. The bulk of the CO_2 transported as well as that temporarily buffered (for one day) is at a maximum permissible operating pressure of 16-22 bar. A key element of the system is the 83 km oil pipeline between Rotterdam and Amsterdam.

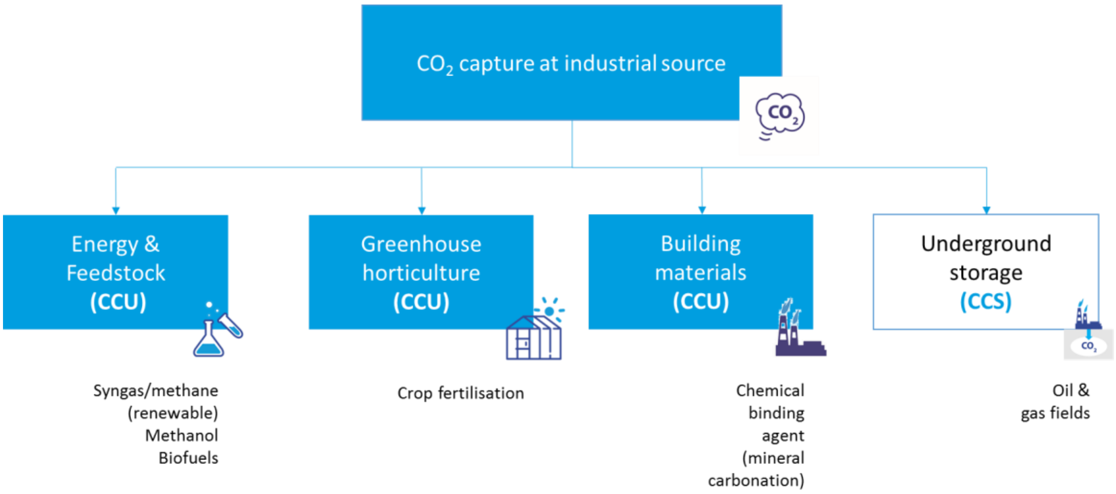
In elaborating the project alternatives it was opted to base work as far as possible from the current OCAP backbone, which is at any rate suitable for 40 bar transport and storage (source: OCAP). Current expectations are that this will allow for annual transport of 3.3 Mt CO_2 from the various sources to consumers, provided logical regional combinations can be established between supply and demand points[1]. It was assumed further that the CO_2 is supplied at 40 bar.

2.3 Project alternatives

In this SCBA two project alternatives are compared with a reference scenario. The following two project alternatives are considered:

1. CCU.
2. CCS+CCU.

CCU project alternative



This project alternative considers only CCU, with CO_2 being supplied to certain users with CO_2 needs. There is no CO_2 buffer in the form of CCS storage (excess CO_2 is discharged to the atmosphere). This project alternative does include day-night buffering, that is, ‘night-time supply’ of CO_2 is buffered in the pipelines for daytime supply to greenhouses as required.

Because of the limited scope for *seasonal* buffering, users will have to accept a certain risk of supply shortages, if there are insufficient supplementary sources in summer, for example. This means horticulturalists will still need some form of back-up, as is generally the case at present. The price

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[1] With the projected annual volumes, it is inconceivable that the 3.3 Mt transport capacity can be fully utilized in North-South and/or South/North transport directions.

asked for the supplied CO_2 will consequently be close to the current CO_2 price (external delivery price[2]).

This alternative embodies an extension built around the existing pipeline grid, hooking up new consumers as well as sufficient new suppliers to meet post-expansion demand.

What is CCU?

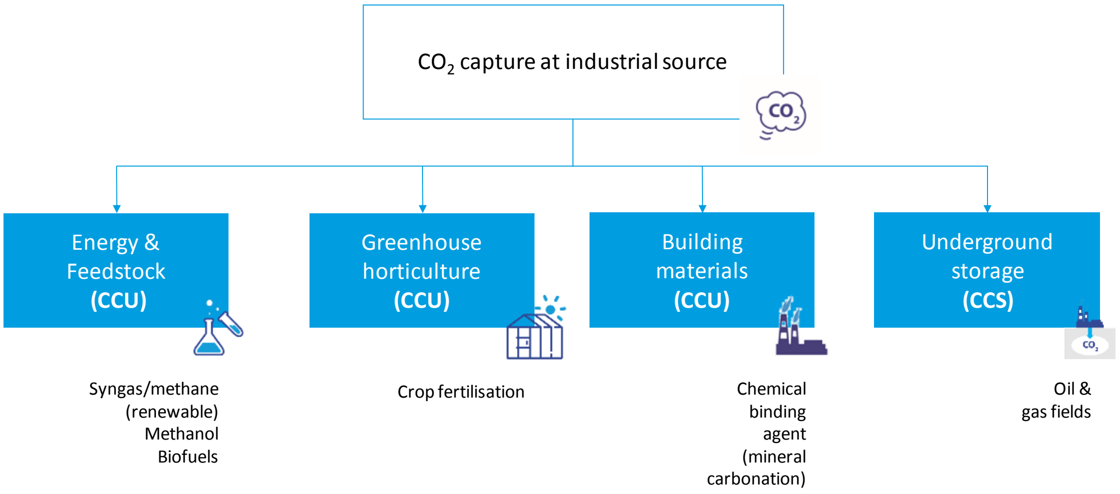
With Carbon Capture and Utilisation (CCU), captured and conditioned CO_2 is used as a feedstock or auxiliary in an industrial process. Familiar existing examples include:

- use in greenhouse horticulture to promote plant growth;
- addition to carbonated beverages;
- use as an auxiliary in oil recovery (Enhanced Oil Recovery, EOR);
- use as a feedstock for extremely pure calcium carbonate for use in papier, for example (the white colour of paper);
- use as a feedstock for plastics production (polycarbonates, polyols);
- use as an extinguishing agent in fire-extinguishers and automated extinguishing systems.

For CCU the CO_2 does not always have to be in pure form. OMYA in Moerdijk, for example, uses the CO_2-rich flue gases from the SNB Moerdijk sludge processing plant for production of pure calcium carbonate. Although in some applications the CO_2 is not chemically bound, there is still a reduction of fossil CO_2 emissions, as is the case with use of CO_2 in greenhouse horticulture.

The purity of the CO_2 and its concentration in the gases being used is important in certain CCU applications, including greenhouse crop fertilisation, for which there are specific quality criteria in force (with respect to ethylene levels, for example), to ensure the gas poses no risk to either humans or crops. As this sector is the main consumer, these criteria will also have to be adhered to as a minimum for the entire CCU grid. For storage in depleted gas fields there are even more stringent specifications in force (supercritical, or 'capture-ready'). See the text box on CCS.

CCU+CCS project alternative



This is the project alternative that is most in line with the 'demonstration-sized CCUS grid' considered in the feasibility study (Ecofys, 2017). Excess CO_2 will be permanently sequestered in depleted North Sea gas fields. In this project alternative the sources supply CO_2 in a virtually uninterrupted flow, day

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[2] This does **not** refer to the social costs of CO_2.

in, day out, the whole year round. Demand from greenhouse horticulture is not constant; plants grow harder in summer than in winter, which means demand is greatest in summer[3].

In this project alternative excess CO_2 is sequestered in depleted North Sea gas fields via a pipeline between the existing grid and these fields. Captured CO_2 is sent to a central coastal collection area for final compression and conditioning before it is transported offshore. This underground sequestration requires a second treatment step to render the CO_2 suitable for permanent storage (see text box). For storage offshore the CO_2 pressure must be raised to at least 100-120 bar. In the CCU variant it is fed into the grid at a lower pressure (40 bar), which means a considerable amount of energy will be needed to get the CO_2 to the required pressure.

The buffering capacity of the CCS add-on provides horticulturalists with additional flexibility in connection with seasonal fluctuation of their CO_2 requirements[4]. As security of CO_2 supply is better guaranteed in this alternative it has added value, which will be reflected in a higher willingness to pay for CO_2. With higher year-round volumes, the CCU+CCS alternative thus creates more scope for utilising the full capacity of the grid.

What is CCS?

Carbon Capture and Storage (CCS) is a five-step process:

1. Capture of CO_2 from flue gases and other gas streams (syngas from e.g. ammonia and hydrogen production, natural gas, biogas, product gases at breweries, yeast plants and distilleries).
2. Preparing the CO_2 for transport and storage by purification, drying and compression to a supercritical liquid.
3. Transportation of conditioned CO_2 by pipeline or ship.
4. Injection of the conditioned CO_2 into depleted gas and oil fields or deep aquifers.
5. Abandonment of the storage site, sealing it for permanent sequestration.

Not all these steps have yet been fully developed, though most involve tried and tested technologies. Transportation of supercritical CO_2 and subsequent storage already takes place in various parts of the world, as does pre-combustion capture. Capture from flue gases and other low-pressure gas streams with limited CO_2 still only occurs on a minor scale, on the other hand, while abandonment of sequestered CO_2 is still entirely virgin territory. Several years of further development are therefore still required before CCS can be rolled out on any substantial scale and for a broad range of industries. That time is needed above all for further development of CO_2 capture technologies to a commercial scale for gases at lower pressures and with modest CO_2 concentrations.

Source: CE Delft, 2016.

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[3] Plants grow more in the daytime and therefore need more CO_2 than at night. In the CCU variant the required buffering is already provided for.

[4] By not emitting that CO_2 to the atmosphere but storing it in the sea bed, there is always enough CO_2 available and demand in summer may sometimes even exceed supply.

2.4 Reference scenario

The reference scenario is the world without either of the project alternatives. This is not generally the same as ‘doing nothing and just sitting back’. Companies are always in search for ways to make a profit, and work out the most cost-effective way to operate their production processes including supply of CO_2.

In this study the date **31 December, 2017** has been taken as cut-off point. This means all supply contracts signed prior to that date fall under the reference scenario. The pipelines currently carry 0.5 Mt annually. This already includes the extension to west-Monster greenhouse area[5]. Including the Aalsmeer and PrimAviera areas, the total volume being supplied then comes to 0.6 Mt. This is the reference scenario. These figures are in line with the data supplied by LTO Glaskracht (the greenhouse horticulture trade organisation).

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[5] Without this, the figure would be 0.45 Mt.

3 Method

3.1 Introduction

In this chapter the method employed in this study is discussed in more detail, as follows:

- the SCBA methodology in brief (Section 3.2);
- the premises adopted in this SCBA (Section 3.3);
- CO_2 supply and demand in the project alternatives (Section 3.4);
- the CO_2 price adopted (Section 3.5).

3.2 The SCBA methodology in brief

The social cost-benefit analysis was performed in accordance with the official Dutch SCBA guidelines developed by the Netherlands Bureau for Economic Policy Analysis and the Netherlands Environmental Assessment Agency (CPB ; PBL, 2014) and comprised the following steps:

- In the **first step**, problem analysis, the underlying problem (or opportunity) is analysed and potential solutions identified (alternatives to resolve the problem). In the case of the CCU Smart Grid we are concerned mainly with potentially cost-effective measures to address climate change. These do not materialise of their own accord, because of the (lead) costs involved in collaboration and coordination among numerous parties. Institutional barriers and a potentially unprofitable component in the required investments may also play a role. In five interviews with stakeholders in the envisaged CCU Smart Grid, the premises adopted in this study were established in greater detail. A list of interviewees is provided in Appendix A.

- In the **second step** we describe the potential alternatives for solving the problem and exploiting the opportunities. There are two such project alternatives: CCU and CCU+CCS.

- The **third step** is the core of the analysis. In this step welfare impacts (costs and benefits) of the alternatives are quantified and compared with those of the reference scenario. The reference scenario is the most likely development anticipated if the CCU project does not go ahead. In this context it is important to realise that the future is by definition uncertain, with all kinds of scenarios possible. As a reference for the future we use the so-called WLO scenarios (see Section 3.5.2).

- In the **fourth step** the one-off and annual costs and benefits are compared by calculating back to the baseline year. These costs and benefits are presented in a clear and compact table.
  In assessing the welfare impacts we will be focusing explicitly on the problem analysis and the underlying aim (to address climate change). To what extent do the alternatives contribute to tackling the problem?

