Carbon Take Back Obligation

an Economic Evaluation

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This report is a background document as part of CTBO phase 2 report (De Gemeynt & Kuijper, 2022) and prepared by: Johannes Bollen, Lucas van Cappellen, Daan Duijn, Frans Rooijers

Delft, CE Delft, June 2022

Publication code: 22.210317.081

Carbon Take Back Obligartion, Carbo Dioxied Removal / Carbon Capture Storage, Biomass with CCS
FT: Green Hydrogen

Client: De Gemeynt

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Further information on this study can be obtained from the contact person Johannes Bollen (CE Delft)

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Content

Summary

The world is searching for emission pathways that ensure the Paris climate targets can be met. Net-zero emission scenarios are key to achieving these targets. Also, the EU proposed net-zero emission targets for 2050 in its Green Deal. There is already a wide pallet of instruments trying to reduce emissions, mostly focussing on managing emissions on the demand side while ignoring the supply-side. In this report we analyse the economic impacts of a particular supply side instrument called the Carbon-Take-Back Obligation (CTBO).

The CTBO is a new policy instrument which makes producers of fossil energy responsible for ensuring sufficient carbon storage also to take place. When a CTBO is introduced, fossil producers and importers are required to buy Carbon Storage Certificates (CSU) and in this way fulfil their CTBO. The companies that store it permanently (for example, underground) receive these CSUs and can sell them. This creates opportunities and additional financing for carbon capture and storage (CCS) projects. The CSUs give the right to production and import of fossil energy. Tradable CSU's yields — like an emissions trading scheme — an efficient outcome with respect to CCS-projects and fossil energy use in the market. CTBO can also stimulate negative emission technologies (for example Direct Air Capture and Storage) and thus ensure that, no matter how much fossil energy is still needed, the net impact on the climate can be reduced to zero.

In this report we will analyse two scenarios: a Dutch scenario with a start-up version of CTBO in the Netherlands on gas till 2030, and an EU-scenario that will analyse a long-term scenario (2030-2050) with an EU-wide version of a CTBO for all fossil energy sources in Europe. The analysis in this report investigates the economic impacts of a CTBO.

The choice to start the CTBO in the Netherlands with a fixed CTBO percentage — may initially lead to an unstable or uncertain outcome for the CSU price — and is therefore not logical. As to avoid large fluctuations of the CSU price during the initial phase (months or a year), we instead assume for the Dutch scenario a CTBO on gas supply starting with a fixed CSU price of € 40/tCO_2 in the period up to 2030. This will likely result in a CTBO% at around 15% in 2030. In this way, there is no uncertainty on the CSU price. The fixed CSU price is fully passed on to all consumers. It is important to realize that under these circumstances a CSU price of € 40/tCO_2 at a CTBO percentage of 15% yields an average equivalent of a CO_2 price of € 6/tCO_2 for the consumers of gas. The estimated CSU is limited to only 1 euro cent per m^3. Thus, the Dutch scenario seems to deliver a safe trial phase till 2030 with limited economic impacts in the Netherlands. For example, households will on average see a decline of their disposable income of 0,1%. Indeed, we find for all stakeholder groups that the implied costs are limited. Most non-ETS businesses are expected to pass on the costs of their higher energy bill to their customers, while international operating gas-intensive sectors will only partially be able to pass on the costs of the CSU price to their sales price. The government will lose some gas-tax revenues brought about by energy savings from the CSU price. Finally, the CSU price increases the gas price thus lowering demand. This in turn lowers the output of gas suppliers — about 1.3%.

However, if during the trial phase till 2030 the CTBO is not restricted to gas but also includes oil, then the CSU price will also be passed on to those consuming oil. This has little consequences for the stakeholders, but it does double the economic impacts on non-ETS businesses and the households' disposable income. Nevertheless, these impacts are still moderate.

However, with respect to emission reduction the impact of the Dutch scenario is more complex. The reason is that there is interaction between the CSU price and the subsidy-system in place on CCS projects. To be more precise, CCS projects can also apply for a subsidy covering a non-profit margin of the project that makes such a project worthwhile for investors to setup a CCS-project in the market. This subsidy is an extended version of the ‘Subsidie Duurzame Energie’ and is labelled SDE++. Note also that there is a cap of 9.7 $MtCO_2$-eq. on subsidies for CCS to ensure that there is sufficient progress on the mitigation of CO_2 emissions as well as on the renewable energy transition.

So, companies can choose to be subsidized by the SDE++ subsidy or participate in the CTBO at a sufficiently high enough CSU price. This means that CCS-projects may switch from SDE++ to CTBO, and hence CCS is simply financed in a different way. Nevertheless, we can observe some extra emission reduction at a CSU price of € 40/tCO_2 and an ETS price of € 70/tCO_2. CTBO absorbs CCS projects of the low merit-order (low marginal costs of abatement) that could alternatively have engaged in SDE++. While at the same time, SDE++ will attract higher merit order projects (with higher marginal costs of abatement). This leads to an additional 2 Mt of CCS reductions in 2030.

If, however, the ETS price turns out to be € 80/tCO_2 or more, then the cheaper CCS options will already be in the market, and the merit-order shift of a CSU price no longer applies. On the other hand, if the SDE++ no longer applies, then the CSU price introduction generates extra emission reductions. In sum, the expected emission reduction will be smaller than initially brought about by CTBO as it substitutes for potential CCS projects to apply for SDE++, but still the overall expected impacts larger than zero. Note also that a CTBO will reduce the required SDE-funding for gas + CCS projects to close to zero. Most of the remaining SDE-funding for CCS will be for oil refineries in 2030.

The setup of the European scenarios assumes an EU-wide CTBO on all fossil energy carriers, with a fully functioning CSU market under a CTBO% of 50% in 2040 and 100% in 2050. Based on this scenario, we conclude that CTBO in Europe may deliver a lower climate bill (GDP losses from climate policy) if there is a fixed carbon budget. The reason is that CTBO lowers energy scarcity because it gives negative emission reductions a business case. The negative emissions in one part of the EU economy reduces the need for expensive emission reductions elsewhere in the economy, for example energy neutral housing. Less energy scarcity translates in lower prices of energy and carbon. However, this only applies when relatively few CCS projects are realised in the baseline scenario without a CTBO. If, CTBO increases CCS compared to the base case, then generally there will be economic gains from this CTBO.

In other words, CTBO improves the carbon efficiency of strategies achieving net-zero emissions by 2050. This also implies that in the long run the CTBO instrument can serve as an insurance to achieving these net-zero targets. In a similar way, if EU climate policy is not on the trajectory for zero-emissions by 2050, then a CTBO has most added value by helping to achieve that more stringent climate goal.

Currently, only the carbon removal technologies like Direct Air Capture and Storage (DACS) or Biomass gasification (producing Energy carrier H2) with CCS (BECCS) are considered in the model, but have no business case, because the rules of the current emissions trading system (ETS) don’t reward negative emissions. But CTBO can provide these technologies with a business case by means of a CSU. BECCS’ negative emissions makes it ‘compete’ — not just with electricity-generation options — but high-cost abatement measures outside the ETS. And indeed, BECCS also reduces the need for expensive emissions abatement technologies elsewhere in the economy, for example energy neutral housing.

While net-zero emissions highly depend on wind-energy, BECCS may substitute nuclear power to contribute to electricity security. The reason is that the hydrogen produced by gasification as part of BECCS can be in a hydrogen-based powerplant as an alternative to short-cycle gas-fired powerplants. In this way BECCS, can accommodate high shares of wind energy. Moreover, despite that BECCS and DACS both produce negative emissions, it is BECCS outcompeting DACS. The reason is that there are net-economic gains at play of avoiding high electricity prices in periods when there is no supply of wind-energy.

Biomass in this analysis restricts to sustainable biomass. CTBO stimulates BECCS but lowers the supply of biomass as Europe's BECCS replaces energy inefficient "biofuel blending" for transport purposes. Blue H2 production can also be substantial, provided the rest-of-the world does not absorb all gas supply. Coal gasification with CCS can even further lower the climate bill by further stimulating BECCS while delivering much more H2. If this is an undesirable outcome, then coal can be excluded from a CTBO.

So, a CTBO start-up phase implementation in the Netherlands has little economic impacts but leads probably to some extra emissions reductions. And a mature CTBO in Europe — with sufficient trade volumes of CSUs — will in the long run yield economic gains or extra emission reductions, or a mild combi of emission reductions and/or economic gains. Because of the current lack of policies in EU for CCS and carbon removal technologies a CTBO also means more certainty that the required volumes of fossil-energy CCS and Carbon Removal CCS will be reached on time.

1 Introduction

The world is searching for emission pathways that ensure the Paris climate targets can be met. Net-zero emission scenarios are key to achieving these targets. IEA and IPCC make it abundantly clear that techniques like Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR) are essential to achieving net-zero emissions. Example technologies fitting this category such as Biomass Energy with Carbon Capture and Storage (BECCS) and Direct Air Capture and Storage (DACS) in their scenarios. Also, the EU proposed net-zero emission targets for 2050 in its Green Deal. There are still many things open for discussion in that plan, but policies rely mostly on instruments focussing on emissions on the demand side while mostly ignoring the supply-side. In this report we analyse the impacts of a particular supply side instrument called the carbon-tack-back obligation (CTBO).

The idea of a CTBO — is that producers/importer of fossil energy will be made responsible for permanently storing a similar amount of carbon as they produce. This doesn't mean that the producer or importer must do that themselves, but at least organize and pay for the additional costs of capture and permanent storage above the ETS price (minus subsidies related to CCS). Note that a CTBO applies to ALL fossil gas produced and imported in a country (ETS covers only part of that). The CTBO system organises a system of carbon storage units (CSUs) that can be traded by third parties; or by (collectively) setting up a transport and storage company that generates sufficient CSUs to the obligatory overall CBTO. For more details on explanations of a CTBO, we refer to link. We will analyse here the economic impacts of introducing CTBO in the Netherlands for gas and a broader application in the whole European area.

1.1 From a Dutch scenario till 2030 to EU wide scenarios till 2050

We will analyse the impact and economic effects of a CTBO from two scenarios: A Dutch scenario and a EU wide scenario:

1. Dutch scenario of introducing a CTBO by a CSU price of € 40/tCO_2 by 2030. We will analyse how many CSU's are involved and what the economic impacts are in the Netherlands for the year 2030. A CTBO policy is applied to all production and import of gas sold in the Netherlands. CSU's will be awarded for every ton of stored CO_2 from fossil gas use or burning. We will also show a sensitivity case in which we assume CSU's to apply to the supply of both gas and oil and CCS from also both gas and oil use.

In this model exercise, the CTBO scenario introduces a fixed CSU price during the pilot phase (not endogenous from a fixed CTBO percentage). In other words, the CSU price is fixed, and we analyse its impacts on the CTBO percentage (ratio between the CO_2 volume of CCS/CUS projects and the residual carbon emissions in the Netherlands). Note also that we build this scenario on top of a baseline scenario assuming existing policies of the Dutch Climate Accord plus a carbon taxation plan for the industry, which accounts for almost 49% reduction of national emissions. The reduction effort accrues to approximately 34 Mt CO_2 eq. An important part of the Dutch policy plan is to stimulate CCS, which is equal to 30% of the total emission reduction effort.

2. EU wide scenarios assuming a long-term EU-wide application of the instrument on both gas and oil or even all fossil energy carriers. At the same time CCS refers to fossil

sources, but also DACs and bioenergy (BECCS), Also in that case we will inspect the economic consequences, in this case for the EU economy.[1]

Under these scenarios the CTBO percentage is fixed for 2030 at 1%, for 2040 at 50%, and for 2050 at 100% to endogenously evaluate the CSU price.[2] We will build upon a scenario assuming existing policies in Europe, i.e. the most efficient plan to meet net-zero emission by 2050 with an upper abound on CCS in 2050.[3] The upper bound defined as 15% of the emission reduction effort (current emissions), which is equal to halve of the upper bound assumed for the Netherlands in the Dutch scenario in 2030.

The analytics differs between the Dutch and EU-wide scenarios. Up till 2030, the potential responses in the Netherlands in the electricity system or induced electrification in industry are simply limited because of the limited timespan and investment cycles in key energy markets. But also, the moderate CSU price of € 40/tCO_2 tag on CO_2 will induce little fuel-switching opportunities – e.g., blue instead of green hydrogen or electrification of heating processes. However, the impacts on fossil end-use energy prices may be more profound and will be investigated for the most important sectors. Finally, a Dutch CSU price on fossil energy may have impacts on tax income and expenses of the government. The latter are more easily affected as initial CSU price will stimulate CCS and make the CCS-projects subsidized under SDE+ also cheaper for the government and taxpayer.

But after 2030, a wider CTBO system with CSUs covering all EU countries and all sources of fossil energy use will change prices of carbon, electricity, fossil fuels and hydrogen change and thus may affect the deployment of clean technologies.[4]

1.2 Scope

This study looks at the economic impacts for 2030 of setting up a CTBO scheme for the Netherlands related to either ‘gas’ or ‘oil and gas’, and the wider setup involving all fossil energy in Europe.[5] We have not analysed in the Dutch example:

1. High prices of gas/oil. The price developments of energy in the baseline are crucial. This also holds for the gas price. Very recently, the gas price has increased

1 All technologies that lead to permanent carbon storage are eligible for CSU's. Mineralisation and pyrolysis (forming carbon black) could also be eligible. These technologies are less well developed and therefore not included in this analysis.

2 The 1% is chosen arbitrarily. We could also start with higher values like 10-15%, and this will surely impact some of the results for 2040, but the 2050 results are hardly affected by it.