- In the **fifth and final step** we carry out a sensitivity analysis to establish how robust the results are when the parameters having most influence on the final outcome are varied.

3.3 Premises adopted in this study

As stated in 3.2, this SCBA was carried out according to the official Dutch SCBA guidelines (CPB ; PBL, 2014) and, in particular, in line with the guidelines for Environmental SCBAs (CE Delft, 2017b). In addition, use will be made of the already cited WLO scenarios (CPB ; PBL, 2015).

3.3.1 Discount rate

Calculated impacts are expressed as net present value (NPV) in the baseline year (2018). This means impacts occurring at a later date carry less weight than impacts occurring early on. The weighted sum over the years derived in this way for a particular impact - the net present value - is calculated using a discount rate.

In 2015 a national taskforce drew up recommendations on the preferred discount rate (Werkgroep Discontovoet , 2015), which the Cabinet subsequently made mandatory in all government work (Ministerie van Financiën, 2015). In virtually all cases this means a real discount rate of 3%, a figure that includes a risk premium. This also holds for environmental impacts, with a specific distinction being made in the recommendation between impacts on biodiversity and on health.

For public investments involving major fixed costs, like infrastructure, the discount rate is 4.5% for both costs and benefits. As ‘fixed costs’ the taskforce takes those costs that vary little, if at all, with utilisation of the project. These may be initial investments at the start of a project (sunk costs), such as the cost of constructing a road, but also fixed costs arising during the project’s lifetime, such as fixed operating costs and fixed maintenance costs.

3.3.2 Price levels

All impacts are expressed in terms of their present value in the baseline year 2018, which means these prices have been corrected for inflation. The value assigned to impacts over the years may deviate from average inflation, however.

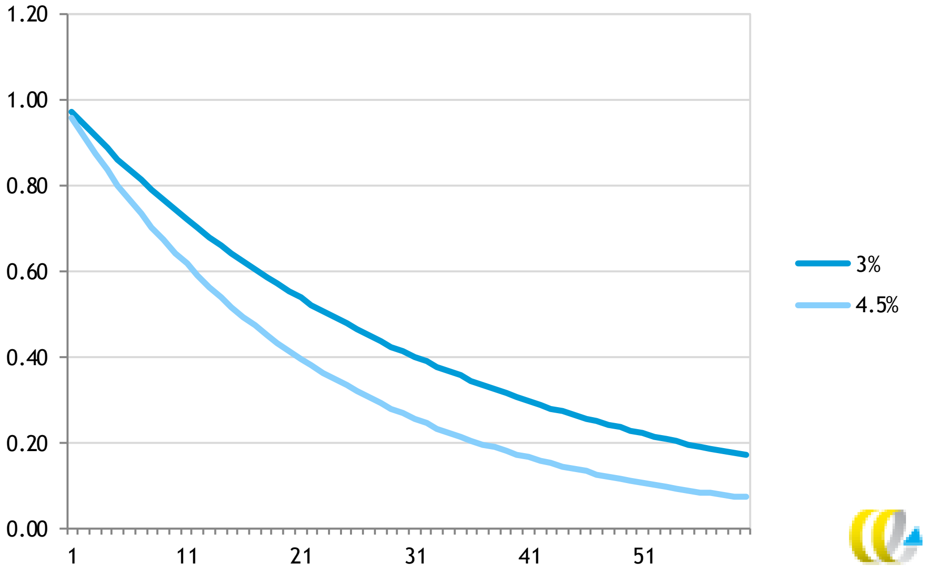
3.3.3 Accounting period

It is recommended in SCBAs to adopt an infinite accounting period, to ensure that long-term (environmental) impacts are duly reflected in the cost-benefit balance calculated (CE Delft, 2017b). The core group voiced a preference for a period of 50 years, though, as this means the two project alternatives can be fleshed out in more concrete terms, with less uncertainties.

Figure 4, showing the present value of a future euro as a function of time, illustrates the importance of an infinite accounting period. At a 3% discount rate, a benefit of 1 euro in 50 years’ time is now worth 23 euro cents, while at a 4.5% discount rate this is 10 euro cents. The 10 residual cents remaining value of one euro in 50 years’ time at the latter discount rate is largely within the uncertainty margin of the other factors.

The accounting period for the SCBA has thus been taken as 2018-2068.

Figure 4 - Discounting of 1 euro at discount rates of 3% and 4.5%



3.4 Supply and demand in the project alternatives

Based on the interviews and available feasibility studies, in the scoping phase we inventoried the potential supply and demand sides, identifying the most obvious CO_2 sources for feeding such a grid and potential users. Elaboration of the project alternatives is not therefore rooted in business cases or elaborate market analyses.

3.4.1 Demand-side potential

Table 3 provides a synopsis of CO_2 demand in the final situation from the various sectors in the CCU Smart Grid delivery area. Below, we indicate how these figures were arrived at.

Table 3 - Synopsis of demand (final situation), Mt CO_2/a

	Reference scenario (CO_2 Mton)	CCU alternative (CO_2 Mton)	CCU+CCS alternative (CO_2 Mton)
Greenhouse horticulture	0.6	1.2	1.2
Building materials	0	0,1	0.1
Methanol	0	1	1
CCS	0	0	1
Total	**0.6**	**2.3**	**3.3**

Note: The CCU+CCS alternative is part of a larger CCS infrastructure.

Source: Own calculation by CE Delft.

Greenhouse horticulture

The potential demand of the greenhouse horticulture sector is projected to be 1.2 Mt (source: LTO Glaskracht). This is demand for off-site CO_2 by the Noord-Holland and Zuid-Holland horticultural district. In this study this district has been taken as defining the potential OCAP area. The figure of 1.2 Mt is based on the sector's ambition to be climate-neutral in 2040. To achieve this goal hinges on a guaranteed alternative supply of CO_2. It has therefore been adopted a basic premise that the sector's CO_2 requirements must be fully covered by the year 2030, providing enough time to switch to climate-neutral[6].

As a result of the horticultural area shrinking, however, demand for CO_2 will fall (cf. WLO scenarios[7]). On the other hand, Wageningen Economic Research (WECR) also projects an intensification of growing methods (in particular, increased lighting), pushing up CO_2 demand again. The underlying assumption in calculating the figure of 1.2 Mt is that the impacts on demand of these two trends (intensification and area reduction) will offset one another. The reference scenario proceeds from up to 0.6 Mt growth, a figure incorporating all supply contracts finalised as of 31 December, 2017. Projected demand growth from greenhouse horticulture is thus 0.6 Mt, with the bulk of demand arising in the summer season.

When considering use of CO_2 to fertilise greenhouse crops it is crucial to realise that most of the gas escapes through windows as a result of venting, with only a small fraction being fixed in plants. The horticultural sector is consequently engaged in efforts to boost CO_2 utilisation by limiting venting losses, under the project *Het New Telen* ('A new way of cultivation'), for example. On top of this, the carbon fixed in plants is also soon released to the atmosphere as the products are digested or decay ('short-cycle CO_2'). In other words, the CO_2 (temporarily) fixed in vegetables and other plants cannot be regarded as CO_2 emissions reduction.

Today, greenhouse horticulturalists generally use natural gas to meet their CO_2 requirements (as well as for heat and electricity). If they use CO_2 supplied from off-site, less gas will therefore be burned, particularly in summer, when greenhouses require little if any heating, but additional CO_2 because there is more light and therefore increased plant growth.

Building materials

The market for sustainable building materials in which CO_2 is chemically bound is currently virtually non-existent. In public-works tenders and in the house-building market there is scarcely any financial reward for a product's ecological footprint and the amount of CO_2 it binds[8]. Production of building blocks containing bound CO_2 is currently at the innovation stage, although such materials have already been used in several UK construction projects (TRL-9). As yet, this makes it hard to get returns on investments in new production plant and establish an viable business case. On a small scale, various parties in the Netherlands are currently experimenting with new processes for binding CO_2 in sand-lime bricks (obviating the need for heating). Upscaling this process to an industrial scale is anticipated in a few years, provided there is sufficient demand for these 'green' building blocks.

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[6] This also allows for the fact that energy demand is lowest in summer, and will therefore be first to be addressed by efficiency measures or renewables, while CO_2 demand is then highest.

[7] The WLO study assumed a reduction in the horticultural area, by 30% in Low and by 10% in High. In addition, energy demand falls as a result of efficiency measures (by 5% in Low and 20% in High).

[8] This could be remedied by crediting sustainability performance in tenders, via the so-called MKI score of building materials, for instance. This would create a discount for more sustainable bidders in public works tenders. For the private market (dwelling construction) mandatory criteria will need to be laid down in the Building Decree.

In the CCS+CCU project alternative it is assumed that from 2021 onwards one or several production facilities is up and running, representing a total demand of 0.1 Mt CO_2. A typical brick plant is estimated to need 50-100 kt CO_2/a. It is then essential that such facilities, which will take 2-3 years to build, are located in the OCAP delivery area.

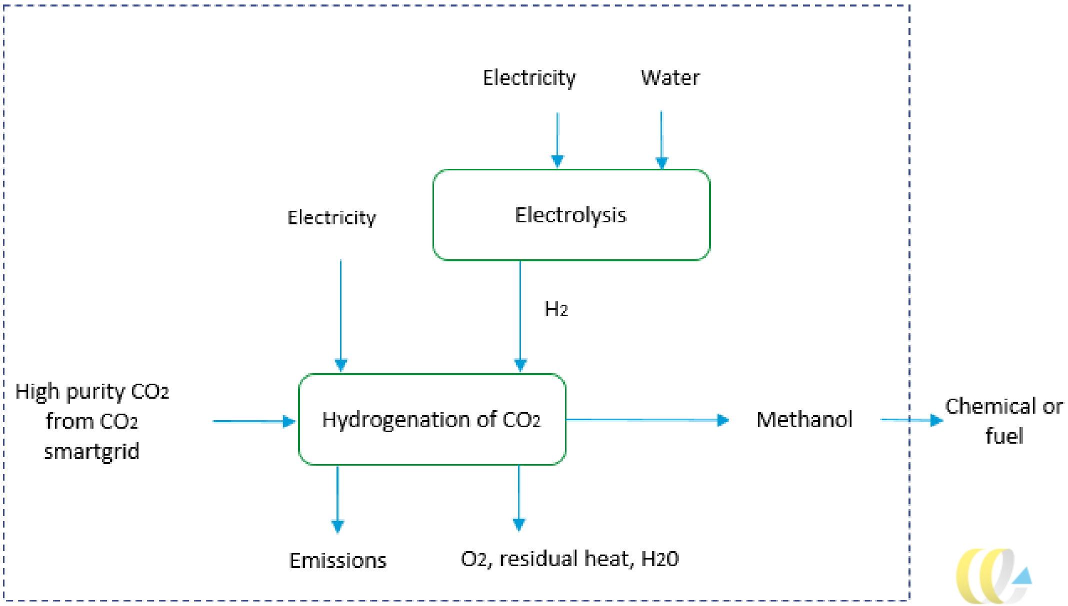
Methanol

According to Ecofys, the potential Dutch market for CO_2-based methanol could be 0.2 Mt within ten years (Ecofys, 2017). A typical methanol plant has a capacity of 1-3 Mt, however (Dahl, et al., 2014). In methanol production, pure CO_2 is hydrogenated using separately produced hydrogen. In the CCU route considered here, this hydrogen is produced via electrolysis, with electricity being used to split water into hydrogen and oxygen. In the LCA study cited earlier (CE Delft, 2018) methanol production was elaborated on two alternative bases with respect to electricity source: a fossil fuel mix and a direct renewables connection.

Electrolysis is a very power-intensive process and it therefore makes sense to use renewables surpluses for this purpose, i.e. electricity available when there is surplus wind and/or solar but little demand for power. Methanol plant should consequently preferably be sited close to both sources/ pipelines supplying pure CO_2 and to a physical connection to renewables generating plant.