3 In Appendix A2.2 we further elaborate on the climate policy baseline assumptions, but as there is so little concrete policy plans worked out for Europe for the years beyond 2030 besides the overall overarching climate goal of net-zero emissions in 2050, we decided to use the model to allocate an efficient energy system fitting with that goal. However, we impose some restrictions on specific technologies. For example, we exclude BECCS from the base case climate policy case as there are no indications that the EU is willing to grant the negative emissions by BECCS within ETS. This may deviate from IEA’s NZ scenarios, which assumes many more stringent policy plans beyond the current existing policy plans or countries’ pledges made for the Paris climate agreement.

4 It is important to realize that in our scenarios we assume the start of a CTBO system in 2030 and later years. But the optimal planner knows this already at forehand. So, CTBO is announced before being implemented, which implies that there are relatively little sudden shocks in the simulated European energy system.

5 In the Dutch case we lack the information on how energy markets precisely evolve for these transitional years between 2025-2030. Nevertheless, we think the impacts — like setting up a CTBO scheme — will gradually built up to structural economic impacts that we sketch for the year 2030.

tremendously because of supply-side constraints and the Ukraine-Russia war. If higher gas prices prevail, then this might reduce the use of gas-related CCS from a drop in the demand for gas, or from electrification as substitute for gas. Nevertheless, this will only have a moderate impact up to 2030.[6]

2. How impacts evolve over time from a CSU price before 2030 is not within the scope of this analysis. Nevertheless, the results presented here, serve as a good upper bound of the impacts between 2025-2030.

The shortcomings of our long-run analyses refer to the model characteristics of MERGE-analyses in general. The numbers produced by model simulations should not be taken as fully realistic or the absolute truth. The numbers presented in this report only resemble part of the reality, especially considering that we employ an optimization planner perspective in the simulations. Also, the country dimension is neglected in the analysis as the European region is modelled as one region. Nevertheless, the model simulations provide new qualitative insights on potential feedbacks in energy markets and the use of CTBO.

1.3 Structure of this report

We start Chapter 2 by explaining the most important elements of the methodology of the Dutch scenario, which deals with of a moderate CSU price on gas-related carbon leading to CCS projects on gas related CCS projects, and the implied costs for end-users. Then we will explain in Section 2.2 more in-depth European scenario by specifying relevant modelling aspects of the MERGE model. For more details, we refer to Annex A.2.1. Chapter 3 explains the main results of the Dutch scenario (Section 3.1) and the European scenario (Section 3.2). For more details on results, we refer to Annex B. We conclude the report with our main conclusions.

[6] We neglect CCS of biowaste treatment/energy installations because it is not profitable at € 40/tCO_2 (biofuel-blending might also substitute for CCS options). Nevertheless, if the EU were to credit negative emissions/carbon from Biomass Carbon Removal and Storage projects, they would be able to sell emission credits and CSU's. But it is not part of current policies.

2 Methodology on Dutch and Europe-wide scenarios

2.1 Netherlands scenario till 2030

To determine the effects of a Dutch CTBO, we assembled a list of 64 existing point sources, all of which have yearly CO_2 emissions larger than 0.1 Mton CO_2-eq. per year. The latter cut-off point was chosen for tractability and because CCS is seldom a viable abatement choice for sources smaller than 0.1 Mton CO_2-eq. per year. The list includes both gas-related, oil-related, and coal-related sources. From most sources it is clear how to connect emissions to energy — especially the ones depending on only one type of fuel. This also holds for the gas-related: 40 of the 64 sources have CO_2 emissions that stem from burning natural gas or fertilizer industries. For the other point sources with multiple fuels, we employ shares over fossil sources as reported in van Dam et al (2021).

For each of the 64 point sources, we estimated the CCS potential in 2030, CCS costs in 2030 and eligibility for SDE++ subsidy compensation. A detailed explanation of the corresponding methodology and a list of the 64 point sources can be found in Annex A.1. In the Dutch policy scenarios we assume that the infrastructure for transport and storage of carbon only applies to the Rotterdam area. Note that we merely considered existing sources, and potential new point sources such as blue hydrogen are to some extent allowed in the model. However, we neglect negative emission sources, because the time frame is simply too short for implementing and realizing significant amount of emissions captured by means of those options.[7] Also, given that a CTBO in the Netherlands would probably be introduced with a relatively small and fixed price, we believe the inclusion of — mostly expensive — negative emission sources would not meaningfully change the results.

Using the emission- and cost data described above, we estimated which point sources will employ CCS at which CSU price. This enables us to compute the CTBO percentage at a given CSU price. Underlying this step is the assumption that companies will choose the most profitable abatement technology and will only employ CCS if the monetary benefits exceed the costs. Again, a detailed explanation of the corresponding methodology can be found in Annex A.1.

Because CCS costs at specific installations are uncertain and based on grouped data, simply running the model using our best point-estimates would yield unrealistic outcomes (one would find large discrete steps in the relation between the CSU price and the CTBO percentage). To avoid this problem, we added random symmetric cost mutations to the CCS cost estimates and ran the model 100 times to determine a realistic, average outcome.

Finally, the model also calculates the CTBO's effect on energy prices. Based on the increase in energy prices and information on tax shares in energy bills for different groups (households, small and large firms), the model calculates the percentual increase in energy costs for the different groups. We also estimate the demand effect (higher energy prices lead to smaller demand for energy) using demand elasticities taken from (CE Delft, 2021).

[7] We neglect the relatively small efforts of CCS projects planned for waste-power generation, also including biomass-CO_2. But this hardly impacts the main results of our analysis.

We use the reduction in energy demand to compute the loss in tax income for the Dutch government.

We compute the results for a couple sensitivity analyses in Section 2.1. These are:
- a higher ETS price in 2030 given the price increase in early 2022: € 100/tonne CO_2.
- more CO_2 infrastructure: pipelines do not only apply in the Rotterdam area, but now extends to all five industrial clusters.[8]
- no SDE++ subsidies for CCS projects.
- There could be new blue hydrogen installations in the next five years: 4 Mt CO_2/year (without CCS).
- Also CTBO for oil production and import (leading to sales of oil products in NL).[9]

The objective of the CTBO is ‘producer responsibility’. Producers must collect and dispose of waste produced by their product. The costs of transport and storage are roughly € 40/tCO_2, hence we fix the CSU price at this level.[10] After a few years (2030 or later) this could be changed to a market-based system in which the CTBO percentage determines the CSU price through the market.[11]

It is important to emphasize the complexity of the setup of a CTBO with the subsidy schemes on CCS in the Netherlands. It is agreed and part of current policy that this subsidy finances for 15 years of a project the extra costs not covered in the market prices of energy and carbon (the so-called ‘onrendable top’). SDE++ subsidies are high enough to make ‘cheap’ CCS projects profitable. There is only a restriction on the number of projects, i.e., all subsidized projects may not exceed 9.7 Mt CO_2. As the SDE++ covers the unprofitable top, higher CSU prices lead to smaller subsidies if these are also corrected for the market, including CTBO. Net income for companies that employ CCS in CTBO will hence remain unchanged (the financing method differs, however).

But whether CTBO is in its starting phase with a fixed price or a full market with an endogenous price (with or without CCS subsidies), in both cases the CSU price translates in higher prices for gas and electricity, which in turn determines the broader economic impact of CTBO, which is the main topic of this part of the research project.

The duration of the period in which a fixed CSU price is used should be kept as short as possible. But needs to be determined based on uncertain progress with CCS infrastructure and with uncertain outcome of other countries joining in with a CTBO approach for fossil gas. As such we emphasize that the 2030 year as the maturing year is also arbitrary.
A sufficiently liquid market for CSU’s requires a mature CO_2 transport and storage infrastructure and a large enough market (for example, North Sea level could work).

8 Boat/truck/tanker transport from other locations are not included in this analysis.

9 Primary oil demand is equal to 1025 PJ in 2030 (PBL, 2021b), while oil as non-energy resource is not included in the analysis.

10 Given the ambitious ETS price of € 70/tCO_2, the industrial carbon taxation plan, and the subsidies on renewable energy and CCS in the baseline scenario, it is a moderate price level not expected to yield competitiveness losses. This is also holds if one or a few countries decide to lead the way on testing and implementing a CTBO policy. We will say more on this point also later in the results section.

11 Options like banking and borrowing and a Market Stability Reserve (to limit price fluctuations) can further add to a well-functioning market for CSUs. It should also be possible to link to other countries that have implemented a CTBO. On the other hand, it should not be allowed to purchase or use CSUs from countries that do not have a comparable CTBO-policy in place, which could harm a stable investment-environment and environmental integrity of a CTBO.

At the time of conducting this research, the new Dutch government coalition agreement was not yet published. Some measures that have since been announced such as the subsidy for CO_2 free gas powered plants are therefore not yet included in this study. Similarly, the model was built when gas prices were just starting to rise. The rapid rise in gas prices that we have witnessed in the past months has therefore not been included in the model. In the next chapter, we do provide a qualitative discussion of how the results can change in gas prices remain structurally elevated.

2.2 European scenarios in the 2030-2050 period

To determine the effects of a European-wide CTBO in the long run we use a modified version of the MERGE model.[12] The modifications include capacity market for electric energy, hydrogen production through gasification with or without CCS, hydrogen demand in electric and non-electric markets, and one equation to account for the volumes prevailing at the CTBO market.[13] Compared to Dutch case up to 2030, the scale of analysis is much larger as it now concerns the whole European energy market, and the analysis allows for more flexibility in energy-capital decisions as it concerns early announced restrictions imposed by the a European wide CTBO the in the longer term. The latter binding assumption – i.e., a binding constraint on the ratio between all emissions handled by CCS and the induced emissions from fossil energy in Europe, generates a shadow-price that can be interpreted as the CSU price. Note that we employ a system-dynamic energy model with trade in energy, so there are also consequences from a CTBO on all other energy prices.

MERGE falls in the category of Integrated Assessment models like REMIND, MESSAGE, WITCH, and DICE/RICE. The main set of assumptions that characterize the MERGE are given below:
- Dynamic Optimization: time horizon is 2100 in ten year timesteps.
- Covering the world in five regions.
- Stylized representation the economy & energy system.
- Encompasses all GHG.[14]
- Costs of (mitigation) options are in line with projections from IEA and IIASA, see link.
- Biomass is converted to biofuels or gasified for a hydrogen powerplant. Global biomass supply restricts to 150 EJ per year.[15]
- Biomass can be traded.
- H2 can be produced from electrolysis, fossil or biomass gasification (with or without CCS). Demand for hydrogen is for heating, transport or electricity.
- Europe's region is modelled with an Investment-dispatch model.[5]

[12] See Blanford, G.J., J.H. Merrick, R.G. Richels, and S.K. Rose (2014a). Trade-offs Between Mitigation Costs and Temperature Change. Climatic Change 123(3-4), pp 527-541.

[13] Blanford, G, R Aalbers, J Bollen and K Folmer (2015), 'Technological uncertainty in meeting Europe's decarbonisation goals', CPB Discussion Paper, 301.

[14] In principal, air pollutant emissions, and agriculture and LULUCF related GHG emissions and many mitigation-options are included in the model. Air pollutant emissions may be important if a CTBO simulation shows a significant increase of BECCS and biomass emissions. In that case, we can also add extra air pollution policies that mitigate the extra air pollutant emissions from employing BECCS. Aalbers and Bollen (2017b) show that these extra end-of-pipe air pollution costs are very limited compared to the total CO_2 mitigation costs (less than 1%). So, we omitted this here in the report.

[15] PBL, 2012, Sustainability of biomass in a bio-based Economy, A quick-scan analysis of the biomass demand of a bio-based economy in 2030 compared to the sustainable supply, PBL Note 500143001, The Hague.

- The current level of DAC-cost is € 450-650/tCO_2, but is assumed to be € 185/tCO_2 by 2030, and further declines to approximately € 150/tCO_2-eq. by 2050 because of learning-by-doing, see also [WRI link](#).[16]
- DAC requires electricity, while storage & transport costs amounts to € 10-12/tCO_2-eq.

Electric Options in the model are (for more cost details we refer to Annex A.2.1)[17]:
- Gas (also one cycle gas for backup), Coal, Biomass (all with and without CCS).
- Coal gasification and GSR with and without CCS (24/7 plants).
- Nuclear and Advanced Nuclear, Hydro, Onshore and Offshore wind, Solar PV (no CSP!).

With respect to climate policy the following important assumptions are made:
- Scenarios all assume net-zero emissions by 2050 (in line with EU's green deal, see link.
- Limit on CCS is equal to 0.2 Gt CO_2-eq., which is 15% of Europe's total emissions in 2020, which can be interpreted as Europe's reduction effort up to 2050.[18] This is a crucial assumption for the economic impacts of CTBO, and we will especially elaborate what are the consequences of assuming more CCS as part of the EU green deal.
- There is no CSU market or CSU policy.[19]

With respect to the CTBO policy, we restrict to three variants of a CTBO in Europe:
- Two variants of CTBO without coal, i.e. we assume in both cases a binding constraint on the evolvement of CTBO percentage for oil and gas (CCS also includes DACS and BECCS). This means that the binding constraint in the optimal outcome can be associated with a dual (shadow) price that resembles the CSU price matching the binding (volume) constraint on the CTBO percentage. There are two 'no coal' variants:
  - CTBO_100%: CTBO% = 1%, 50%, 100% in 2030, 2040, and 2050, respectively.
  - CTBO_nocoal: CTBO% = 1%, 75%, 190% in 2030, 2040, and 2050, respectively.[20]
- CTBO with coal, i.e. coal suppliers may also join the CTBO market while CCS projects in that case also include coal-based activities. There is only one variant, i.e.:
  - CTBO_coal: CTBO%= 1%, 75%, 190% in 2030, 2040, and 2050, respectively.[21]

The economic impacts are measured as changes particular from the base case scenario, which is in our case is WEO 2019.