It is important whether the methanol is used as a fuel or a feedstock. In the former case the fossil-sourced CO_2 will eventually end up in the atmosphere, while in the latter the CO_2 will be removed from the carbon cycle if the products are 'circular'.

Figure 5 - The methanol production complex



Source: (CE Delft, 2018).

3.4.2 Supply-side potential

Within the present supply area the potential capacity available at major CO_2 emitters was inventoried. Their magnitude and location was recorded, mainly to ensure that the sources match the potential demand implied in both the CCU and CCS alternatives. The capacity of the potential suppliers is shown in Table 4.

Currently, CO_2 is supplied solely by the Alco bio-ethanol plant (second source) and the Shell Pernis refinery (first source). Some of the 1 Mt CO_2 generated in this process is destined for the food industry, while the rest goes in gaseous form to the CCU grid. With limited additional investment, Shell can potentially deliver 1.5 Mt annually, as the plant's maximum hydrogen production capacity has not yet been reached. The required expansion investment is limited, because compressor capacity is already sufficient. For Alco (bio-ethanol) additional investment in compressors will be needed, though.

When AEB, AVR and Tata Steel are also taken on board, the total number of sources that can potentially supply the grid rises to five, giving a total estimated annual volume of 3.3 Mt.

Table 4 - Potential CO_2 supply, Mt/a

CO_2 sources	Potential CO_2 supply (CO_2 Mton)	Process
Shell	0.75	Hydrogen production
Alco	0.75	Bio-ethanol production
Tata	1	Various processes (incl. Hisarna)
AEB	0.5	Waste incineration
AVR	0.3	Waste incineration
Total	**3.3**	

Capture at Tata

For Tata the potential for CO_2 capture depends very much on what new steel production technologies have to offer, with the Hisarna technology promising when it comes to reducing the carbon footprint. This could potentially provide over 1 Mt of CO_2 for capture. A pilot plant is already up and running and the next stage is design, construction and testing of a large industrial-scale Hisarna plant.
This is expected to be operational by about 2023. Besides this, there are ideas at Tata for potential additional capture of 3-4 Mt. These are at a far less advanced stage of development, though. With the Hisarna technology the energy consumption and consequently CO_2 emissions of a steel plant can be reduced by at least 20%. The remaining CO_2 stream is almost pure and according to Tata meets the 'capture-ready' criterion. This is therefore relatively simple to capture and store and would be suitable for CCU and CCS. Discussion is still possible on the degree to which the 'supercritical' specifications (100% pure) are met that are required for final underground sequestration. This is one of the things the pilot phase must demonstrate. Combined with CCS, emissions can then be reduced by at least 80%.

At present it is unclear whether the Hisarna process will be rolled out on an industrial scale and, if so, when. It depends on numerous uncertain factors. Even without it, though, Tata currently has several flue-gas sources, varying in ease of capture (blast furnaces, coke furnaces, power plant). We assume similar CO_2 capture potential will be available even if the Hisarna process is not implemented.
The associated costs will then be substantially higher, though (see next section).

We have assumed that Hisarna will be rolled out in the WLO High scenario (scenario with international cooperation, higher growth and climate policy), but not in the WLO Low scenario (low growth, international tensions, limited climate policy).

3.4.3 Merit order of sources

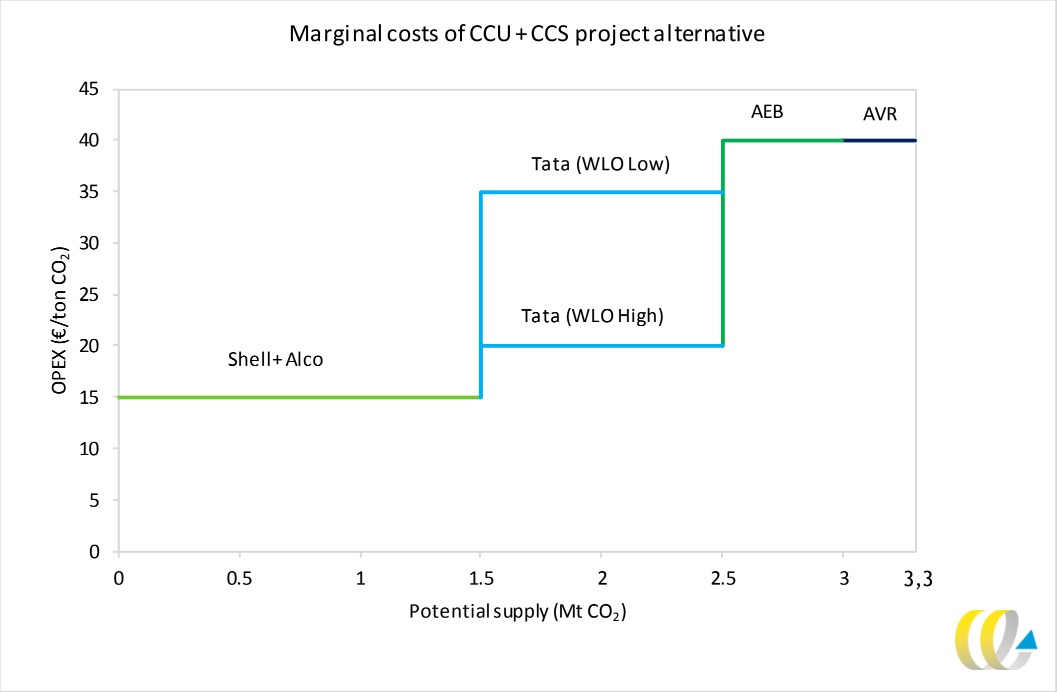
In the CCU+CCS project alternative CO_2 demand will be met by five sources, with the merit order determined by their respective marginal costs (OPEX). In other words, the emitters with the lowest costs for capture/storage of process CO_2 determine the average cost of meeting demand.

Besides cost optimisation, other considerations may also play a role. These include CO_2 quality, security of supply and whether the gas is of biogenic origin. For horticulturalists CO_2 can make an important contribution to making their operations more sustainable, in terms of both heat and inputs (CO_2). In addition, it may be the case that AVR and AEB will be able to feed into the grid at an earlier date, for example. If an allocation criteria other than cost optimisation is used, this will lead to a different merit order and cost profile, with the waste incinerators then being able to meet a greater fraction of CO_2 demand. The majority of the waste incineration CO_2 is of biogenic origin.

For the pipeline grid we assume gas-phase transport and an annual capacity of around 3 Mt, which means the CO_2 must be compressed to 40 bar and supplied as such. In this study the costs of transport and storage have been calculated per tonne of stored CO_2. A smaller volume can be captured at relatively low cost (€ 15-30/t, our estimate), since the CO_2 already leaves the processes in relatively pure form. In such cases it usually only needs to be dried and compressed. At AEB and AVR, capture costs have been estimated higher because of the additional purification, drying and compression steps required.

In the WLO High scenario Tata Steel is assumed to switch over to the Hisarna production process in 2023, after which the CO_2 will be far easier to capture. The assumption made here, based on the information provided by Tata, is that this stream is pure and capture-ready, implying relatively low-cost grid delivery. In the WLO Low scenario this cost has been taken higher: about € 35/t CO_2, as the present flue gases are far harder to capture. Hisarna therefore does not affect the merit order or marginal costs, as capture at the incineration plants is probably more expensive. This does not hold for the average costs, though, which will be higher in WLO Low than in WLO High.

Figure 6 - Capture costs per tonne CO_2 for the various sources in the project alternatives



Source: CE Delft, own estimate.

3.4.4 Projected supply/demand

CO_2 supply is a market transaction between supplier and consumer. Table 5 shows the *annual* demand and supply if there is maximum capacity utilisation (in 2030), with source-user allocation based on minimum marginal costs and all seasonal fluctuations in horticultural demand suitably matched to supply. In Appendix B we consider the sources required to meet seasonal demand over three 4-month periods.

Table 5 - Matching CO_2 supply and demand in de final situation (2030), Mt/a

CO_2 source	Reference scenario (CO_2 Mton)	CCU alternative (CO_2 Mton)	CCU+CCS alternative (CO_2 Mton)
Shell	0.3	0.75	0.75
Alco	0.3	0.75	0.75
Tata		0.6	1
AEB		0.1	0.4
AVR		0.1	0.4
Total	**0.6**	**2.3**	**3.3**

The following results should be noted:

- The supply with the lowest marginal costs will be used first (merit order). Because at Tata the capture technology (WLO High: Hisarna; Low: alternative) only comes in line in 2023, demand will first be met by Shell and Alco (both in equal measure).
- From 2030 onwards the methanol plant will also need CO_2, creating an additional 1 Mt demand, which will be supplied by Shell, Alco, Tata, AVR and AEB (2.3 Mt). This last aspect is independent of the WLO scenarios.
- AEB and AVR, with their higher OPEX, will only contribute after the others have come on line[9].
- In the CCU+CCS alternative total demand (incl. CCS) equals maximum grid capacity (3.3 Mt).

We stress that the merit order is a crucial parameter when it comes to costs. If it is opted to give preference to CO_2 from *biogenic sources* this will change the merit order and lead to higher costs.

If the CO_2 is once more freed up, i.e. emitted, after use of the products in which it has been temporarily bound, due allowance for this will have to be made in the social costs (see Section 3.5).

3.5 CO_2 price

A distinction is made between the price of externally supplied CO_2 for use as a process feedstock and the social value of the CO_2 emission avoided when a tonne of captured CO_2 is supplied to a user for process application, thus doing away with the need for the sand-lime heating process or summer greenhouse heating, for example. The tonne of CO_2 supplied does not replace the production process emission 1-to-1, however, as this depends on the CCU or CCS application. In Section 3.5.2 these CO_2 impacts are quantified and valued.

3.5.1 Price of externally supplied CO_2

Supply of CO_2 from off-site is a market transaction between the supplier and consumer, with a market price reflecting the willingness to deliver and pay. This transaction forms the basis for the financial benefits to the party operating the CCU Smart Grid. With the ensuing revenue the operator endeavours to create a healthy basis for a profitable business case to recoup his investment.
The supply price of OCAP CO_2 presently stands at € 55-60/t CO_2, which is generally cheaper than the cost price of the alternatives currently available to greenhouse horticulturalists.

Given the multi-year delivery contracts and the latent demand for CO_2 from horticulturalists, among others, this price is not likely to fall any time soon. Market players indeed expect it to rise with increasingly robust climate policy and scarcity in the gas market. In our SCBA we have conservatively assumed that the price for off-site CO_2 will, in real terms, remain much the same as today's contract prices in the future, and we therefore adopted a figure of € 57.50 per tonne.

3.5.2 Value of avoided CO_2

WLO scenarios

To provide background for policy-makers and others, several years ago the Netherlands Environmental Assessment Agency (PBL) and the Netherlands Bureau for Economic Policy Analysis (CPB) published the scenario study 'Welfare, Prosperity and the Human Environment', referred to by is Dutch acronym WLO (CPB ; PBL, 2015). In this study two basic scenarios were explored, known as High and Low, differing in several aspects, including with respect to climate policy, as set out in the

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[9] In the CCU project alternative demand thus varies according to the season and the waste incinerators will have to hooked up in summer to meet overall demand (1.03 Mt; see Table 12).

text box below. In the SCBA for the present study these scenarios were taken as the background for estimating the impacts of the project alternatives.

These impacts are highly dependent on CO_2 prices, which are in turn very contingent on international uncertainties regarding climate and energy issues. This is why we have worked in parallel with WLO Low and High, as these yield a likely range of results given the uncertainty about future developments with respect to the prices of gas, CO_2 and electricity, among other things.

One of the key assumptions of the WLO scenarios is that international climate policy will in the long term determine European climate policy, which will in turn determine Dutch climate policy. Both the Low and the High scenario are based on countries' pledges during the UN climate negotiations to reduce greenhouse-gas emissions.

High scenario

The High WLO scenario combines relatively high population growth with high economic growth. It assumes low energy prices (oil, gas and coal) and rapid technological advance. The CO_2 price rises to € 160/tonne in 2050. A 65% reduction in carbon emissions is achieved relative to 1990, slow at first but more rapid after 2025, following assumed introduction of a global emission trading system post-2030, among other factors. Additional climate policy is gradually phased out. In this scenario a 2.5 to 3 degree temperature rise is projected.

Low scenario

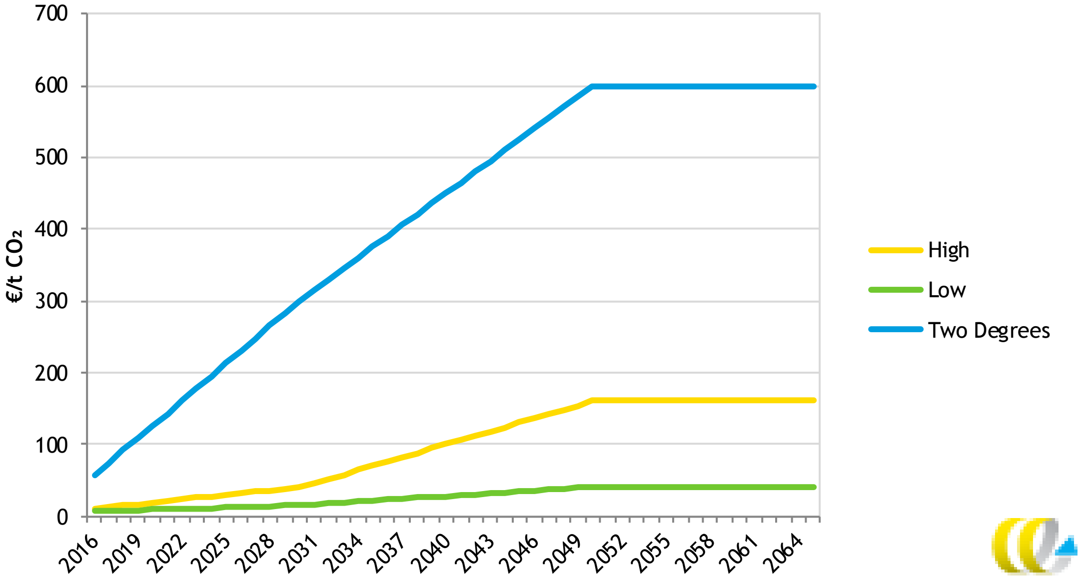
The Low WLO scenario has lower population growth and lower economic growth. In this scenario there are growing geopolitical tensions, leading among other things to a higher oil price and making it harder to secure international climate agreements. In the Low scenario more modest climate targets are adopted, leading to only 40% reduction in carbon emissions by 2050. Temperature rise will consequently be 3.5 to 4 degrees. CO_2 prices remain relatively low, rising to only € 40/tonne in 2050.

Sensitivity analysis: exploring the uncertainty of two degrees warming

Besides the previous two scenarios, the WLO study also explores uncertainties. On the theme 'Climate and Energy ' this is a Two Degrees scenario, a variant of High assuming more robust climate policy in order to secure the stated Paris target of no more than two degrees temperature rise. This requires 80-95% emissions reduction, which means a sharp rise in the CO_2 price in the near term already. This two-degree scenario has been included in our sensitivity analysis.

Figure 7 shows the CO_2 prices used for *avoided CO_2 emissions.*

Figure 7 - Efficient CO_2 price paths used in this study



Source: (CE Delft, 2017b).

3.5.3 Correlation between the two CO_2 prices

In the context of CCU there is currently no internalisation of the costs of CO_2 emissions or other environmental impacts. CCU applications are abatement options not covered by any form of policy. A key instrument like the EU ETS has no provisions for CCU (see following text box) and binding CO_2 in building materials yields no financial benefits in civil engineering tenders, nor is it a mandatory element of the building standards in force for private house-building.

On top of this there is scarcely any internalisation of the cost of CO_2 emissions in energy prices for most energy consumers, including industry and greenhouse horticulture. Current contract prices for externally supplied CO_2 are, in other words, determined solely by market considerations (quality, security of supply, direct costs relative to alternatives) for the product in question. For market parties there are thus environmental benefits or saved emission permits to be earned. There are no signs of this situation being remedied any time soon.

Looking further into the future, this situation may change, though, certainly in WLO High, where CO_2 emissions trading is assumed to become economy-wide, with numerous sectors participating. The resultant scarcity that is expected to arise has not been included in our estimated CO_2 contract price, however (taken as remaining a constant € 55-60/t). In other words: future CO_2 contract prices and emission trading prices can be seen as being uncorrelated. The financial benefits are consequently unrelated to the social benefits. Put differently, there is no double-counting.

CCU in the EU Emissions Trading directive

Today, if one party supplies CO_2 to another (at a different facility) for a purpose other than CCS there is no provision for earning carbon emission permits, as such transactions are not covered by the EU Emissions Trading directive. The only exception is mineral carbonation in the precipitated calcium carbonate (PCC) process, which counts as a valid means of reducing CO_2 emissions. This process is not operated in the Netherlands, however.

After 2021 this may change, although this is as yet unclear, as it requires agreement across the EU. What is clear, however, is that the European Commission is very wary of applying this to cross-sectoral carbon flows, because then artificial fertilisers could also be regarded as a CCU technology, implying that a very major emissions source would no longer be regulated. We have therefore assumed that emitters earn no emission permits via CCU in the future, as at present.

4 Social costs and benefits

4.1 Introduction

This chapter describes the welfare impacts of the project alternatives item by item. The direct welfare impacts consist of one-off investment costs and annual operating costs and the sales revenues from off-site supply of the CO_2. Together, these give an indication of the business case. The social impacts include the contribution to tackling climate change and additional employment. These have been categorised as CO_2 benefits, air-quality benefits and other impacts. The impacts of the project alternatives are described relative to those of the reference scenario.

4.2 Basic premises

The basic premises of the SCBA are as follows:
- A 50-year horizon (2018-2068).
- Costs and benefits are counted starting on 1 January, 2018.
- Costs and benefits are expressed in prices of 1 January, 2018.
- Costs and benefits are subject to a 4.5% discount rate.
- Costs and benefits are presented both at an aggregated level and using a set of indices per object.
- Costs and benefits are presented with reference to the impacts for the various stakeholders. No allowance is made for funding costs.

This chapter looks at the results and the calculation method used for each cost item.

4.3 Financial impacts

This section considers the financial impacts for the grid operator. These impacts have not been obtained via in-depth engineering studies but are based on currently available data. Neither are they based on a concrete design of the CCU grid.

4.3.1 Capital expenditure

Tables 6 and 7 summarise the investment costs, or capital expenditure (CAPEX), for the CCU project alternative. These depend on the scenario adopted. In the High scenario (and the Two Degrees variant) it is assumed Tata has rolled out the Hisarna technology and that the CO_2 from this process is virtually capture-ready. The remaining van € 20 mln. investment is for compressing[10] the captured CO_2.

In the Low scenario Hisarna is unavailable and the CO_2 will therefore have to be captured from the existing Tata process, requiring a far more robust investment in capture plant, assumed to be € 125 mln., based on the figures for AEB and AVR and on a capacity of 0.6-1 Mt.

For CAPEX at AEB and AVR the figure is for gaseous capture (left-hand column), including a day/night gas buffer so nighttime output can be supplied the next day.

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[10] Required for final storage of the CO_2.

On the user side, several additional investments in the CCU Smart Grid have been taken on board:
- € 35 mln. investment in distribution grids branching off from the main OCAP pipeline;
- € 48 mln. investment in liquefaction plant and distribution grids, mainly ‘mini-grids’ for satellite areas that cannot be connected to the existing OCAP pipeline.

Table 6 - CAPEX in CCU project alternative, WLO High and Two Degree variant (not discounted)

	Capture (€ mln.)	Grid connection (consumers) (€ mln.)	Grid connection (sources) (€ mln.)	Total (€ mln.)
Shell	0			0
Alco	20			20
Tata	20		15	35
AEB	125		1.1	126
AVR	75		0.8	76
Distribution grids, consumers (gaseous)		35		35
Distribution grids, consumers (incl. liquefaction)		48		48
Total CAPEX	**240**	**83**	**16.9**	**340**

Table 7 - CAPEX in CCU project alternative, WLO Low (not-discounted)

	Capture (€ mln.)	Grid connection (consumers) (€ mln.)	Grid connection (sources) (€ mln.)	Total (€ mln.)
Shell	0			0
Alco	20			20
Tata	125		15	140
AEB	125		1.1	126
AVR	75		0.8	76
Distribution grids, consumers (gaseous)		35		35
Distribution grids, consumers (incl. liquefaction)		48		48
Total CAPEX	**345**	**83**	**16.9**	**445**

For AVR and AEB, finally, investments in connection are limited, as these facilities are only 0.5-1.5 km from the current OCAP pipeline. In the case of Tata, connection to OCAP can be achieved by repurposing the existing offshore oil pipeline to the Amsterdam Port area. According to a study by TNO (TNO, 2018) there are no technical barriers to using this for CO_2, though this option would require further analysis (Gasunie and EBN, 2018). If the Amsterdam Port oil pipeline is used, an additional 5-15 km pipeline would need to be laid to connect Tata. See Table 8.

Table 8 - Source-side CAPEX (not discounted)

	km from OCAP to source	Cost (€ mln.) /km	Total (€ mln.)	Type
Shell	0	0.75	0.0	Connection
Alco	0	0.75	0.0	Connection
Tata	10	1.5	15.0	Transport line
AEB	1.5	0.75	1.1	Connection
AVR	1	0.75	0.8	Connection
Total	**12.5**		**16.9**	**Connection**

In the CCU+CCS project alternative the basic investments are the same as for CCU but with additional costs of purification and compression for storage in depleted gas or oil fields. Table 9 provides a summary, based on the study by Gasunie and EBN (Gasunie and EBN, 2018). In the CCU+CCS alternative only a fraction of the total storage capacity of the Low scenario is used, so we assumed one-tenth of CAPEX for this project alternative[11]. In the sensitivity analysis we do the sums for a variant in which no large-scale CCS infrastructure is built in the Netherlands. In this variant the total transport and storage CAPEX are thus for the CCS+CCU alternative.

Table 9 - Investment costs in CCU + CCS project alternative (not discounted)

OCAP-CCS	CAPEX (€ mln.) Low case	CAPEX (€ mln.) project alternative	Start of construction	On-line
CAPEX, offshore pipeline	419	41.0	2019	2022
CAPEX, 5 MW compressor	14.5	1.4	2019	2022
CAPEX, repurposing of storage plant	133	13.0	2019	2022
CAPEX, construction of new storage plant	428	41.8	2019	2022
CAPEX, dismantling	40	3.9		2068

4.3.2 Operating expenditure

The operating expenditure (OPEX) of both project alternatives, CCU and CCU+CCS, consist of the costs of at-source CO_2 capture, which are generally the predominant item in the aggregate cost of capture, transport and storage (Gasunie and EBN, 2018). The purer the CO_2 from the source, the lower the capture costs. Besides a possible purification step, compression costs are a major contributor to the OPEX. It has been assumed that the sources supply the grid in a merit order based on rising marginal costs (see Section 3.4.3). For transport and exploitation of the grid a break-even price of € 10 per supplied tonne of CO_2 has been taken.

In the CCU+CCS project alternative, additional OPEX for compressor stations for aquifer injection have been included in the transport and/or storage costs (€ 3/t). On top of this come the OPEX for such things as inspections, general maintenance and specific maintenance (€ 0.7/t). Finally, there are the costs of storage (€ 1.6/t). This gives a total figure of around € 6/t (see Table 10).