[16] Underlying these estimates is a paper by McQueen et al. (2020).

[17] We disregard here the option of energy storage by batteries, although we do account for costs storage of H2 for hydrogen-fuelled power stations, see Blanford et al. (2015).

[18] In the Dutch case there are plans to subsidize CCS, which is set to 9.7 Mton, which is approximately 31% of the 31 Mton CO_2-eq. emission reduction required to mee the target of the 49% emission reduction target of the Climate agreement, see link. Nevertheless, it remains to be seen whether this will happen before 2030, because the Porthos-project (accounting for 2-3 Mton CO_2-eq. CCS) is also subject to a serious law-suit asking to stop the project because it wouldn't be compatible with the Dutch Nitrogen Law because of No^x emissions during the construction phase (link only in Dutch). Although CCS is high in the merit-order of abatement, still the 31% assumption in Holland could prove to be optimistic, because there has been very limited enthusiasm for CCS at EU level so far, which also means a lack of policies, targets and plans at this moment in time. Hence, we choose arbitrarily to halve this assumption for Europe, and assumed 15% (0.2 Gt C) for the EU.

[19] Nevertheless, also in the base case climate policy scenario there is some CCS and fossil fuel emissions.

[20] The 190% is chosen as to produce binding cases for all scenarios (thus delivering a CSU price), including the coal case- if allowed to be used in Europe.

[21] Energy feedstocks are ignored, which is relevant for the Netherlands as one of the countries having significant amount of energy feedstocks. However, be aware that it is difficult to think of a mechanism at the European scale to build strategic reserves, considering also the model has a ten year period between two simulation years.

3 Results

3.1 Introduction

In this chapter we present the model results for the two systems: a Dutch CTBO with a set of fixed CSU prices (up to 40 euro/t CO_2) and a European CTBO in which the CSU price is determined by the market based on the fixed CTBO percentage, which increases from 1% in 2030, 50% in 2040, and 100% in 2050.

3.2 Dutch Scenario

For the Dutch case we assume a fixed CSU price in the start-up phase until 2030.We start with a CTBO at a fixed price reflecting the costs of transport and storage of roughly € 40/tonne CO_2. A price-instrument has an uncertain outcome with respect to the CTBO%, whereas the initial idea of the CTBO is to ensure certainty on the obligatory amount of permanent storage. From that perspective, the CTBO should move as soon as possible into a system with a pre-scribed and increasing CTBO%.

As we will see, in 2030 a higher CSU price does not automatically yield more CSUs in a CTBO because of the interaction with the SDE++ subsidy system in place. But whether a CTBO starts out with a fixed price or an endogenously determined price (with or without CCS subsidies), in both cases the CSU price translates in higher prices for gas and electricity. These higher prices determine the broader economic impact of CTBO, which is the main topic of this part of the research project.

A gas-only CTBO scenario

In Figure 1 the relationship between the CSU price and the CTBO percentage is presented for the Dutch context. The graph displays the average of 100 model runs given a CTBO for gas producers/suppliers. To show the interaction between a CTBO and the SDE++ (the current main policy instrument for CCS), we also show the effect of a CTBO in a scenario where CCS projects do not receive any SDE++ subsidies. In Annex B, we present sensitivity analyses.

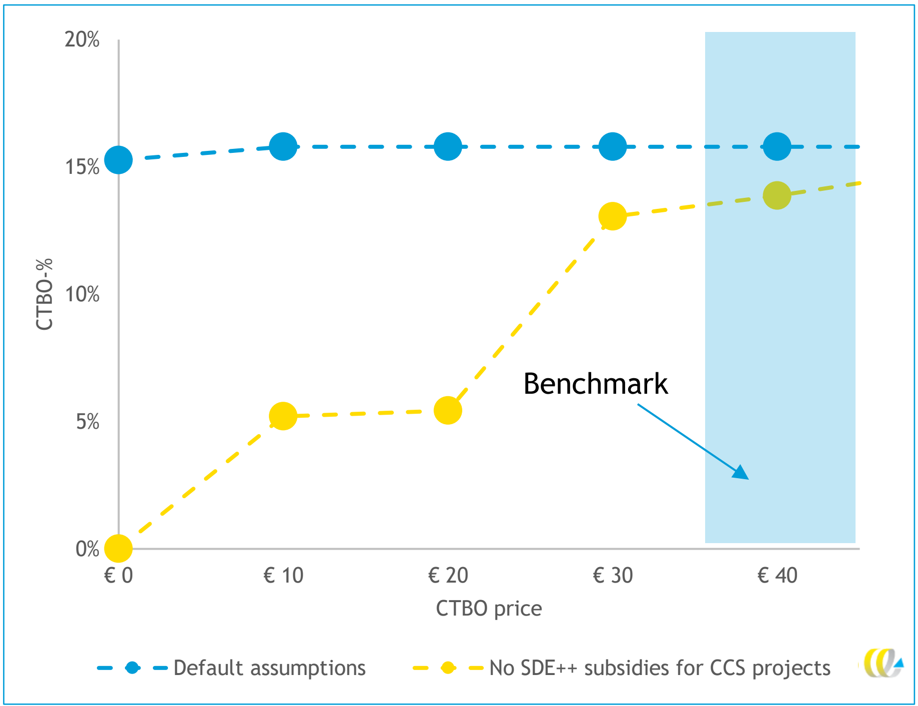
The model shows that — despite all uncertainties that can be considered — around the median outcome a flat relationship exists between the CSU price and the CTBO percentage. The explanation for this somewhat counterintuitive result is that in the baseline, SDE++ subsidies are high enough to make 'cheap' CCS projects profitable. As the SDE++ covers the unprofitable top, higher CSU prices lead to smaller SDE++ expenditures.[22] Net income for companies that employ CCS will hence remain unchanged (the financing method differs, however).

The flat supply curve between the CSU price and the CTBO% implies that fixing a CTBO percentage around 15% (or approximately 7,5 Mt CO_2-eq. on CCS projects) will generate a very uncertain outcome for the CSU price: a percentage that is slightly too low will result in a CSU price of € 0, while a percentage that is slightly too high may result in much higher CSU prices as the CCS reduction options till 2030 are limited. On the other end, fixing the

[22] We assume that SDE++ subsidies are indeed corrected for CTBO incomes.

CSU price in the € 0-40 will yield very stable market outcome: the CTBO will have a moderate effect on the number of CCS projects (for fossil gas) and their size, but will lead to different financing schemes and costs/benefit distributions. If SDE++ prevails for CCS projects, then a fixed price enables a robust outcome of the CTBO%, thus indicating at a safe testing phase. However, when SDE++ does not apply to gas-related CCS in a CTBO only for gas, then a CSU price of 30 or more E/ton is needed to get to a CTBO% of more than 10% by 2030. In that case a CTBO% also produces a safe landing for the CSU price, and the refinements that produced a stable ETS market (a floor or maximum price) also applies to the CTBO.

Figure 1 - CTBO % for a Dutch gas-related CTBO in 2030 at a CSU price of € 0-40/tCO_2



Note that Figure 1 only displays the relationship in 2030. If energy-prices, CO_2 prices and CCS costs do not change significantly over the period 2025-2030, one can also infer the effect of a fixed CSU price during the period 2025-2030. In these years, whenever the CSU price stays between € 0 and € 40, the effect of this increasing CSU price on the number of CCS projects and their size is negligible (with or without SDE++). We can however expect the CTBO percentage to rise in discrete steps since CCS installations are not installed overnight (it takes time for a company to make an investment decision, to obtain SDE++ subsidy, sign contracts and to design and build the installation).

SDE++ expenditures

Why would a higher CSU price ever lead to more CSU's? In the first phase the percentage is not determined by a CSU price but by a stored SDE++-volume. In the 'market-phase' the percentage determines the number of CSUs.

So, a higher CSU price does not automatically yield more CSUs in CTBO. We already showed that because of this interaction a full market of CSUs will tend to ‘one’ CTBO percentage. This creates a dilemma for switching from a fixed CSU price level to a market with a fixed

CTBO percentage that fully determines the CSU price. On the other, hand, this complicated interaction will not hold without the subsidy for CCS projects, which could also be part of a maturing strategy of CTBO. A system of CTBO could lower the yearly SDE++ expenditures. After all, that the SDE++ covers the unprofitable top, which becomes smaller when the CCS project can generate CTBO income. In practice, this mechanism requires the Dutch government to adjust SDE++ subsidy levels for CTBO incomes.

Figure 2 - SDE++ expenditures and the total number of CCS projects at different CSU prices for a Dutch gas-related CTBO in 2030

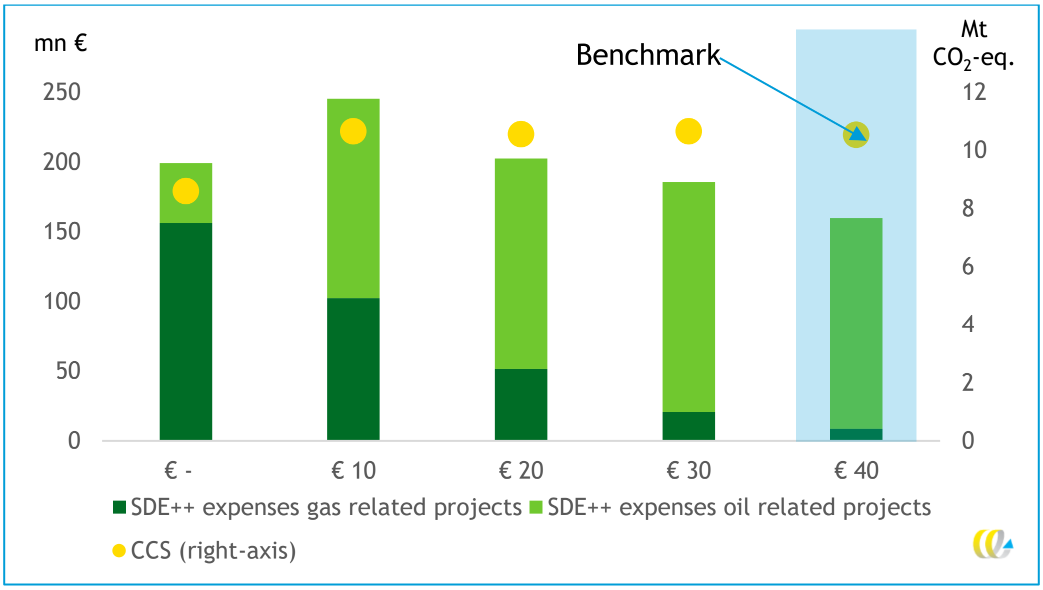


Figure 2 clearly shows that total SDE++ expenditures for CCS projects on gas decrease while the CSU price increases. At a CSU price of € 10, however, yearly SDE++ expenditures temporarily rise. This effect originates from the interaction with the SDE++ CCS ceiling: at a price of € 10, a couple hydrogen producers suddenly find it profitable to employ CCS without SDE++ subsidy (at an ETS price of € 70 euros, and CCS costs between € 70 and € 80 per tonne CO_2, the CSU price is just high enough to make CCS profitable[23]). Given that these cheap projects no longer count towards the CCS ceiling within the SDE++, there is now room for more expensive projects to make use of the SDE++ budget for CCS. This causes a temporary bump in SDE++ expenditures. At a CSU price of € 30, the effect is fully negated since the larger CSU price decreases the unprofitable top of all CCS projects that can generate CTBO income. The increase in SDE++ expenditures leads to a relatively small increase in the CTBO percentage when we consider a gas-only CTBO. This is explained by the fact that the additional CCS projects that are now funded by SDE++ subsidies are mainly oil-related projects. Since the CTBO is gas-only, these projects do not increase the CTBO %. Note also that the share contribution for gas projects in SDE++ decline rapidly to 5% or so and become dominated by oil projects.

At the proposed CSU price (40 E/t) the total amount of CCS to be applied in the Netherlands — given the ETS price of 70 euro/tCO_2 and the SDE++ subsidies to be capped at 9.7 $MtCO_2$,

23 See Annex A.1 for the specific point-sources.

will increase with 2 Mt CO_2.[24] So, these two extra MtCO_2 reduction (by CCS) is good news for the overall goal of the Climate Accord.

3.2.1 CTBO and the implied costs passed on to energy consumers

As described in the previous paragraph, a CTBO will lead to higher energy prices. After all, gas (and oil) producers/suppliers face a cost increase (they need to buy CSUs), which they will pass on to consumers. In this paragraph, we will quantitatively analyse the implied cost effects to five different sectors/groups. We first sketch the qualitative effects:

- *Gas producers/suppliers*: will pass on CTBO costs to consumers. Higher consumer prices will reduce demand.
- *Industry ETS*: will be confronted with higher energy prices. They have little market power to pass on these higher costs to its consumers (mainly abroad).
- *Business non-ETS*: pay higher energy prices and pass it on to the consumer.
- *Households*: pay higher energy prices, possibly lower energy taxes linked to the SDE++ budget[25]. Will reduce gas use by a small amount due to relatively low demand elasticity and large share of energy taxes in energy prices.
- Government: first order effect entails lower SDE++ expenditures and energy tax revenues (dependent on policy), while second order effect may involve a reduction in demand for gas which also causes loss in tax revenues. Possibly compensation for households and energy-intensive firms.