Table 10 - Costs of CO_2 transport and storage in CCU+CCS project alternative (not discounted)

	€/tonne
Maintenance and inspection	**0.7**
Transport	3.0
Storage	2.2
Total, CCS	**5.9**

4.3.3 Operating benefits

The operating benefits consist of the revenues accruing to the operator for supply/sale of the CO_2 to users. In this study it has been assumed that the current contract price of € 55-60/t is a good reflection of the future price of CO_2 as a feedstock in the various processes. We devoted no effort to researching the business cases of individual consumers. It is likely, though, that the business cases for the CCU applications mineral carbonation and methanol production will soon be profitable in the Netherlands. In Germany (BASF) and the UK (Carbon 8) the first business cases have already been

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[11] Approx. 46 Mt/476 Mt CO_2 stored.

elaborated and BASF has begun construction of a methanol facility. Greenhouse horticulturalists are already willing to buy CO_2 for this price. Parties directly involved currently state that at today's price there is considerable latent demand for off-site CO_2 from this sector provided there is sufficient security of supply. Climate policy for the sector will lead to a major increase in this demand.

The operating benefits should therefore be seen as the income from capture, transport and supply of CO_2 under break-even business conditions for users. These amount to € 1.2 billion (NPV). This figure is the same in both project variants: CCU and CCU+CCS.

4.4 Avoided CO_2 abatement costs

By supplying CO_2 to potential consumers the CCU Smart Grid can help prevent CO_2 emissions.
In the first place, this can occur directly, by CO_2 being permanent fixed (chemically bound), particularly in building materials like concrete and sand-lime bricks. Because the CO_2 can then only be released at very high combustion temperatures, it can safely be assumed that such materials provide virtually 100% secure CO_2 sequestration. In addition, supplying these gases to greenhouses, for instance, may lead to avoidance of fossil energy use in other production processes (indirect reduction). Finally, CO_2 can serve as a feedstock for fuels that can in turn serve as chemical feedstocks. Overall then there are numerous CCU routes, each with their own upstream and downstream ramifications, with the overall carbon footprint depending on the applications involved.

Supplying CO_2 as a feedstock for other processes does not mean one-to-one reduction of aggregate emissions down the chain, however. Indeed, some processes may be so energy-intensive that the carbon footprint of the CCU application ends up being negative on balance. This may be the case for methanol production, for instance, which requires a huge amount of electricity. Only if enough of this is from renewables will the chain as a whole have a lower footprint. In this context due allowance must also be made for the energy needed for gas compression and transport. Table 11 summarises the footprint factors adopted for the CCU routes examined here. A positive value indicates a net reduction in the overall chain, a negative value that the CCU route leads to a net increase in emissions.

Table 11 - CO_2 emission reduction (tonne) per tonne captured and supplied CO_2

CO_2 source/CO_2 consumer	Horticulture		Building materials	Methanol		CCS
	Summer use of gas boiler	Current situation		100% renewables	Grey	
Shell (fossil oil refining) + Alco (bio-ethanol production)	0.947	0.5	1.041	0.465	-1.6	0.847
Tata (blast furnace)	0.856	0.45	0.95	0.375	-1.69	0.756
AEB+AFV	0.838	0.44	0.931	0.356	-1.7	0.738

Source: (CE Delft, 2018).

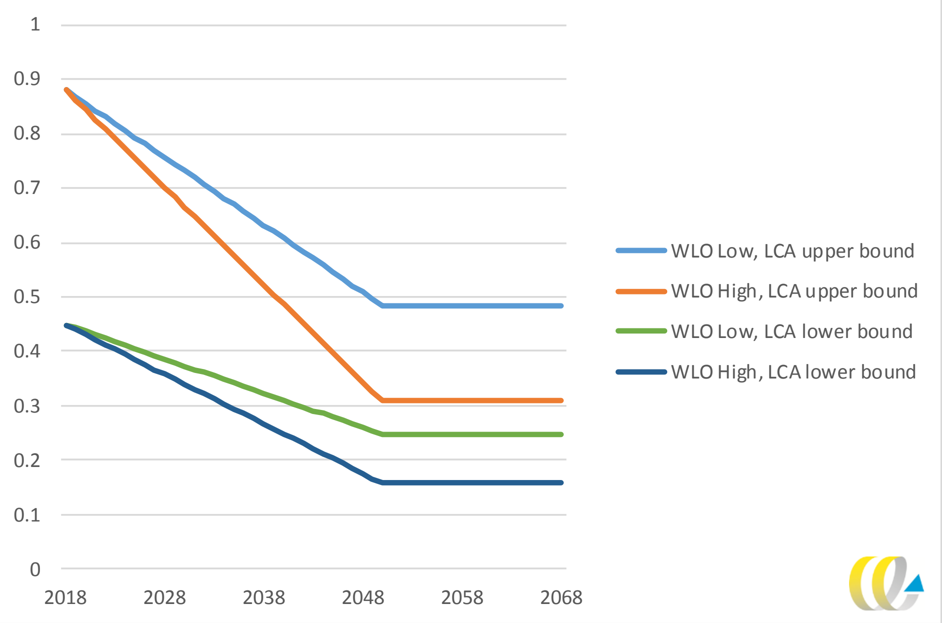
As can be seen, how the methanol route for the chemical industry performs depends very much on the electricity mix used. The net emissions reduction is in fact negative for the current average mix ('grey' in Table 11), while it is positive if 100% renewables are used. Even then, though, the overall carbon footprint is considerably less favourable than that for mineral carbonation in building materials. Horticulture lies in between, with the footprint depending on how allocation to summer gas consumption is done (reference gas consumption for CO_2 dosing). This is highly dependent on the crop and cropping system, and on whether heating is by boiler or cogeneration plant (and how the latter is utilised for on-site power, grid feed-in and heat production)[12].

Reference through to 2068

For greenhouse horticulture, the underlying reference for these footprint factors is the present situation. However, the sector has stated its ambition to wean itself off the gas grid and use alternative heat sources. This means that by 2040 there will no longer be any fossil energy consumption attributable to CO_2 dosing. Even more importantly, the CO_2 fed into the grid by industry will need to be of *biogenic origin* (biomass), as industry will itself then have to have stopped use of fossil carbon as a chemical feedstock.

In the SCBA, however, the transition rate is dictated by the WLO background scenario's Low and High, with that rate varying from reasonably rapid in High (2050: -65%) to slow in Low (2050: -40%) - in both cases insufficient for 100% zero-carbon in 2050. This therefore implies that even then there will be a (now smaller) CO_2 benefit from the CCU application in greenhouse horticulture. Figure 8 shows how the greenhouse horticulture footprint develops in WLO High and Low. The CO_2 issue however remains a basic condition for further greening of greenhouse horticulture.

Figure 8 - Trends in average carbon footprint of greenhouse horticulture, WLO Low and WLO High



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[12] One of the LCA cases is based on current real-world data provided by LTO Glaskracht. In 2015 OCAP supplied approx. 440 Kt CO_2 to 2,000 ha of greenhouses. On average this supply saves out 7 m^3 natural gas/m^2 annually (Van der Velden & Smit, 2016) (Appendix 4 of Discussion paper on CO_2 emission reduction by CO_2 supply to greenhouse horticulture from waste-to-energy plant). This means a CO_2 emission reduction of 7 x 1.78 (1 m^3 natural gas contains 1.78 kg CO_2) x 2,000 ha x 10,000 m^2 = 249,000,000 kg CO_2, equating to a reduction factor of approx. 0.5.

From carbon footprint to carbon benefits

To value avoided CO_2 emissions an ‘efficient’ CO_2 price was used. In the WLO study each scenario proceeds from a CO_2 emissions budget for the rest of the century and an associated rate of emissions reduction. With efficient pricing, the thus established emissions cuts are achieved at maximum cost-effectiveness. In the approach adopted by WLO a measure like the CCU grid yields zero net CO_2 emissions reduction. It does yield a net cost reduction, though, as it makes alternative measures unnecessary. This cost reduction is equal in value to the avoided CO_2 emissions times the efficient price (see Figure 7) (cf. CPB ; PBL, 2016). In WLO High the CO_2 price rises to € 160/t in 2050, in WLO Low to € 40/t. In the Two Degrees variant (cf. sensitivity analysis) the price starts out at € 180/t, eventually rising to € 600 /t. After 2050 we assumed a constant CO_2 price.

In the project alternatives the climate benefits are the second-largest item (after the operating benefits for the grid operator), but they are highly dependent on the assumptions made regarding the availability of renewable electricity for methanol production. As use of ‘grey’ electricity means a negative net carbon footprint, the contribution of this CCU route to the overall performance of both project alternatives is negative, despite rising CO_2 prices in the background scenarios. If renewables are used for methanol production (with direct hook-up to a wind farm) the climate benefits improve dramatically, though it must be ensured there is no double counting, since wind-power generation is already booked as a climate measure.

4.5 Other emissions

Besides reducing CO_2 emissions, the heating alternatives also help reduce other air-polluting emissions, through savings on gas consumption for conventional heating by greenhouse operators, for example. This implies an improvement in air quality, indoors in greenhouses as well as outdoors.
As natural gas combustion causes zero particulate emissions (Gasunie, 2011) we considered only NO_x emissions. To quantify the reduction in these we took an average emission factor of 16 g NO_x /GJ in 2018 for the gas-fired CHP plant and boilers used in greenhouses, based on TNO (TNO, 2014).

The environmental benefits were calculated by multiplying the emissions associated with each alternative by the environmental price of the emission concerned. In contrast to the CO_2 benefits, the price used for NO_x emissions was taken constant. This was taken from the (Dutch-language) ‘Environmental Prices Manual’ (CE Delft, 2017a); see Table 12. In our analysis we used the ‘central’ value from the manual.

Table 12 - Environmental price of average Dutch NO_x emissions (€$_{2015}$/kg)

	Lower	Central	Upper
NO_x (€$_{2015}$/kg)	24.1	35	53.7

Source: (CE Delft, 2017a).

Reduced burning of natural gas to generate CO_2 for greenhouse crop fertilisation reduces NO_x emissions by 98,000 kg in 2018, rising to double that in 2030 when only off-site CO_2 is used. This holds for both project alternatives. The monetised benefits (not discounted) total about € 3.4 mln. in the first year, rising to € 6.8 mln. in 2030 – a modest figure compared with the CO_2 benefits.

4.6 Regional economic impacts

Investments in CCU and CCS solutions create additional demand for labour, but not all of this translates to welfare gains in the SCBA. With the labour market, it is only changes to existing market imperfections that can lead to additional welfare impacts. This is because the extra jobs in the alternatives can lead to loss of other jobs elsewhere in the region. This is anticipated mainly in the case of highly skilled labour: if such personnel are not employed in CCU and CCS projects, they will likely be working somewhere else in the region, in which case no extra welfare will be created.
If there are new jobs for unskilled and medium-skilled workers this may count as additional employment, but here too it will need to be analysed, segment by segment, to what extent this new employment creates jobs for those presently unemployed. The current situation in the construction labour market shows the unemployment rate can soon fall.

CCU and CCS can boost the competitiveness of the Rotterdam Port Area and the Westland, B Triangle and Aalsmeer horticultural region. A more competitive Port will attract new firms, while off-site CO_2 supply will allow greenhouse horticulture to transition to climate-neutrality. There are only a limited number of serious alternatives conceivable for CO_2 crop fertilisation. The fact that the greenhouses are so clustered together in one region can then create advantages in terms of efficient use of collective infrastructure for both CO_2 and heat, with economies of scale eventually leading to lower costs for each. This will give the region a competitive edge compared with other (greenhouse) horticultural areas. Similar considerations may also hold for other CO_2 consumers like producers of building materials (mineral carbonation) and syngas, though this is far from certain at the moment.

Finally, CO_2 supply to the greenhouse horticulture sector is also crucial for its continued survival in a climate-neutral world in 2040, for without it the sector will lose its very *raison d'être* and largely relocate abroad. In the WLO scenarios the rate of transition is substantially slower than climate-neutral in 2040, however. This economic impact was not taken on board in the present SCBA, however. Indeed, none of these direct and indirect impacts have been included in the SCBA, because of the major uncertainties involved.

5 SCBA outcome

5.1 Introduction

This chapter reports the overall balance of the costs and benefits of the CCU and CCU+CCS project alternatives. We report results for the WLO Low and High scenarios, taken to be the 'autonomous trend' or 'baseline' against which the cost-effectiveness of the alternatives is assessed. If that is positive on balance, then the alternative constitutes a socially efficient solution compared with the policy package envisaged in WLO Low and High.

In both WLO scenarios climate policy is intensified, but at very different rates and with very different ambitions. In Low it becomes clear around 2030 that there is no desire to tighten standing agreements any further, while in High these agreements are made more stringent around 2025.

Because of the major sensitivity to assumptions regarding the CO_2 benefits associated with the two routes horticulture and methanol production (for energy and as a chemical feedstock, respectively), we have here worked with upper and lower bounds; see Table 13.

Table 13 - Upper and lower bounds for carbon footprint

	Upper bound of CO_2 benefits	**Lower bound of CO_2 benefits**
Greenhouse horticulture	Use in gas boiler (LCA, CE Delft)	Use in current situation (LCA, CE Delft)
Methanol production	Wind power assumed (LCA, CE Delft)	Average electricity mix assumed (LCA, CE Delft)
Presentation	Uncertainty bar in graphs (highest point)	Uncertainty bar in graphs (lowest point)

This chapter reports the principal results of the social cost-benefit analysis of the project alternatives against the background of these scenarios.

5.2 Results for WLO High

All the impacts reported - direct, indirect and external - relate to the difference between the reference scenario and the two project alternatives.

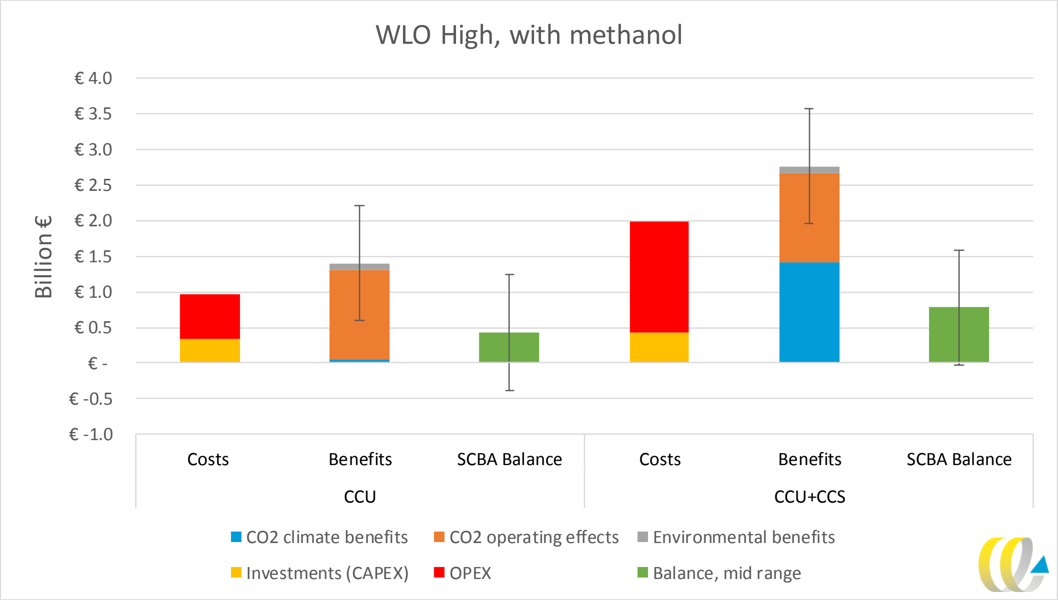
In the High WLO scenario, globalisation continues apace. Besides making markets even more interlinked, this also facilitates international discussion and coordination, on tackling climate change, for example. This scenario combines relatively high population growth with high economic growth of around 2% per annum. It assumes that established policy is supplemented by intended policy, i.e. policy plans, whether or not elaborated into concrete measures.

In the High scenario, the temperature rise due to global warming is assumed to peak in the long term at between 2.5 and 3 degrees Celsius, translating to a need for the Netherlands to reduce its carbon emissions by 65% relative to 1990.

In High the efficient CO_2 prices are significantly higher than in Low: € 80/t CO_2 in 2030, gradually rising to € 160/t in 2050. In this scenario the principal policy instrument, at both the global and European level, is taken to be pricing, backed up by emission standards and innovation policy.

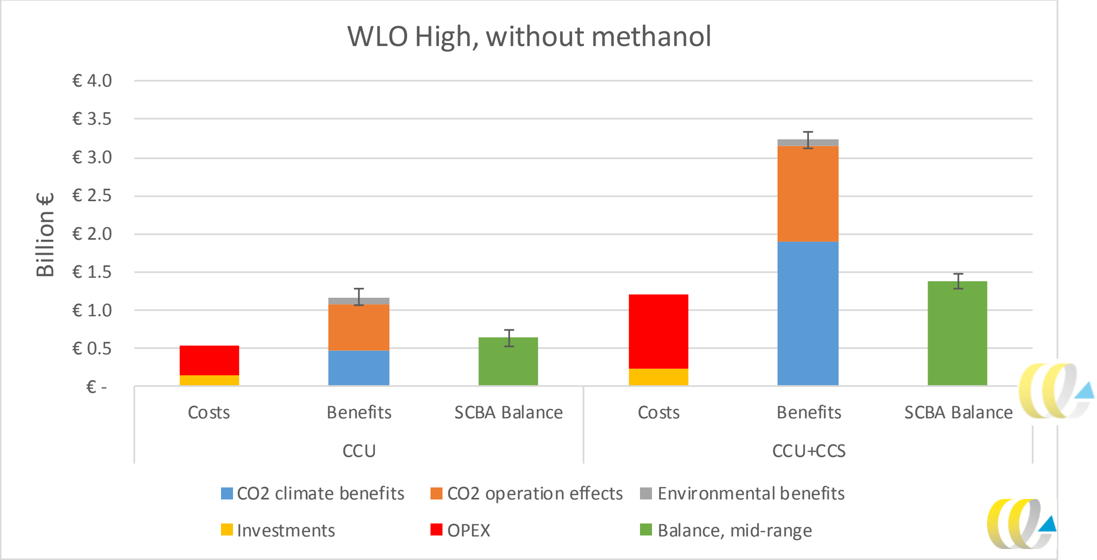
In the present SCBA, CO_2 benefits have been valued using the CO_2 price trends adopted in the WLO study, which are in line with the recommendations of the Discount Rate Taskforce, underwritten by the Cabinet. The results are reported in Figures 9 and 10, for variants with and without methanol - production, respectively.

Figure 9 - Synopsis of SCBA results, variant with methanol production, 2018-2068, WLO High (NPV)



NPV = Net Present Value.

Figure 10 - Synopsis of SCBA results, variant without methanol production, 2018-2068, WLO High (NPV)



NPV = Net Present Value.

The most salient points in these results are as follows:

- In the more ambitious climate scenario (High) the potential balance of the CCU alternative with methanol production has a very broad range of uncertainty, from € 0.4 billion negative to € 2.2 billion positive, depending on assumptions regarding the carbon footprint down the chain. With methanol, this project alternative does not have a robust positive result. Without methanol, the SCBA result is robustly positive, though.
- In the CCU+CCS project alternative, the net balance may still work out negative, but in the WLO High scenario this is extremely unlikely. This project alternative provides scope for storing CO_2, above all in the winter period, with these benefits weighing up against the additional capital expenditure on CO_2 transport and aquifer storage under the North Sea.
- In the CCU project alternative, it is methanol production (in 2030) that tips the positive balance over to negative. This technology is power-intensive, and if the current average electricity mix is assumed (first LCA case) there will be net additional CO_2 emissions, with a major negative impact on the SCBA balance. Only with 100% renewable electricity (second LCA case) will methanol production give a positive SCBA result. Until such time as national demand can be fully met by renewables, this benefit cannot be allocated to the chemical industry. This situation is not expected to have materialised by 2030.
- The SCBA balance hinges far less strongly on the carbon footprint assumed for greenhouse horticulture. Here, too, we see a negative impact if a less favourable footprint is assumed[13]. This currently stands at about € 0.2 billion, however. With the declining demand for gas by greenhouse operators in the background scenario, the avoided volume of CO_2 emissions will gradually decline as more and more CO_2 is supplied from off-site. After all, discontinuing on-site CO_2 and heat production will allow them to achieve a far better match to seasonal fluctuations in CO_2 and heat requirements. It should be noted again, though, that off-site CO_2 is a sine qua non for further greening of this sector.

Financial balance

- The financial balance can be regarded as the result for the grid operator, on the basis of 4.5% return on investment (ROI). On the consumer side, break-even business cases have been assumed for the volumes concerned.
- As can be seen in Figure 11, the financial balance is positive for the CCU project alternative but negative for the CCU+CCS alternative. The main reason for this is that in the latter case the benefits come in the form of *social* climate benefits. Only if savings on emission permits are multiplied by a sufficiently high ETS price will the business case for CO_2 sequestration under the North Sea be viable.
- The fact that this alternative does not get off the ground, then, is due not so much to the unprofitable component[14] but to issues of coordination and agreement among multiple stakeholders.

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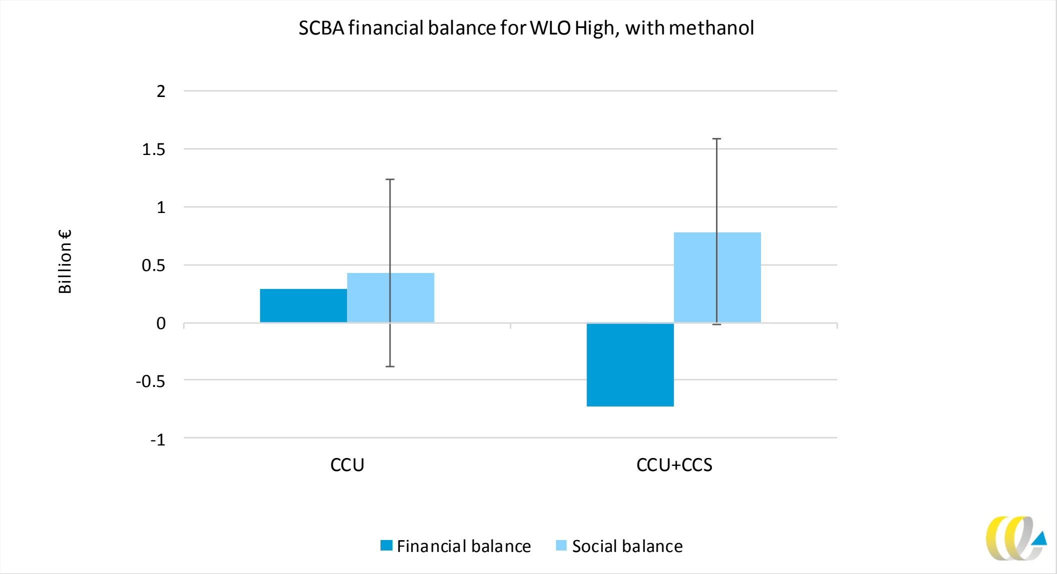
[13] A footprint of 0.5 tonne per captured tonne of CO_2 instead of 0.85 tonne avoided per captured tonne.

[14] NB: With a different ROI (incl. a market-based 'risk premium') the financial balance may be more negative.

Figure 11 - Financial results, variant with methanol production, 2018-2068, WLO High (NPV)

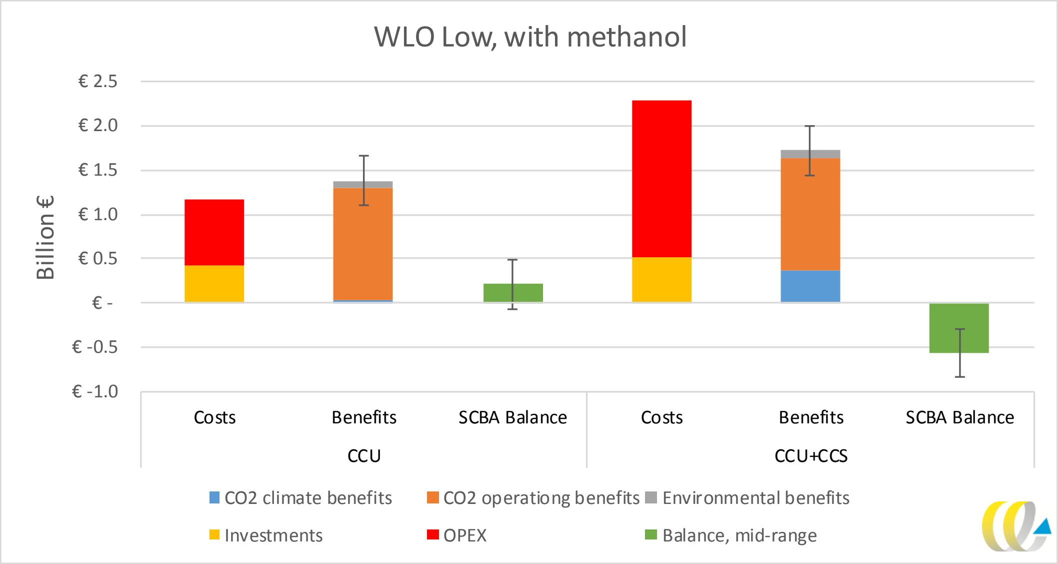


NPV = Net Present Value.