Table 1 - Changes in prices of gas and electricity at a fixed CSU price of € 40/tCO_2

	Changes compared to the base Benefits
Gas	€ 1 ct per m^3
Electricity	€ 20 ct per MWh[26]

In Table 1 we present the effect of a gas-only CTBO on Dutch gas and electricity prices. Since the CSU price is only paid over a relatively small percentage of natural gas supplies (to be exact: over the CTBO percentages), the effect on gas prices is limited. It is important to realize that a CSU price of € 40/tCO_2 at a CTBO percentage of 15% is on average equivalent to an effective CO_2 price of € 6/tCO_2. Note also that since there will still be electricity generated by gas-fired plants in 2030, electricity prices will rise along with gas prices. The increase in electricity prices, however, is much more limited than the increase in gas prices. Only 26% of Dutch electricity production is expected to come from natural gas in 2030 (KEV 2021), gas-fired plants have substantial fixed costs and higher prices due to a CTBO will make it more profitable for Dutch energy suppliers to import electricity from neighbouring countries without a CTBO (the size of the latter effect is uncertain but represented by the range estimates.[27]

A Dutch CTBO and the accompanying rise in energy prices have different effects on different groups. In Table 2 these effects are quantified. Households and gas-intensive firms see their energy bills slightly rise, while gas producers/supplier can expect a modest

[24] The overall costs of the SDE++ subsidy will decline from higher prices of gas and electricity.

[25] Note that up till 2021 the entire SDE++ budget was financed through the Opslag Duurzame Energie, an energy tax additional to the regular energy tax.

[26] This is a median estimate of a wide range 5–31 ct/MWh. This range reflects uncertainty to what extent the Netherlands will import electricity when foreign production is cheaper.

[27] At higher imports, the price increase is limited (5 ct/MWh). If we were not to import, then the price increase is substantially larger (31 ct/MWh). This indeed impacts domestic emissions but is pure carbon leakage.

reduction in sales due to lower demand for natural gas. The effect of a Dutch CTBO on ETS companies varies with the energy bill. Companies with low energy costs might have the possibility to pass on the costs induced by the CSU price.

Table 2 – Median Impact in 2030 on stakeholder groups by a CSU price of 40 €/tCO_2

	Costs	Benefits	Total	Comments
Producers/ Importers	Purchase CSUs at 40 €/tCO_2	Carbon Storage Surcharge (CSS) of 1 ct/m^3 40 €/tCO_2	0	The CSU price is fully passed on to gas consumers. There are winners as by those that can store at less than 40 €/tCO_2 (only one CSU price exist like with an ETS)
	Less demand -1.3%		1,3% of output	Overall, the gas price of 40 euro/tCO_2 increase leads to a small reduction in gas demand
Industry ETS	3,4% higher energy costs	Lower CCS costs (for projects above SDE ceiling)	-0.05% of output	No induced carbon leakage-effect, see Bollen et al. (2019). Government may respond to compensate gas intensive firms by lower gas taxes for their rise in energy costs
Non-ETS business	1% higher energy costs[28]	Passing on these higher energy cost of 1%	0	Costs are passed on to consumers (mainly in the Netherlands)
Households	1% extra energy bill costs & higher prices of consuming goods non-ETS business prices	-	0,1 % of disposable income	Higher gas costs because of a higher CSU price; lower gas demand; total energy bill will increase with 1.1%. Similar impact as with higher prices from non-ETS companies (1% increase of energy costs)
Government	0	Less SDE costs for gas + CCS	-60 mn €	Lower gas tax revenues

Most of these effects are modest, and one could argue that the induced reduction in gas use is even desirable. Since the costs and benefits are not distributed equally and limited to the Netherlands, the Dutch government could nevertheless consider compensating gas-intensive firms or poor households for the rise in their energy costs. This could also help alleviate international competitive disadvantages leading to carbon leakage. A possible way to do so would be by lowering the energy tax on natural gas for vulnerable groups. Compensation by the Dutch government would, however, increase government spending, which would come on top off the loss in tax revenues. A different redistribution mechanism would be to skim off the economic profits made by companies with cheap CCS options. Doing so, however, would involve requires firm-level information about costs and revenues, which seems difficult to gather in practice.

[28] Note that that the energy share of taxes for large users is smaller. A percentage increase in the wholesale price therefore leads to a relatively larger percentage increase in end-user costs.

3.2.2 Sensitivity Analyses

The next step is to assess the robustness of our conclusions against alternative sensitivities with respect of key parameters of the scenario/model design. We identified the following key assumptions:

— a higher ETS price in 2030 given the price increase in early 2022: € 100/tonne CO_2.

The CTBO% will hardly be affected, but the economic output changes as reported in Table 2 and Table 6 will become smaller if the CSU price is the same 40 €/tCO_2 but now on top of the existing but higher international carbon price. Also, the higher ETS itself generates extra savings on gas. The changes in the government budget compared to the base case is difficult to project. On the one hand there will be less SDE++, but on the other hand the gas tax revenues will decline as well. It is also good to realize that the two extra MtCO_2 reduction (by CCS) of the base case policy will evaporate if the ETS price turns out to be 10 €/tCO_2 higher. The reason is that those projects are in that case no longer part of the SDE++-cap, whereas the higher ETS price would have had the same effect on the 'onrendabele top' (but then by making the costs of fossils higher instead of costs of renewables lower).

— more CO_2 infrastructure: pipelines in all five industrial clusters;

As illustrated in the Appendix, additional CO_2 infrastructure in four of the five industrial clusters has no impact on the CTBO% at 40 €/tCO_2 (only an impact for CSU prices more than 120 €/tCO_2). So, also no other economic impacts than the base case.[29]

— no SDE++ subsidies for CCS projects;

The direct impact of a CSU of 40 €/tCO_2 is about 8-9 Mt CO_2 extra abatement by CCS, and little bit lower CTBO%. If the market is established, then it will likely iterate towards a slightly lower CSU price, and hence economic impacts will even decline (from small to very small).[30]

— There could be new blue hydrogen installations in the next five years;

The addition of new hydrogen production sites in the Netherland the CTBO percentage to rise (for an illustration, see Figure 10 in the Appendix). CCS costs for hydrogen production are small: starting at a CSU price of € 10, the new hydrogen sites no longer need SDE++ subsidy, making room for other CCS projects. The new hydrogen production also causes the national gas use to rise, but this effect is relatively weaker. The net effect is hence an increase in the CTBO% of an initial CSU price of 40 €/tCO_2. This means that the economic impacts may increase by another extra 15-30%. This means that the producer will be faced with a 1.5-2.0% production loss, depending on the extra gas demand reductions from a higher CSU price. And similar changes of the impacts apply to the other stakeholder, but they remain small. Nevertheless, now the CTBO will generate an extra net-impact of additional CO_2-eq. emission reduction by CCS.[31]

[29] Note that a large project like Yara is already included in the base case, which means that the ETS price of 70 euro/tCO_2 plus the 'effective' CSU price (recall CTBO% is 15%) would hardly stimulate anymore CCS projects.

[30] This is beyond the scope of analysis, but the government could consider the CTBO while dropping SDE for gas and exempting industry of the marginal carbon tax.

[31] The extra H2 is to be used in industry, electricity production, GO, etc. However, this already included in the baseline scenario without CTBO, so these benefits cannot be attributed to CTBO.

— CTBO on oil production/import (for NL market).

Now the starting phase is again 40 €/tCO_2, but now extends to oil as well- compared to the gas-only CTBO. The Dutch CTBO for oil and gas yields a smaller CTBO% at the same CSU price. Reason for this is that there is for oil less scope for CCS in the Netherlands. But as the CSU price not just restricts to gas, but oil is bad news for households. The gasoline/ diesel price will increase with about 2 ct/litre. This in turn will generate extra losses on disposable income with 0.1-0.15% on average (on top of the 0.1% of the base case policy). But these extra losses mainly concern mid-income levels (their expenses on oil are larger than by households' low-income levels). The government will experience extra losses, likely accruing to 100-150 mn €.

Remaining uncertainties and disclaimers

The model used to generate the results described above does not include 2nd order-effects. That is, the model does not account for interacting impacts of behavioural changes in different sectors or substantially higher energy prices caused by a CTBO.[32] If a Dutch CTBO for natural gas producers/suppliers is introduced, we can expect gas prices to increase. This can have multiple effects:

- Higher gas prices will cause the demand for gas to decrease (for instance due to a lower demand from buildings and horticulture). Total gas use will hence decrease, which causes the denominator in the CTBO% to decline. The result is that when this effect is corrected for, the CTBO% would be slightly higher.
- Higher gas prices could force gas-intensive industry with CCS potential (e.g., Yara) to move to other countries or disappear completely. If this happens the CTBO% will be lower.
- The CCS plant itself relies on the use of natural gas. This means that higher gas-price make CCS costs slightly higher. The result is a slightly lower CTBO% at a fixed CSU price. However, if the CTBO percentage is fixed, then the CSU price will increase as CCS facilities will be faced with higher energy cost that could slightly lower the CTBO%.

A second class of uncertainties follows from the peak in energy prices we are currently witnessing. If gas prices (but also electricity prices) remain at elevated levels till 2030, we could witness changes in investment decisions, energy use and the Dutch economic landscape:

- Higher gas prices could make electrification relatively more profitable than CCS, resulting in a smaller CTBO%s at the same CSU price. But time is short till 2030, and hence electrification will only occur in some cases. Also, structurally higher gas prices could in theory also lead companies to wait until electric abatement options become available, thereby foregoing a transition period with CCS.
- Gas intensive companies with CCS options may go bankrupt or lower their output, thereby decreasing the CCS potential, leading to a smaller CTBO%.
- Sectors without CCS potential will decrease their demand for gas, thereby decreasing total gas use without decreasing the total CCS potential. This leads to a larger CTBO%.
- There is some literature claiming that if gas prices were to rise at a much higher rate than electricity prices, then green hydrogen could become cheaper than blue hydrogen, leading to less CTBO potential and a smaller CTBO%. By 2030 however, this seems unlikely.
- Currently, natural gas is so expensive that biomethane is often cheaper. This could lead to more investment in biomethane plants adopted with CCS installations and hence to

[32] We do include energy consumption savings due to relatively smaller energy price changes of initializing the CTBO.

(more) negative emissions. The negative emissions will increase the CTBO% at a fixed price.

Finally, the main model does not consider new point sources. In 2030, we could see new industries or point sources with negative emissions (presumably biobased). In the sensitivity analysis displayed in Annex B, we show the effect of additional (blue) hydrogen production. New industries are too uncertain to include at this point. We furthermore expect negative emission point sources not to be profitable at low CSU prices and regular gas prices and have hence excluded them from the main analysis. Only if carbon removal activities can sell both emission credits and CSU's then this may increase the chance of a business case for negative emission point sources. In theory, given fast technological process (possibly combined with high gas prices), negative emissions could become profitable at low (€ 0-50) CSU prices. In such case, we would see higher CTBO percentages at fixed CSU prices.
Conclusion on the Dutch scenario

The Dutch scenarios assume a CTBO on gas supply that starts with a fixed CSU price of € 40/tCO_2 in 2030. Note that this means an effective price increase of gas of € 6/tCO_2. In this way it can deliver a safe trial phase till 2030 with limited economic impacts in the Netherlands.

We find for most stakeholder groups that the costs are limited, even when assuming that the cost increase from a CSU price is fully passed on by the producers/importers of gas. Households will on average see a decline of their disposable income of 0,1%. However, if during the trial phase till 2030 the CTBO not only applies to gas but also includes oil, then the pass-on of costs extends to oil as well. The impacts on non-ETS businesses and the households' disposable income will double. Still, we also then conclude that the overall economic costs will be moderate.

We observe two extra MtCO_2-eq. emission reduction at a CSU price of € 40/tCO_2 and an ETS price of € 70/tCO_2. CTBO absorbs CCS projects of the low merit-order (low marginal costs of abatement) that could alternatively have engaged in SDE++. While at the same time, SDE++ will attract higher merit order projects (with higher marginal costs of abatement). If, however, the ETS price turns out to be € 80/tCO_2 or more, then the cheaper CCS options will already be in the market, and the merit-order shift of a CSU price no longer applies. On the other hand, if the SDE++ no longer applies, then the CSU price introduction generates extra emission reductions. In sum, the expected emission reduction will be smaller than initially brought about by CTBO as it substitutes for potential CCS projects to apply for SDE++, but still the overall expected impacts larger than zero.

3.2.3 Conclusion on the Dutch scenarios

In our view three overall conclusions stand out:
1. The economic impacts of a 40 €/tCO_2 CSU price have a very modest impact on most of the stakeholders.
2. The CTBO might generate an extra amount of CO_2-eq. emissions reduction, because CTBO pays for projects of the low merit-order (together with ETS), while SDE++ still will include higher merit order projects that were not possible before because of the restriction of maximal allowable emissions handled by CCS in the SDE++ subsidy (9.7 MtCO_2). An additional 2 Mt/y is expected due to this effect.
3. A CTBO effectively takes over the role of SDE for gas + CCS projects leading to a 95% reduction of SDE funds spent on gas + CCS.

And the sensitivity analyses reveal that:

1. If during the trial phase till 2030 the CTBO is not restricted to gas but also includes oil, then the CSU price will also be passed on to those consuming oil. This has little consequences for the stakeholders, but it does double the economic impacts on non-ETS businesses and the households' disposable income. Nevertheless, these impacts are still moderate.
2. If the ETS price turns out to be € 80/tCO_2 or more, then the expected emission reduction will rapidly decline to zero at higher ETS prices. Note also that a CTBO will reduce the required SDE-funding for gas + CCS projects to close to zero. Most of the remaining SDE-funding for CCS will be for oil refineries in 2030.

3.3 Europe

3.3.1 The climate policy scenario to net-zero emissions

To understand the impacts of the CTBO variants compared to 'No CTBO' baseline scenario, we first have to understand the development of this latter climate policy scenario towards net-zero emissions. Figure 1 plots for Europe the assumed pathway for carbon emission and the efficient carbon price to achieve the emission reduction. The carbon emissions include emissions of all fossil energy sources, cement production, energy related methane emissions, and other non-energy related GHG emissions.

The setup of this net-zero scenario is at the macro-level in the spirit of the IEA-NZE scenario designed for their WEO.[33] Also, the regional economic trends and population assumptions are the same, but again they are explicitly based on region-specific assumptions as described in WEO (stated policies scenario).

But at a more detailed level there are differences. In this report assumes an optimal carbon price over time for the Rest of the World (ROW) and another optimal carbon price profile for Europe to meet net-zero emissions in Europe (and then also adding for Europe a CTBO in Europe with or without coal). The IEA-NZ scenario assumes a set of concrete measures in different sectors.[34]

This report focuses on a CTBO for Europe, and hence we decided not to compare the global development of specific energy technologies between the two reports. For example, the shares of 800 technologies in the WEO model are directly based on their cost levels.[35] But this is different from the approach in IAMs like MERGE, which solves for optimal prices of energy and electricity and quantities in different energy markets simultaneously.

We now move to characterize our baseline scenario towards net-zero emissions by 2050. Figure 3 plots for the 2020-2050 period the Europe's efficient carbon price and CO_2-eq. emissions. We can see that the efficient carbon price increases to more than € 500/tCO_2 by

[33] In our baseline scenario the world is moving to net-zero emissions by 2050 just like IEA-NZE scenario. But, in our analysis also Europe itself as one region is also explicitly moving to net-zero emissions (see Figure 3). The results of IEA-NZ scenario only refer to outcome for the entire world. Since the analysis here is focussing on Europe, we simply assumed for the entire Rest-Of-World a uniform carbon price moving their aggregate emissions to net-zero by 2050. This means that some regions go to negative emissions, while other more expensive carbon-abatement regions stick to positive emissions (for example ROW with all the energy-exporters).

[34] It is unlikely that IEA-NZ scenario is a cost-efficient pathway to net-zero emissions.

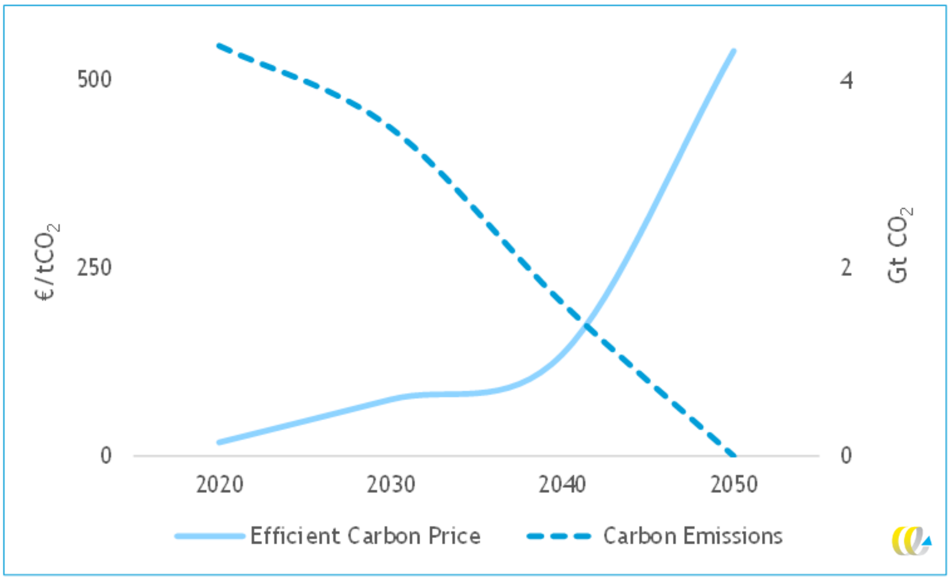
[35] Based Logit and Weibull functions.

2050, which stimulates clean technologies that lead to net-zero CO_2-eq. emissions in that year.[36]

The carbon price lies considerably above the marginal costs of abatement by Direct Air Capture (DAC), which mainly stems from the limit on CCS. Other factors that can increase the gap between the optimal carbon price and the abatement costs of applying cheap mitigation measures are twofold. Firstly, despite that there are cheaper options in, for example, the electricity sector, they face expansion or decline limits. These limits reflect the idea that it takes time, practice, and implementation effort (e.g., legal issues) to expand or reduce on specific technologies. Secondly, there are also saturation levels to be avoided in the market. Or in other words, full specialization of using one specific electricity generation technology (for example, a 100% share of windmills in electricity generation) is to be avoided, thus the approach here always achieves a portfolio of energy options with the consequence that there are differences in marginal costs of abatement.

Despite that we assume here a tighter emissions scheme of zero emissions by 2050, we can expect that the level of the efficient carbon price is lower than in the WLO two degrees scenario (link, only in Dutch) because we employ more recent insights on the marginal abatement costs of DAC (see main assumptions) and less binding constraint on the expansion rate of DAC technologies.[37]

Figure 3 - The emissions and price of carbon in the EU climate policy scenario to net-zero emissions by 2050



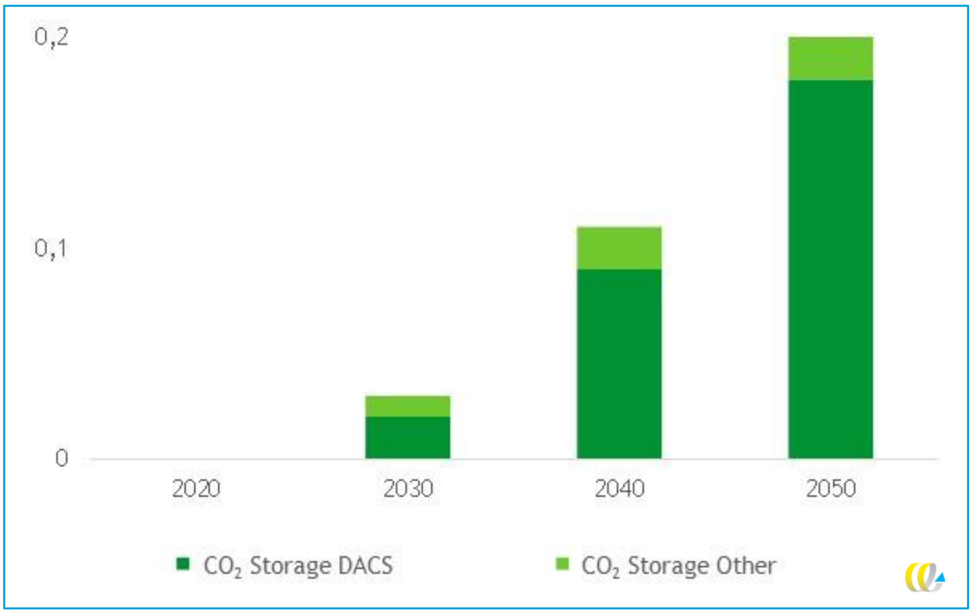
The important takeaway from Figure 3 is that the efficient carbon price is considerable and leads to significant savings in fossil energy. This implies that establishing a CTBO in a world that will be unfolding in the way sketched as in Figure 3, may in the long run prove to become a challenge as by that time most fossil fuels will no longer be used in our consumption pattern from high carbon prices. Carbon price increase rapidly between 2040

36 In link (only in Dutch) the concept of the efficient carbon price is explained. Here it suffices to say it is the efficient shadow price of the carbon constraint that assumes net-zero emissions by 2050.

37 We no longer employ the market share of DACS compared to all abatement options as a binding constraint on the expansion rate. This constraint now follows the concept of expansion constraint employed for all clean electric technologies.

and 2050. The reason is the 15% restriction of CCS in the climate policy baseline scenario, which is binding in the base case climate policy scenario — indicating that it is cheaper for net-zero emission scenarios to be achieved by allowing for more CCS projects. However, establishing a CTBO also has the purpose of an insurance, i.e., it ensures that emission reduction will be done anyway, either through the efficient carbon price or by the fossil suppliers paying for permanent storage. Note also that next to the fossil emissions, the other residual emissions (land use, cement) can be offset by CCS. Recall that a maximum of 15% of the total reduction effort may be done by CCS.

Figure 4 - Storage through DACS, and other sources in the EU climate policy scenario to net-zero emissions by 2050 (Gt CO_2-eq.)



So, in the baseline scenario high carbon prices stimulate carbon savings, but we can also detect at forehand to what extent in such a world, and how emissions are stored under the North Sea (there is sufficient capacity, see also Aalbers and Bollen, 2017b). Figure 1Figure 4 plots for the 2020-2050 period the permanently stored emissions by all sources. In the climate policy baseline only DACS applies, because BECCS is still not accounted for in the ETS-system (in the climate policy baseline).[38] Aalbers and Bollen (2017b) argue that BECCS has no business case because of governmental failure, because negative emissions are not rewarded in the current setup of the ETS. Also, we can see that that there is almost 0.1 Gt CO_2-eq. in 2040 and 0.2 Gt CO_2-eq. in 2050 stored permanently underground, mostly by DACS.

3.3.2 The CTBO variants

Figure 5 plots results for the year 2050 the ‘100%’ case, ‘nocoal’ and ‘coal’ cases. Storage can be done on COAL and GAS, on CDR by BIOMASS (i.e. BECCS) or DACS. Finally there are OTHER processes that also can be subject to CDR options to compensate for CH_4, N_2O from Agriculture.

[38] Although the EU does not have a policy for DACS, we do allow for it in the policy scenario under the umbrella of the limited allowable amount of CCS. BECCS and DACS have the same barrier/problem at the moment. But EU may define plans to do something about this.

Recall that the ‘100%’ case assumes a CTBO% So, if a CTBO is installed on a European scale in 2030, then we start with a CTBO percentage of 1% in 2030, increase it to 50% by 2040, and 100% by 2050. The ‘NOCOAL’ and ‘COAL’ cases start with 1% in 2030, increase the CTBO percentage to 100% by 2040, and 190% by 2050. In all cases the CSU price is determined endogenously by the shadow price of the CTBO-equation added to the model. In this case all oil and gas supply must be accommodated with permanent storage of carbon (all options allowed).

We can see from Figure 5 that CTBO creates a business case for BECCS that substitutes the DACCS of the climate policy scenario without the CTBO. As a matter of fact, it accounts for all the CCS options in the ‘100%’ case. It is important to realize that BECCS is not earning its’ business case from competing with other electricity options, but mainly earns that because it competes with other expensive climate mitigation options in other sectors. For example, BECCS enables to avoid expensive measures such as energy neutral housing.

Also, we can infer from Figure 5 that in 2050, the CCS fully offsets emissions of OIL and GAS, the CTBO percentage is clearly 100%. From Figure 6 — presenting primary energy use in the 2030-2050 period — we can see that in the base case climate policy, biomass is used. The application of biomass is fuel blending and biomass in electric power generations (without CCS). Europe exports the remaining biomass produced to other regions. In the 100% case the demand for biomass in Europe increases, and now fully accommodates BECCS as a substitute for the biomass of the base case climate policy. So, biofuel blending, and the biomass used for electricity production become obsolete and are replaced by fossil energy.[39] The carbon emissions in the 100% case are compensated by capturing, transporting and storing carbon under the North Sea that is generated by the biomass gasification process, while the hydrogen produced is used in hydrogen power plants.

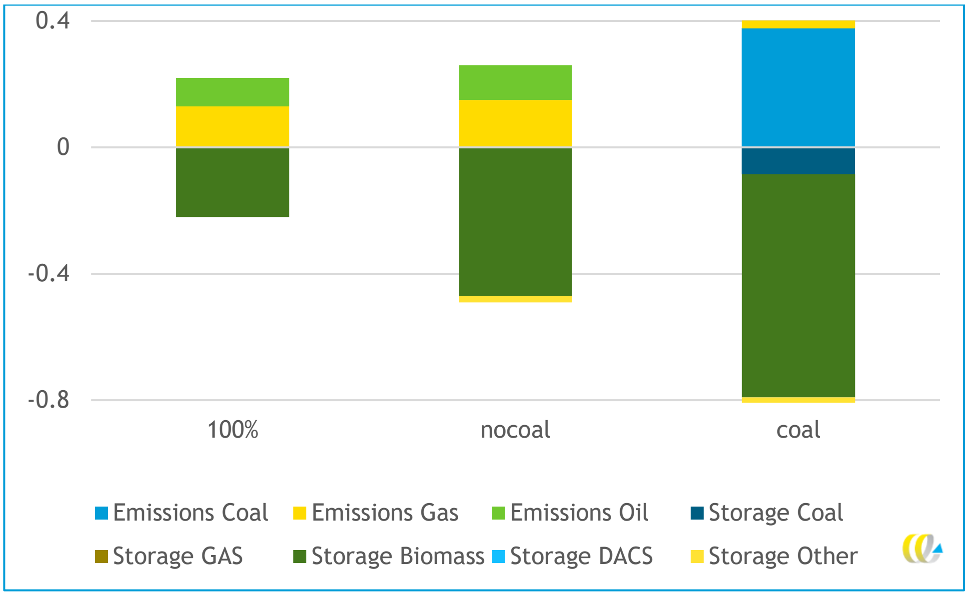
We can also see that increasing the CTBO percentage 190% leads to extra BECCS, and a little amount some storage by OTHER sources.[40] However, if we also allow COAL in the energy system, we can observe that the expansion of OIL/GAS in the 100% and 190% cases is fully replaced by coal. Recall again that the carbon budget is fixed and in the COAL case leads to net-zero emissions by 2050. But coal is cheaper than oil and gas and is used for direct use in the industry and for gasification to H2, but with CCS. The residual emissions of coal ccs for hydrogen production are compensated by extra application of BECCS. It Is worth emphasizing that the global demand for biomass is 190% case with COAL is lower than the global biomass supply of the base case climate policy, so there is no extra land-use involved in the COAL case or higher land-use prices, see also Aalbers and Bollen (2017a).[41]

[39] Not shown here, but worth emphasizing is that part of biomass-energy produced in Europe is still exported, but to a lesser extent than in the base case climate policy.