5.3 Results for WLO Low

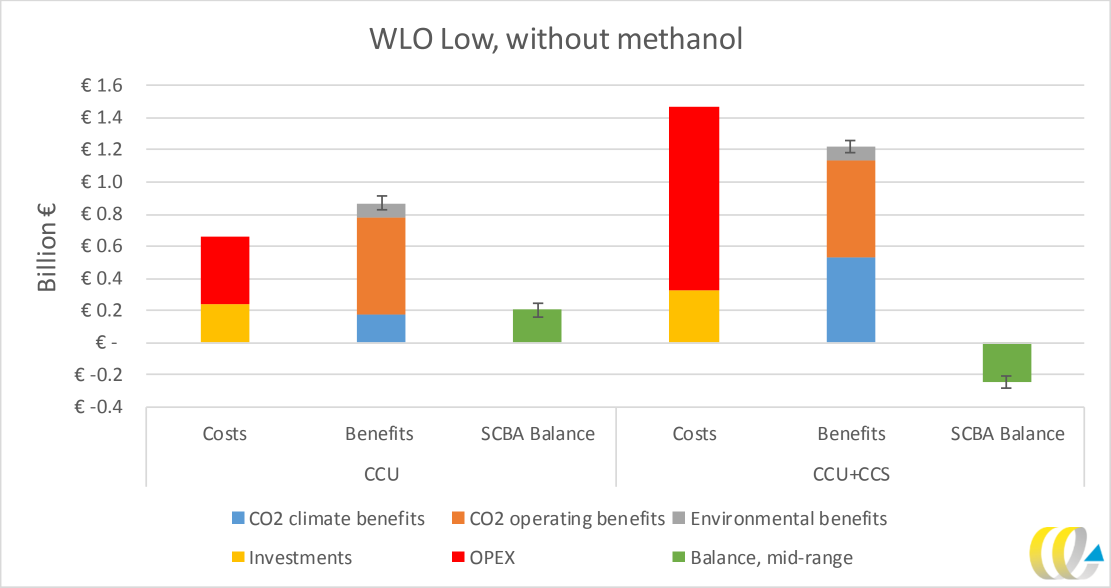
In the Low scenario more modest further globalisation is assumed, resulting in lower economic growth and population growth. In this scenario, policy is taken as far as possible in line with established policy, i.e. with policy targets already elaborated into concrete measures and instruments. There is only a modest rise in the CO_2 price, not enough for securing long-term climate targets. Emissions reduction in 2050 is only 43% relative to 1990 and 30% in 2030. In this scenario, fossil fuel prices are relatively high.

Figure 12 - Synopsis of SCBA results, variant with methanol production, 2018-2068, WLO Low (NPV)



NPV = Net Present Value.

Figure 13 - Synopsis of SCBA results, variant without methanol production, 2018-2068, WLO Low (NPV)



NPV = Net Present Value.

The most salient points in these results are as follows:

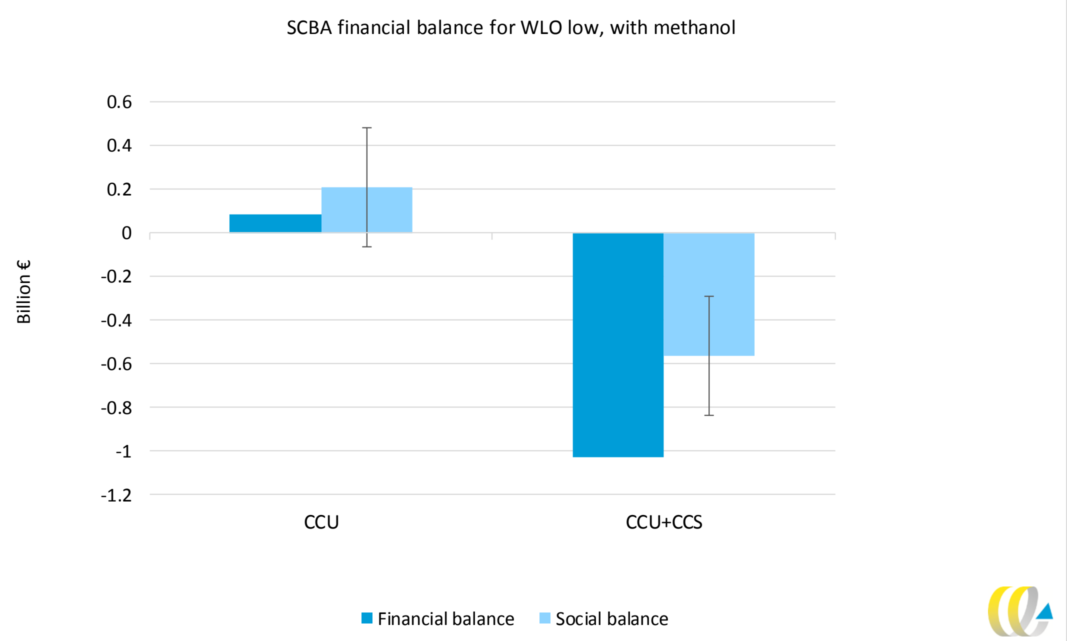
- Because of the lower social value of avoided CO_2 emissions, the results in Low have a narrower uncertainty range than in High. They all point in the same basic direction, though, with the precise results depending on the assumptions adopted in the underlying LCA. Once again there is a good chance of a positive balance, in terms of net social welfare, even if methanol production is part of the project alternative. Again, the producers will themselves have to generate the wind power needed for electrolysis, putting surpluses into the production process. If this is not done, the CCU project alternative will work out less positively on balance, and perhaps even negatively.

- In WLO Low, the CCU+CCS project alternative has a negative SCBA balance. The CO_2 price for saved emission permits is insufficient for social recuperation of the additional CAPEX and, particularly, the higher variable costs of the CCS investments.
- In this scenario, too, methanol production using the current ‘grey’ electricity mix will mean a negative SCBA result, though less so than in High. Once again, the impact of methanol production on the overall result is substantial, far greater than that of varying assumptions regarding CO_2 emissions reduction in horticulture.

Financial balance

- The financial balance can be regarded as the result for the grid operator, based on a 4.5% discount rate. On the consumer side, break-even business cases have been assumed for the volumes concerned.
- The financial balance in WLO Low is essentially the same as in WLO High, though possibly slightly less favourable if the higher capture costs at sources like Tata cannot be passed on to consumers.

Figure 14 - Financial results, variant with methanol production, 2018-2068, WLO Low (NPV)



NPV = Net Present Value.

5.4 Sensitivity analysis

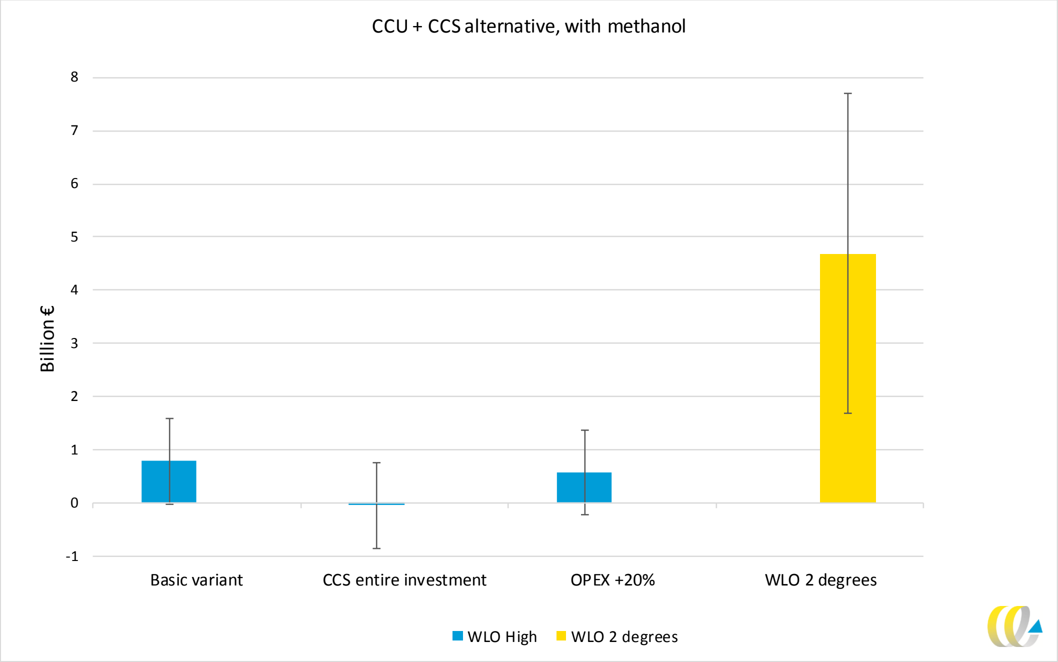
In this section we report the results of the sensitivity analysis and make a comparison with the result for WLO High (including methanol production). The following variants were considered:

- With respect to transport and storage, allocation to the CCU+CCS alternative of the entire investment (CAPEX € 1 billion) for 476 Mt storage capacity. In the basic variant, only for that part of the CAPEX of CCS (10%) is allocated the project.

- Variable costs (OPEX) for source CO_2 capture that are 20% higher than in the basic variant. This variant can be regarded as indicative for further greening of CO_2 sources.
- A variant based on the Two Degrees target, in which CO_2 prices are high enough for steering positively on that target.

Figure 15 summarises the results of the sensitivity analysis.

Figure 15 - Synopsis of results of sensitivity analysis; basic variant is WLO High, with methanol (NPV)



NPV = Net Present Value.

The conclusion of the sensitivity analysis is that the assumptions made with respect to CO_2 price and the overall investment in large-scale CCS infrastructure are extremely important for how the SCBA pans out. If no national CCS infrastructure is built and the present project has to shoulder the full CAPEX burden itself, the balance tips from positive to negative. In contrast, higher capture costs at CO_2 source facilities are of far less influence. This means opting for policies favouring (largely) biogenic sources will have no effect on the results of the basic variant presented here.

6 Conclusions

This SCBA examined two project alternatives for a CCU Smart Grid transporting CO_2 from sources to users: one facilitating exclusive use by three sectors (CCU), the other also providing for permanent sequestration of surplus CO_2 in depleted oil and gas fields under the North Sea (CCU+CCS). Below we first report the key conclusions and then a set of recommendations.

Conclusions on CCU project alternative

- CCU is a broad concept encompassing a range of potential applications in greenhouse horticulture (crop fertilisation), building materials (CO_2 binding via mineral carbonation) and methanol fuel production (via electrolysis). The CO_2 for these applications can be captured in a variety of industrial facilities in various qualities and at various pressures. It depends very much on the routes and applications in question what net reduction in CO_2 emissions is achieved down the chain, whether there is a viable business case, and whether the SCBA pans out positively for the Netherlands.
- The CCU project alternative with methanol production does not have a robustly positive result. What we do see is that the result without methanol is robustly positive. This result holds in both the WLO Low and WLO High scenarios.
- Two of the routes investigated (building materials and horticulture) are more cost-effective than the proposed climate policy assumed in either of the WLO scenarios.
- This is not currently the case for methanol production, though that may change in the near term now renewable electricity is becoming ever cheaper. The methanol routes require a vast amount of power. It is only renewables - connected directly to the electrolysis plant - that can tip the balance over to positive. In practice this means the (social) business case for the methanol route is highly dependent on an assumption of major quantities of cheap renewable power being available on the market and used for hydrogen and methanol production. In both the Low and High scenarios, methanol production on the basis of the current average electricity mix is unviable.
- With respect to greenhouse horticulture, too, the net outcome depends on assumptions about how much gas-fired CO_2 is replaced. The impact of this assumption is far smaller than the assumption on methanol, however.