[40] In the CTBO-COAL and CTBO-NOCOAL scenarios every tonne of fossil carbon is compensated by almost 2 tonnes storage! So the EU is already quite net-negative by 2050 with a smaller carbon budget to be used. Although this may seem unrealistic the amount of BECCS employed in this scenario is substantial and solves for much less costs of mitigation than the base case policy scenario (see Table 3).

[41] In this case, the exports of biomass-energy drop to zero. In 2050, the demand for primary biomass is still lower than the primary biomass requirements for biofuel-blending in the base case. The global supply of primary biomass in the base case is higher than in the CTBO cases.

Figure 5 - Outcomes in 2050 on emissions of fossil energy demand and emissions stored through CCS (either linked to COL, GAS, BIO, DACS, and all other sources ("OTHER"), in Gt CO_2-eq.



As mentioned before, Figure 6 presents Europe's primary energy use of the 2030-2050 period for coal, oil, gas, biomass, nuclear (ur abbreviated from uranium), other sources (oth-tpe), wind-energy (wind), and hydropower (hydro).[42]

Recall that the base case policy scenario for Europe assumes no BECCS and a limit on CCS in 2050 equal to 0.2 Gt C per year (equal to 15% of the reduction effort). Next to that, we also assume a uniform carbon price in Europe to ensure minimal mitigations costs. So, we can see that this results in the demand for biomass for both biofuel-blending outside ETS and some biomass-powered electricity production. The consequence is that to minimize the mitigation costs, wind energy accounts for 60% of production in 2050 while nuclear's role complements this large amount of wind energy. This means that nuclear's role is pushed to maximal levels (compared to the other cases).[43] This may seem unrealistic, but we deal with that argument by elaborating on the changes of the base case impact of CTBO at higher levels of CCS.[44]

The most important conclusion from Figure 6 is that while net emissions are kept at the same level, the CTBO increases the demand for all primary energy as CTBO enables to lower

[42] Hydropower can be seen to be constant over all scenarios. There are slight changes in primary energy wind, which is accommodated by larger fluctuations in the wind energy-capacity. Also, the minor role can be seen to be attributed to the so called other sources.

[43] Maximal means that the current nuclear capacity is maintained, i.e. it scrapped in line with economic considerations, while offset by investments in generation IV nuclear capacities.

[44] We disregard BECCS in Europe as an option to include in the base case, because there are no concrete plans for BECCS. And keep also in mind that the CCS bound also limits the possibility to use BECCS. We think this is a realistic assumption because of Europe's perception on potential other sustainability problems related to biomass (food prices and land-use changes). Nevertheless, we assume biomass to be used for biofuel-blending, while there are no restrictions on biomass and BECCS in other regions (besides the overall global sustainability cap of 150 EJ/year. So, in terms of the global numbers, we are in line with the assumptions of the global IEA NZ scenario.

the energy prices. More energy consumption and lower energy prices are an economic gain. Still, we recall that the setup of the scenarios is that the carbon budget is the same for all the cases. In other words, CTBO reduces energy scarcity while not giving in on the net-impact of carbon. Moreover, the reduced energy scarcity is also relevant considering trade sanctions of gas/oil on Russia because of the Russia-Ukraine war. We can observe that total primary energy use is the smallest in the base case policy, and then by introducing CTBO as in NOCOAL (CTBO percentage is 100% in 2050), BECCS allows for less energy savings (expensive) and more oil/gas in the energy system. However, be aware that more energy goes hand in hand with the same carbon budget. And surprisingly, more BECCS implies less primary biomass demand at the global scale as producing biofuels inefficiently in the base case policy is replaced by less biomass requirements for BECCS in the CTBO cases.

Moreover, the more stringent CTBO case with CTBO-percentage of 190% enforces also more CCS, and further relaxes on the energy scarcity. Note however, that also in this case the carbon budget is the same. Finally, the COAL case magnifies the changes of the other CTBO cases, but also replaces oil and gas by cheaper combination of coal and 'expensive' biomass (the latter offsetting extra residual emissions of the use of coal with CCS). Concluding, CTBO can lower the scarcity on energy while not giving in on the ambitions of net-zero emission in 2050. The explanation is that CCS is promoted by an EU wide system of CTBO on oil and gas sources. If however, the base case policy would allow for more CCS or (more) BECCS, then the economic gains of CTBO would be smaller.[45]

Figure 6 - Total Primary Energy Use in the 2030-2050 period in EJ in all CTBO variants

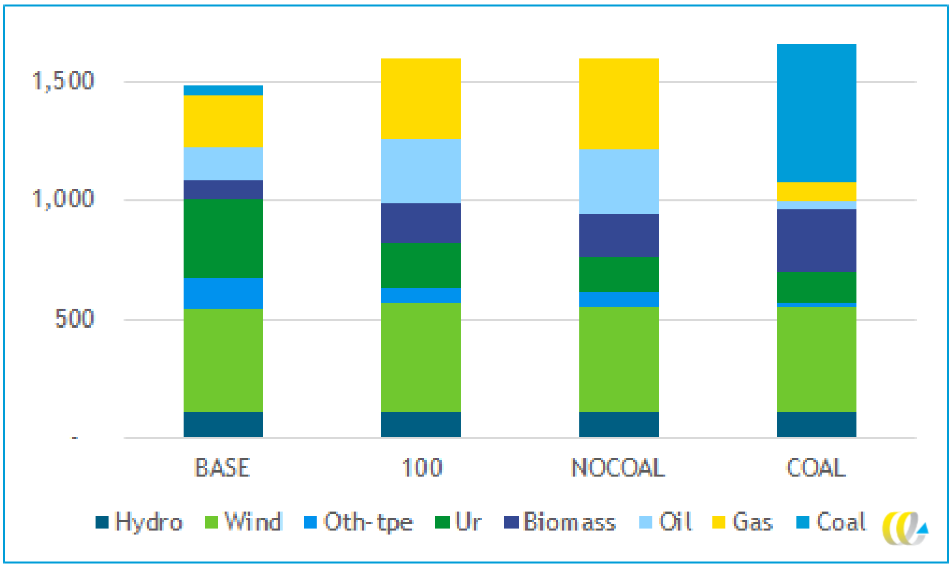


Figure 6 also points at the role of nuclear. The base case policy has the largest amount of nuclear, which is required to complement a large share of renewable capacity. And again, recall that the model optimizes production and capacity to produce electricity also at times that there is no wind available and relatively large amounts of electricity demand (a large residual load). Nuclear in that case ensures electricity supply and keep electricity prices low. Quantify: difference in electricity price between scenario's The base case climate policy is the only scenario with green hydrogen production as there is abundant wind-energy capacity. But as CCS is stimulated in the CTBO cases, there are competitors implicitly

45 Recall that only 15% of EU's reduction effort is allowed through CCS (mainly DACS in the base case policy).

stimulated to substitute for nuclear's role in electricity generation, i.e., BECCS and hydrogen plants (as a substitute for flexible gas-fired powerplants). And green hydrogen is replaced by biomass-generated hydrogen and reduces a little on wind-energy capacity, while increasing its' load factor. Similarly, the demand for nuclear is further reduced when CCS is stimulated more (in the NOCOAL and COAL cases).

Fossil energy is the source reflecting the extent to which the scarcity of energy is relaxed from CTBO, while keeping the carbon budget fixed. Recall also that the simulation extends to years after 2050. And, then we see a similar pattern. Note also that the storage capacity CCS capacity in Europe is only filled for less than 60% by the end of this century, even in the coal case. Some NGOs are concerned that extending the lifetime of fossil energy restricts the renewable transition, but that not the case. It is not shown here, but if we were to stick to current climate policy in Europe (suppose only 55% in 2030 and beyond), then it can be shown that CTBO by stimulating CCS/CDR can achieve more emission reductions than current policies. Also, with a more equitable sharing of the financial burden. Finally, it can also be seen that coal replaces oil in the COAL case. In this scenario, coal is both used for electricity generation with CCS and hydrogen production that serves as the alternative for oil. Despite that there are potentially serious economic gains involved with coal, its' role can be ignored by formulating additional policies that ensure that coal is not going to be used.

3.3.3 Conclusion on the European scenarios

Finally, Table 3 summarizes these economic impacts of all the cases analyzed, i.e., the base policy case without a CTBO market, and the CTBO cases (CTBO100% case, and the more stringent CTBO cases with or without coal). The indicators that are shown comprise prices of carbon, CSU's, electricity, and non-electricity (all potential sources included), and a complex indicator for the overall macroeconomic costs. The macroeconomic costs are measured as the differences between the discounted path of Europe's GDP over the 2020-2050 period of the different cases. For more info why to use this indicator, we refer to also Aalbers and Bollen (2017a).

Table 3 - Effect of a EU CTBO in different variants

		CCS	Discounted	Prices			
			Climate bill gain	Carbon	CSU	Electricity	Non-electric
		In 2050	Till 2050				energy
		In Gt C	In € per European	€/tCO_2	€/tCO_2	€ per Mwh	€/EJ
2020			-	25	-	33	18
2050	Base	0.20	-	539	-	144	29
	CTBO_100%	0.22	4,300	205	153	124	29
	CTBO_nocoal	0.49	6,700	124	163	98	28
	CTBO_coal	0.79	8,400	23	183	87	24

It is important to note that a part of the emissions (certainly for gas and oil) are not yet covered by the ETS, and also that a part of those emissions are also too small and/or too far away from CCS infra. We assume one carbon price for all sources, so some of these fossil fuels will also be phased out by means of a higher carbon price and partly there will be investments in infrastructure to accommodate the transport and storage of CO_2. But next to that, CTBO is primarily the safety net that ensures a limit on the net emissions of unabated oil/gas use. If necessary, by DACS, Blomass Carbon Removal and Storage (BiCRS) compensation (with the costs then incorporated in the price of fossil).

There are economic gains involved with CTBO cases without affecting the net carbon emissions budget. For example, the discounted flow of gains in terms of GDP involves 4,300 euro per person. This is also reflected in the prices, i.e., if we compare the economy wide carbon price drops from 539 to 205 euro/tCO_2, while also energy prices drop significantly. The average electricity price drops from 144 euro per MWh to 124, and for non-electric energy the average price remains constant at 29 euro /EJ. The drop in energy prices reflects and confirms the reduced scarcity of energy, which also leads to more energy demand. Note again, this is without any impact on the carbon budget. A similar line of reasoning applies to the other CTBO cases. Note also that the non-electric price drops when coal is also allowed to be used for CCS, i.e., a shift to cheaper hydrogen (compared to the somewhat theoretical backstop technology in non-electric energy use).

It is also clear that this gain fully hinges on the CCS volume assumed in the policy base case. If we were allowed to use more CCS in the base case, then the gains from CTBO will be lower. If the CCS volumes in the baseline are high enough, then the gains could fully vanish. Nevertheless, CTBO can be seen as an insurance policy. It is only needed whenever CCS is not sufficiently used for permanent storage of CO_2 in climate policy.

4 Conclusions and Recommendations

The world is searching for emission pathways that ensure the Paris climate targets can be met. Net-zero emission scenarios are key to achieving these targets. Also, the EU proposed net-zero emission targets for 2050 in its Green Deal. There is already a wide pallet of instruments trying to reduce emissions, mostly focussing on managing emissions on the demand side while ignoring the supply-side. In this report we analyse the economic impacts of a supply-side policy called CTBO.

The CTBO makes producers of fossil energy responsible for ensuring sufficient carbon storage also takes place. When a CTBO is introduced, fossil producers and importers are required to buy CSUs and in this way fulfil their CTBO. The companies that store it permanently (for example, underground) receive these CSUs and can sell them. This creates opportunities and additional financing for CCS projects. The CSUs give the right to production and import of fossil energy. Tradable CSU's yield — like an emissions trading scheme — an efficient outcome with respect to CCS-projects and fossil energy use in the market. CTBO can also stimulate negative emission technologies (for example Direct Air Capture and Storage) and thus ensure that the impact on the climate of any remaining fossil energy use will be reduced to zero in time.

In this report we analysed two scenarios: a Dutch scenario with a start-up version of CTBO in the Netherlands on gas till 2030, and an EU-scenario analysing a long-term scenario (2030-2050) with an EU-wide version of a CTBO for all fossil energy sources in Europe. The analysis investigates the economic impacts of a CTBO.

The Dutch scenarios assume a CTBO on gas supply that starts with a fixed CSU price of € 40/tCO_2 up to 2030. Note that this means an effective price increase of gas of € 6/tCO_2. In this way it can deliver a safe trial phase till 2030 with limited economic impacts in the Netherlands.

More detailed findings are the following:
- We find for most stakeholder groups that the costs are limited, even when assuming that the cost increase from a CSU price is fully passed on by the producers/importers of gas. The gas price will rise with 1 ct/m3.
- Most non-ETS businesses are expected to pass on the costs of their higher energy bill to customers, while international operating gas-intensive sectors will only partially able to pass on the costs of the CSU price in their sales price.
- Households will on average see a decline of their disposable income of 0,1%.
- Government will lose some gas-tax revenues brought about by energy savings from the CSU price.
- The CSU price increases the gas price with 1ct/m^3, thus lowering demand due to savings. This in turn lowers the output of gas suppliers — about 1.3%.
- We observe two extra MtCO_2-eq. emission reduction at a CSU price of € 40/tCO_2 and an ETS price of € 70/tCO_2. CTBO absorbs CCS projects of the low merit-order (low marginal costs of abatement) that could alternatively have engaged in SDE++. While at the same time, SDE++ will attract higher merit order projects (with higher marginal costs of abatement).

However, if during the trial phase till 2030 the CTBO not only applies to gas but also includes oil, then the pass-on of costs extends to oil as well (to about 2 ct per litre of gasoline). This has little consequences for most of the stakeholders, while it doubles the impacts on non-ETS businesses and the households' disposable income. Still, we also then conclude that the overall economic costs will be moderate.

If, however, the ETS price turns out to be € 80/tCO_2 or more, then the cheaper CCS options will already be in the market, and the merit-order shift of a CSU price no longer applies. On the other hand, if the SDE++ no longer applies, then the CSU price introduction generates extra emission reductions. In sum, the expected emission reduction will be smaller than initially brought about by CTBO as it substitutes for potential CCS projects to apply for SDE++, but still the overall expected impacts larger than zero.

The European scenarios assume an EU-wide CTBO on all fossil energy carriers, with a fully functioning CSU market under a CTBO% of 50% in 2040 and 100% in 2050. Based on this scenario, we conclude that CTBO in Europe may deliver a lower climate bill (GDP losses from climate policy) if there is a fixed carbon budget. The reason is that CTBO lowers energy scarcity, which translates in lower prices of energy and carbon. However, this only applies when relatively few CCS projects are realised in the baseline scenario without a CTBO. If CTBO increases CCS compared to the base case, then generally there will be economic gains from this CTBO.

In other words, CTBO improves the carbon efficiency of strategies achieving net-zero emissions by 2050. This also implies that in the long run the CTBO instrument can serve as an insurance to achieving these net-zero targets. In other words, if CTBO is not implemented and EU climate policy is not on the trajectory for zero-emissions by 2050, then CTBO may help to achieve that more stringent climate goal.

Currently, Biomass Energy with CCS (BECCS) has no business case because the rules of the current emissions trading system (ETS) don't reward negative emissions. But a CTBO can provide BECCS with a business case by means of a CSU. BECCS' negative emissions makes it 'compete' – not just with electricity-generation options – but high-cost abatement measures outside the ETS. BECCS reduces the need for expensive emissions abatement technologies elsewhere in the economy, for example energy neutral housing.

While net-zero emissions is highly dependent on wind-energy, BECCS may substitute nuclear power to contribute to electricity security. The reason is that the hydrogen produced by gasification as part of BECCS can be in a hydrogen-based powerplant as an alternative to short-cycle gas-fired powerplants. In this way BECCS, can accommodate high shares of wind energy.

Biomass in this analysis restricts to sustainable biomass. CTBO stimulates BECCS but lowers the supply of biomass as Europe's BECCS replaces energy inefficient 'biofuel blending' for transport purpose to be redundant. Blue H2 production can also be substantial, provided the rest-of-the world does not absorb all gas supply. Coal gasification with CCS can even further lower the climate bill by further stimulating BECCS while delivering much more H2. If this is an undesirable outcome, then coal can be excluded from a CTBO.

So, a CTBO start-up phase implementation in the Netherlands has little economic impacts but leads probably to some extra emissions reductions (and less SDE expenditure for gas CCS). And a mature CTBO in Europe — with sufficient trade volumes of CSUs — will in the long run yield economic gains or extra emission reductions, or a mild combi of emission reductions and/or economic gains.

Due to lack of time other sensitivities have not been explored, see for example Blanford et al (2015) on technological uncertainty on cost price developments. Also, a much wider set of assumptions on climate policy need to be considered, for example:
- the stated policy scenarios;
- the degree of coordination of climate policy between different regional blocks;
- the stringency of the climate policy (2 degrees Celsius warming, or 1.5 degrees Celsius);
- extent CTBO beyond Europe in different ways (a gradual approach);

Finally to provide more guidance on the NGO's fear that a CTBO leads to more fossil energy use, we propose to investigate to what extent CTBO can bring down emissions compared to a climate policy scenarios based on current stated policies or a 2 degrees temperature target.

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A Assumptions

A.1 CTBO in the Netherlands

In our model we have analysed 64 point-sources from the ETS data gathered by the Dutch Emissions Authority (NEa). Table 4 shows an overview of the potential CCS projects considered in our analysis. The costs are determined by taking the average of 100 models runs with random cost mutations. The data shown in this table is from one random run and may hence deviate slightly from the average.

Table 4 - List of potential CCS projects considered (costs are from one specific run with random cost mutations)

Project description	Cluster	CCS possible?	Size of project in 2030 (Mton CCS)	Costs (€/tonne CO_2)	Maximal SDE++ subsidy (€/tonne CO_2)
Tata Steel IJmuiden B.V. totaal	Noordzeekanaalgebied	Yes, post-combustion	0.41	98.54	88.44
RWE Eemshaven Centrale	Noord-Nederland	Yes, post-combustion	-	-	-
Chemelot - petrochemische producten	Chemelot	Yes, post-combustion	1.88	129.03	88.44
Chemelot - kunstmest en stikstofverbindingen	Chemelot	Yes, pre-combustion	0.91	91.98	15.87
Chemelot - kunststof in primaire vorm	Chemelot	Yes, post-combustion	0.35	128.22	48.44
Shell Nederland Raffinaderij B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.42	77.09	22.09
Shell Nederland Raffinaderij B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.19	144.23	62.09
Shell Nederland Raffinaderij B.V.	Rotterdam/Rijnmond	No	-	-	-
Dow - petrochemische producten	SDR	Yes, post-combustion	1.46	159.71	88.44
Dow - Kunststof in primaire vorm	SDR	No	-	-	-
Vattenfall Power Velsen	Noordzeekanaalgebied	Yes, post-combustion	1.62	221.04	88.44
Yara Sluiskil B.V. totaal	SDR	Yes, pre-combustion	2.24	95.20	15.87
Vattenfall Magnum Centrale Eemsmond	Noord-Nederland	Yes, post-combustion	1.00	233.88	0.00
ESSO Raffinaderij Rotterdam	Rotterdam/Rijnmond	Yes, post-combustion	0.23	76.25	22.09
ESSO Raffinaderij Rotterdam	Rotterdam/Rijnmond	Yes, post-combustion	0.10	145.29	62.09

Project description	Cluster	CCS possible?	Size of project in 2030 (Mton CCS)	Costs (€/tonne CO_2)	Maximal SDE++ subsidy (€/tonne CO_2)
ESSO Raffinaderij Rotterdam	Rotterdam/Rijnmond	No	-	-	-
Shell Nederland Chemie B.V. vestiging Moerdijk totaal	Rotterdam/Rijnmond	Yes, post-combustion	0.25	78.71	22.09
Shell Nederland Chemie B.V. vestiging Moerdijk totaal	Rotterdam/Rijnmond	Yes, post-combustion	0.54	151.57	62.09
BP Raffinaderij Rotterdam B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.21	75.73	22.09
BP Raffinaderij Rotterdam B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.09	153.20	62.09
BP Raffinaderij Rotterdam B.V.	Rotterdam/Rijnmond	No	-	-	-
ENGIE Eemscentrale	Noord-Nederland	Yes, post-combustion	1.71	196.04	0.00
Enecogen	Rotterdam/Rijnmond	Yes, post-combustion	1.48	184.08	0.00
ENGIE Maximacentrale	6e cluster	Yes, post-combustion	0.88	225.09	0.00
Amercentrale	6e cluster	Yes, post-combustion	1.13	87.38	0.00
Vattenfall Power IJmond	Noordzeekanaalgebied	Yes, post-combustion	0.55	235.47	88.44
Sloe Centrale B.V.	SDR	Yes, post-combustion	1.05	213.70	0.00
Zeeland Refinery N.V.	SDR	Yes, post-combustion	0.15	89.90	48.44
Zeeland Refinery N.V.	SDR	Yes, post-combustion	0.07	163.13	88.44
Zeeland Refinery N.V.	SDR	No	-	-	-
Rijnmond Energie C.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.84	204.64	0.00
Vattenfall Centrale Diemen	6e cluster	Yes, post-combustion	1.16	88.79	0.00
Pergen VOF	Rotterdam/Rijnmond	Yes, post-combustion	0.97	176.60	0.00
MaasStroom Energie C.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.53	200.08	0.00
Air Liquide Nederland BV - SMR2	Rotterdam/Rijnmond	Yes, pre-combustion	0.73	79.18	0.00
WKC Moerdijk	Rotterdam/Rijnmond	Yes, post-combustion	0.67	171.84	0.00
Air Products Nederland B.V., Locatie Botlek	Rotterdam/Rijnmond	Yes, pre-combustion	0.69	76.86	0.00
ExxonMobil Chemical Holland B.V. (RAP)	Rotterdam/Rijnmond	Yes, post-combustion	0.38	113.63	22.09

Project description	Cluster	CCS possible?	Size of project in 2030 (Mton CCS)	Costs (€/tonne CO_2)	Maximal SDE++ subsidy (€/tonne CO_2)
BioMethanol Chemie Nederland B.V.	6e cluster	Yes, pre-combustion	0.39	97.33	15.87
Gunvor Petroleum Rotterdam B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.04	77.35	22.09
Gunvor Petroleum Rotterdam B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.02	139.98	62.09
Gunvor Petroleum Rotterdam B.V.	Rotterdam/Rijnmond	No	-	-	-
Eneco Centrale Lage Weide	6e cluster	Yes, post-combustion	0.16	258.22	0.00
Uniper Centrale RoCa	Rotterdam/Rijnmond	Yes, post-combustion	0.20	197.85	0.00
Alco Energy Rotterdam BV	Rotterdam/Rijnmond	Yes, post-combustion	0.23	115.21	22.09
Lyondell Chemie Nederland B.V. - Botlek locatie	Rotterdam/Rijnmond	Yes, post-combustion	0.27	115.25	62.09
Delesto B.V.	6e cluster	Yes, post-combustion	0.22	212.03	0.00
Eneco Centrale Merwedekanaal	6e cluster	Yes, post-combustion	0.21	213.27	0.00
Nouryon Industrial Chemicals B.V. (Hengelo)	6e cluster	No	-	-	-
Cabot B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.19	109.48	22.09
Eurogen C.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.16	194.71	0.00
Cargill B.V. Sas van Gent	SDR	No	-	-	-
Enecal Energy V.O.F.	Rotterdam/Rijnmond	Yes, post-combustion	0.08	241.45	0.00
DAMCO Aluminium Delfzijl Coöperatie U.A.	6e cluster	No	-	-	-
Indorama Ventures Europe B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.03	115.89	22.09
DS Smith Paper De Hoop Mill	6e cluster	Yes, post-combustion	-	-	-
SABIC Innovative Plastics B.V.	6e cluster	Yes, post-combustion	0.14	122.97	48.44
Uniper Centrale Leiden	6e cluster	Yes, post-combustion	0.12	195.91	0.00
NAM B.V. Warmtekrachtcentrale en Oliebehandelings-installatie Schoonebeek (WKC/OBI)	6e cluster	No	-	-	-
Aluminium & Chemie Rotterdam B.V.	Rotterdam/Rijnmond	No	-	-	-

Project description	Cluster	CCS possible?	Size of project in 2030 (Mton CCS)	Costs (€/tonne CO_2)	Maximal SDE++ subsidy (€/tonne CO_2)
Sappi Maastricht BV	6e cluster	No	-	-	-
Emmtec Services B.V.	Rotterdam/Rijnmond	Yes, post-combustion	0.07	220.65	0.00
ADM Europoort B.V.	6e cluster	No	-	-	-
Rockwool B.V.	6e cluster	No	-	-	-

A.1.1 Calculation scheme

The calculation schema has the objective to estimate the CTBO percentage given a fixed CSU price and a set of assumptions. The CTBO potential is a techno-economical percentage in 2030; hereby we mean that it reflects for which companies CCS is technically feasible and has a positive business case given the set of assumptions. The calculation scheme can be summarized in eight steps:

1. NEa emission registration. The NEa is the Dutch Emission Authority, which among other is responsible for the administration of the emissions of EU ETS companies. In the model we use the emission data for 2019, since the emissions data for 2020 are influenced by COVID-19. In this study we analyse the companies with an emission larger than 0.1 Mton CO_2-eq. Some companies have multiple installations registered to the NEa with the same functionality or even same physical installation. These records are combined. In total we analyse 64 point-sources belonging to 53 separate companies.
2. Determine assumptions: Assumptions are made for the ETS and CSU price, energy prices and the implementation of the SDE++ subsidy program. The CTBO can be modelled to include oil and gas or solely gas. The calculation scheme is built with a dashboard which enables to alter all these assumptions and analyse the effect on the CTBO percentage and other key outputs.
3. For each company additional characteristics are added to the dataset:
   - a The type of fossil fuels used causing the emissions. The link between the two is often clear (for example, when the point source only uses one type of fuel). In other cases (multi-fuel usage), we use the most recent version of the Midden-project (van Dam et. al, 2021) to link energy sources to emissions.
   - b The sector and type of industry. Based on the II3050 study and the 'Klimaat- en energieverkenning (KEV2020)' the development in energy use between 2020 and 2030 is estimated. We assume that energy needs of a single point-source are reflected by the development of its sector.
   - c The percentage of the emission for which CCS is viable and which type of CCS is applied (pre- or post-combustion). Note that for some point-sources CCS is not technically feasible or companies have already chosen for other abatement options — in such case we set the viable CCS percentage to 0%. This information is based on the MIDDEN database from PBL (PBL, 2021).
   - d The location of the company is used to determine whether a CO_2 pipeline will be in place in 2030 or liquid CO_2 transport is required. This influences the total CCS cost.
4. Cost calculations: The cost of CCS are split in the capture cost, variable cost for capture and transport and storage cost. The capture cost are based on an European research project on CCU (Ramboll et al., 2019). The variable cost and transport and storage cost are based on analyses from the PBL for the SDE++ (PBL, TNO, 2021).
5. Differentiation of the cost price: The costs for CCS are based on general cost price assumptions. Therefore, there are several projects with the same price, which is

unrealistic and results in an incorrect functioning model. Therefore, a differentiation factor is applied between 90 and 110% which is randomly determined per project.