Conclusions on CCU+CCS project alternative

- There is major synergy between the CCU and CCS+CCU project alternatives. Compared with the CCU alternative, CCS+CCU permits transportation of far greater volumes, improves security of supply because CO_2 can be buffered to respond to seasonal fluctuations, and allows more CO_2 storage overall. Over and against these advantages, though, stand higher capital expenditure on compressor stations and additional pipelines and the higher operating costs associated with the required purification and compression of gases for underground sequestration.
- The CCU+CCS project alternative is more dependent on a sufficiently high social CO_2 price (via the ETS, for example). For transportation and final storage in depleted North Sea gas fields there is no market-based contract price available and value can only arise through effective climate policy (read: ETS). This we see in WLO High (reasonably robust climate policy), for which the SCBA is positive on balance. However, in WLO Low (zero international progress) the CO_2 price is too low to make the CCS portion attractive in terms of social welfare. Put differently, in a world with sufficiently ambitious climate policy this project alternative would soon become cost-effective. This is especially true for the Two Degrees variant (80-95% CO_2 reduction).

- The financial balance for the grid operator is negative. The main reason for this is that in the CCU+CCS alternative the benefits come in the form of *social* climate benefits. Only if savings on emission permits are multiplied by a sufficiently high ETS price will the business case for CO_2 sequestration under the North Sea be viable.

Robustness of results

- The results are surrounded by major uncertainties. Besides the uncertainty due to the assumptions regarding the CO_2 emissions reductions associated with each CCU route, there are also the assumptions regarding the CO_2 price and how the CCS infrastructure is allocated.
  These uncertainties can affect the reported results either positively or negatively.

Recommendations

- From a social welfare perspective, the most promising CCU applications are in greenhouse horticulture and building materials production. In the longer term this might hold for methanol production, too, depending on how soon wind power become cost-competitive.
- This leads to our central recommendation regarding a CO_2 grid: start out small, based on gradual expansion of CO_2 supply to greenhouses and going on from there to develop profitable business cases for other applications based on future developments as these arise. In this way the grid can grow in accordance with concrete user needs as these take shape. The CO_2 sources can then be matched without unnecessary risk-taking in large investments if sources or infrastructure must later be taken off-line for insufficient utilisation.
- Concrete investment decisions [inhoud/taal] aan de afnemer als aan de vraagzijde inclusief CCS kunnen genomen worden op basis van een uniforme opgestelde mini-SCBA and mini-LCAs.
  Both the CO_2 impact and the social impact need to be unambiguously established.
- Greening of the sources (biogenic CO_2) feeding into the CCU grid is desirable as well as necessary. If industrial processes are not advancing fast enough in this respect, acceleration can be achieved by using largely biogenic CO_2 sources for the CCU grid via waste incinerators. The capture costs will then be higher, though.

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A Validation interviews

Validation interviews were held with the following persons:

Organisation	**Person**
Tata Steel	Gerard Jägers, Ingrid de Caluwé, Zitong Zhao
Ministry of Economic Affairs and Climate	Kees van Drunen
LTO Glaskracht Nederland	Dennis Medema
RuwBouw group	Steffen van Rijs
OCAP	Jacob Limbeek

B Volumes per alternative

B.1 Seasonal volumes

Because of seasonal fluctuations in CO_2 demand in greenhouse horticulture, supply and demand need be seasonally matched in the CCU alternative. The tables below show the supply sources required in three four-month periods. To meet demand in the summer months (1.03 Mt), waste incinerators will have to boost supply (Table 14). In the CCU+CCS alternative, total demand (including CCS) equals the maximum pipeline capacity (3.3 Mt; Table 15).

Table 14 - Seasonal variation in supply (Mt CO_2), CCU alternative (2030)

	Winter (Mt CO_2)	Spring/Aut. (Mt CO_2)	Summer (Mt CO_2)	Total (Mt CO_2)
Shell+Alco	0.50	0.50	0.50	1.50
Tata	0.05	0.23	0.33	0.61
AEB+AVR	0.00	0.00	0.20	0.20
Total	**0.55**	**0.73**	**1.03**	**2.31**

Table 15 - Seasonal variation in supply (Mt CO_2), CCU+CCS alternative (2030)

	Winter (Mt CO_2)	Spring/Aut. (Mt CO_2)	Summer (Mt CO_2)	Total (Mt CO_2)
Shell+Alco	0.50	0.50	0.50	1.50
Tata	0.33	0.33	0.33	1.00
AEB+AVR	0.27	0.27	0.27	0.80
Total	**1.10**	**1.10**	**1.10**	**3.30**

B.2 Year-on-year volumes

The following four figures show projected CO_2 supply and demand in the two alternatives over the course of time.

Supply

Figure 16 - Projected supply, by source, CCU project alternative

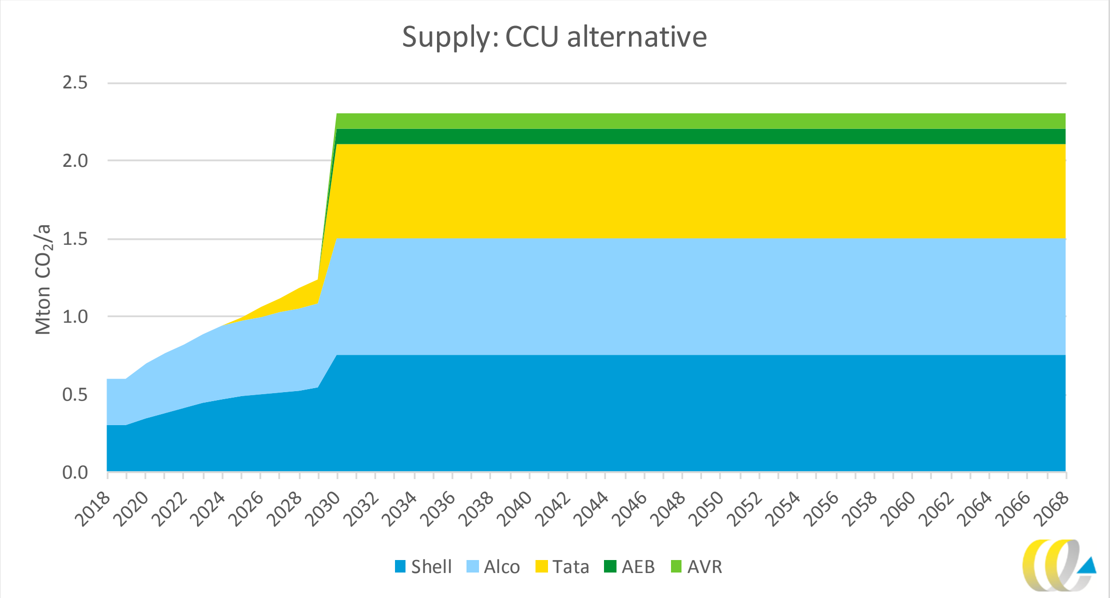
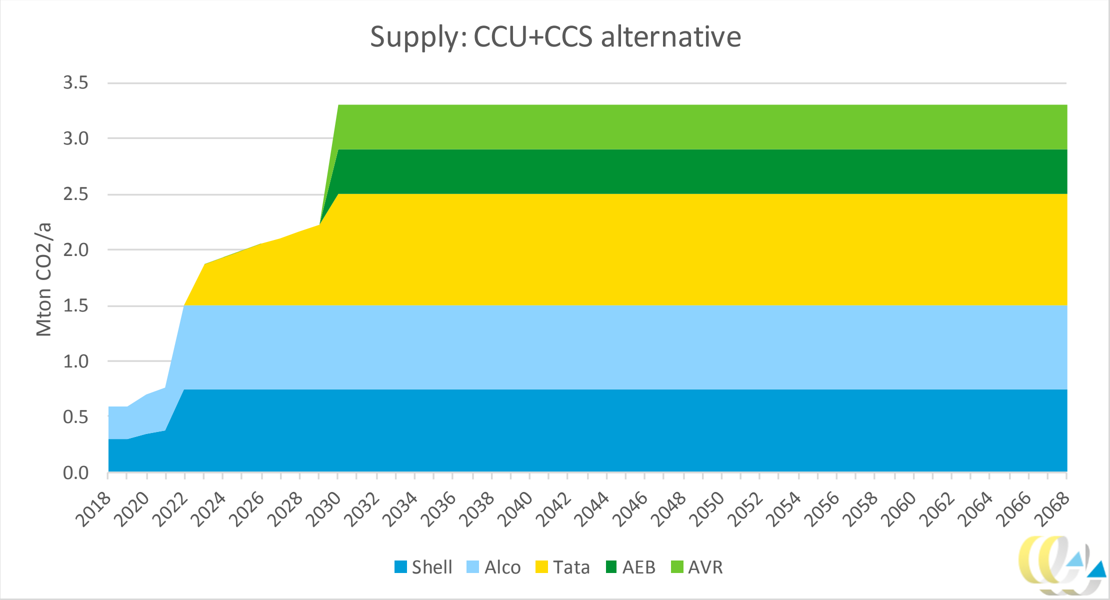


Figure 17 - Projected supply, by source, CCU+CCS project alternative



Demand

Figure 18 - Projected demand, CCU project alternative

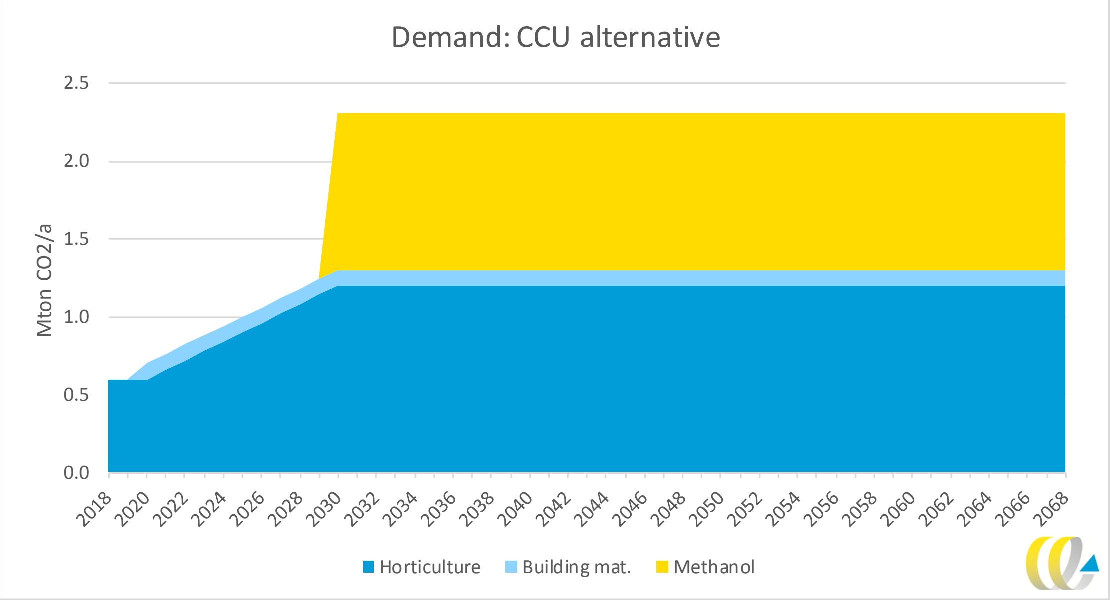


Figure 19 - Projected demand, CCU+CCS project alternative