6. SDE++ subsidy program: Based on the assumptions related to the SDE++ program the model determines which project receive SDE++ subsidy. The SDE++ is awarded to the projects with the lowest additional cost per ton CO_2. The model includes the maximum subsidy for CCS projects as included in the regulation. We assume that CCS projects will generally score well in the merit order and will thus receive SDE++ subsidy as long as the CCS ceiling has not been reached.
7. Determination of CTBO percentage: We assume that all projects that have a positive business case will be realised. The total CTBO percentage is determined by dividing the captured CO_2 by the total emissions related to natural gas emission or natural gas and oil emissions in the Netherlands.
8. Model runs: The model is executed 100 times with different differentiation factors for each company and each run. This results in a confidence interval for the expected CTBO percentage at the assumed price levels.
9. We run the model for 21 different CSU prices: € 0 to € 200 in steps of € 5. This enables us to create a graphical relationship between the CSU price and the CTBO percentage. Note that a Dutch CTBO would probably be introduced with a relatively small and fixed price (€ 0-50). The higher price ranges serve mainly to check if the model behaves in a logical and explainable way. Outputs for higher price ranges can be found in Annex B.
10. Based on the inferred relationship between the CSU price and the CTBO percentage, the model calculates the CTBO's effect on energy prices. Note that gas prices increase both when the CSU prices increases (price-effect) and when the CTBO percentage increases (volume effect).
11. The model then calculates the effect of the increased gas price on the electricity price. We assume that roughly 27% of electricity is generated in gas fired plants by 2030, that 50% of operating costs at gas fired plants stem form energy expenditures and that competition and additional import of electricity from countries without a CTBO damps the increase in electricity prices by 20-80%.
12. Based on the increase in energy prices and information on tax shares in energy bills for different groups (households, small and large firms), the model calculates the percentual increase in energy costs for the different groups. We also estimate the demand effect (higher energy prices lead to smaller demand for energy) using demand elasticities taken from (CE Delft, 2021). Using the found decrease in energy demand, we compute the loss in tax income for the Dutch government.

The main assumptions of the model calculations in this report are given below:

- Fix the CSU price in 2030 to € 0–50, and have the model calculate the CTBO%.
- ETS price in 2030: € 70/tonne CO_2.
- Gas price in 2030: € 0,22/m^3 (KEV 2021).
- Electricity price in 2030: € 47/MWh (KEV 2021).
- SDE++ subsidies: based on the SDE++ concept advise 2022 (PBL). We assume the current mechanism remains valid by 2030 (that is, projects are funded based on their rank in the merit order).
- CCS cap within SDE++: set at 9.7 Mton (updated from the previous 7.2 Mton after release of the 'Miljoenennota')[46].
- CCS costs and feasibility: based on MIDDEN database (PBL).

[46] Note that the CCS cap within the SDE++ subsidy is a volume cap: the total volume of subsidized CCS projects may not exceed the stated 9.7 Mton. This means that a 1 Mton project that only requires a small subsidy (say € 10 per tonne CO_2) contributes as much to the cap as an expensive (say € 100 per tonne CO_2) 1 Mton project.

- CO_2 infrastructure: only CO_2 transport around Rotterdam/Rijnmond.[47]
- KEV (2021)[48,49];
  - total gas use in 2030: 26.9 bcm;
  - total oil use in 2030: 1,025 PJ.

A.1.2 Scope of analysis and uncertainties

The calculation scheme has certain limitations and uncertainties. Firstly, the cost of CCS projects is based on sector-level literature and are general numbers. Therefore, the costs for specific companies are uncertain. Whether a project would have a positive business case may slightly differ from reality.

Second, the model calculates a techno economical CTBO potential. It is uncertain if a company will choose the CCS route or decide another decarbonisation route (in 2030 or later) or not decarbonise in 2030 at all. Companies may decide to choose an alternative abatement option even if CCS is the most profitable, for instance because of air pollution concerns or the wish to directly invest in a 'final' technology. Also, if for example electrification or hydrogen are feasible shortly after 2030, companies will most likely not implement CCS in 2030 for a short time period. We have analysed at the sector level if CCS is possible but have not analysed the technical feasibility at company or installation level.
Thirdly, the development of companies and technology towards 2030 is uncertain.
This influences both the total natural gas consumption in the Netherlands (which is denominator of the CTBO percentage) and CCS potential (the numerator). The growth or decrease of sectors and companies is dependent on international development and company police but will influence the total emissions and CCS potential. Especially the natural gas sector in the Netherlands is heavily influenced by European policy, energy price levels and national trends.

A final important limitation is the relative simplicity of the model. The model does not include feedback loops related to the effect of the CTBO. An example could be the effect on the energy production in natural gas power stations if a CTBO is implemented. Therefore, the external effects of the CTBO should be further analysed in a qualitative analysis'.

47 The Aramis project (link) is not explicitly included in this analysis as it is still unclear how it is implemented and financed. Instead, we make several more general assumptions, see Appendix A.1.1 (Step 4 and Step 5).

48 We did not account for any consequences of the Ukraine invasion, nor of the limits on oil and gas trade with Russia.

49 For detailed assumptions on the translation of future demand changes of oil and gas to the point sources, we refer to Annex 1.1, Step 3.

Remaining uncertainties and disclaimers

The model used to generate the results pictured above does not include 2nd order-effects. That is, it does not account for behavioural changes that result from the higher energy prices caused by a CTBO. If a Dutch CTBO for natural gas producers/suppliers is introduced, we can expect gas prices to increase. This can have multiple effects:

- Higher gas prices will cause the demand for gas to decrease (for instance due to a lower demand from buildings and horticulture). Total gas use will hence decrease, which causes the denominator in the CTBO percentage to decline. The result is that when this effect is corrected for, the CTBO percentage would be slightly higher.
- Higher gas prices could force gas-intensive industry with CCS potential (e.g. Yara) to move to other countries or disappear completely. If this happens the CTBO percentage will be lower.
- The CCS plant itself relies on the use of natural gas. This means that higher gas-price make CCS costs slightly higher. The result is a slightly lower CTBO percentage at a fixed CSU price. However, if the CTBO percentage is fixed, then the CSU price will increase as CCS facilities will be faced with higher energy cost that could slightly lower the CTBO%.

A second class of uncertainties follows from the peak in energy prices we are currently witnessing. If gas prices (but also electricity prices) remain at elevated levels till 2030, we could witness changes in investment decisions, energy use and the Dutch economic landscape:

- Higher gas prices could make electrification relatively more profitable than CCS, resulting in a smaller CTBO percentages at the same CSU price. But, time is short till 2030, and hence electrification will only occur in some cases. Also, structurally higher gas prices could in theory also lead companies to wait until electric abatement options become available, thereby foregoing a transition period with CCS.
- Gas-intensive companies with CCS options may go bankrupt or lower their output, thereby decreasing the CCS potential, leading to a smaller CTBO percentage.
- Sectors without CCS potential will decrease their demand for gas, thereby decreasing total gas use without decreasing the total CCS potential. This leads to larger CTBO percentages.
- There is some literature claiming that if gas prices were to rise at a much higher rate than electricity prices, then green hydrogen could become cheaper than blue hydrogen, leading to less CTBO potential and a smaller CTBO percentages. By 2030 however, this seems unlikely.
- Currently, natural gas is so expensive that biomethane is often cheaper. This could lead to more investment in biomethane plants adopted with CCS installations and hence to (more) negative emissions. The negative emissions will increase the CTBO percentages at a fixed price.

A third class of uncertainties follows from a CTBO that extends to oil producers/suppliers. In comparison to the gas-only CTBO, a Dutch CTBO for oil and gas yields a smaller CTBO-% at the same CSU price. Reason for this is that there is for oil less scope for CCS in the Netherlands.

Finally, the main model does not take into account new point sources. In 2030, we could see new industries or point sources with negative emissions (presumably biobased). In the sensitivity analysis displayed in Annex B, we show the effect of additional (blue) hydrogen production. New industries are too uncertain to include at this point. We furthermore expect negative emission point sources not to be profitable at low CSU prices and regular gas prices and have hence excluded them from the main analysis. Only if carbon removal activities can sell both emission credits AND CSU's then this may increase the chance of a business case for negative emission point sources. In theory, given fast technological process (possibly combined with high gas prices), negative emissions could become profitable at low (€ 0-50) CSU prices. In such case, we would see higher CTBO percentages at fixed CSU prices. Governments set the CTBO%. If they decide to increase the CTBO% above 100% (requiring fossil energy producers/users to also pay for historic clean-up) then there will be net removal as long as fossil carbon is produced/used, Thus, a proper business model could be made for negative emissions.

A.1.3 Predicted total fossil gas use in 2030

To determine the CTBO percentage we relied on data from the KEV 2021 for total gas use in 2030. In 2019, total Dutch gas use equalled 1,333 PJ, whereas PBL expects this to drop to 933 PJ by 2030. As is depicted in Figure 7 and Figure 8 the decline in gas use stems predominantly from the smaller share of gas-powered electricity.

Figure 7 - Natural gas use in different sectors — the Netherlands — 2019 (PJ)

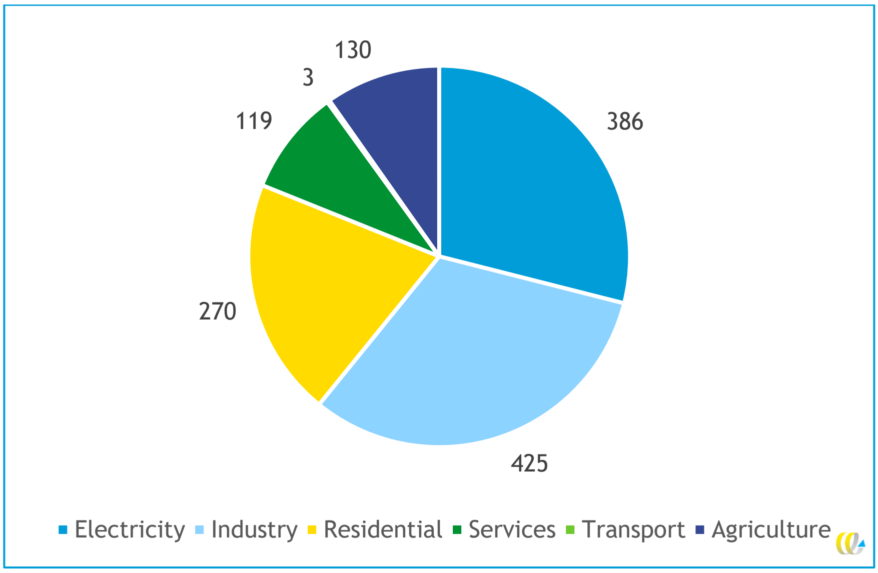
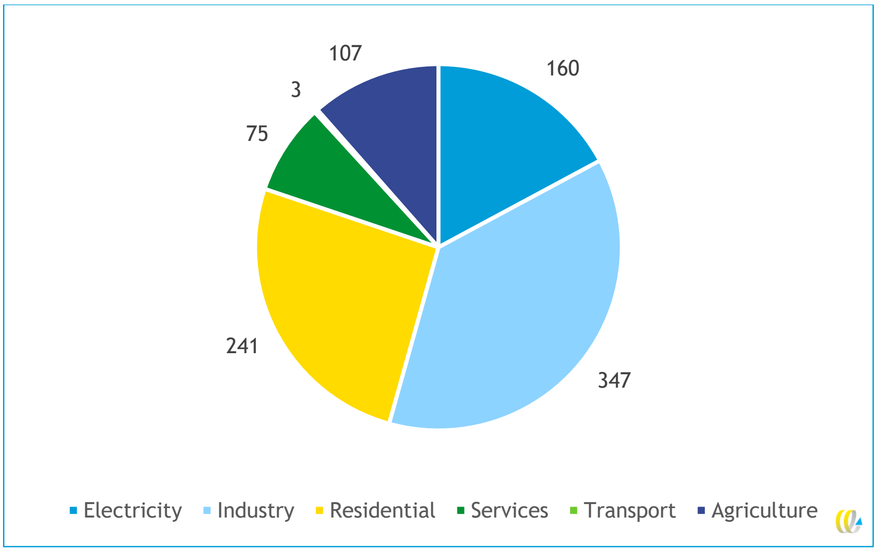


Figure 8 - Estimated natural gas use in different sectors — the Netherlands — 2030 (PJ)



Industry goes down quite a bit also, which is based on the II3050 study and the 'Klimaat- en energieverkenning (KEV2020)' with the production of the single point-source reflected by the development of its sector. The recently announced gas + CCS power plant in the 'Regeerakkoord' is not accounted for in this baseline.

A.2 CTBO in Europe

A.2.1 MERGE model overview

MERGE is a model for estimating the regional and global effects of greenhouse gas reductions. It quantifies alternative pathways of climate change. Here the model is used to design cost-effective emission reduction strategies.

MERGE contains submodels on the domestic and international economy energy-related emissions of greenhouse gases non-energy emissions of ghg's global climate change. The domestic economy is modelled as a Ramsey-Solow model of optimal growth. Intertemporal choices are strongly influenced by the 'utility' discount rate.

Price-responsiveness is handled by a top-down production function, in which output depends upon the inputs of capital, labour and energy. Energy-related emissions are calculated from a bottom-up perspective with technologies for electric and non-electric energy.

MERGE is operated here in a 'cost effective' mode — supposing that international negotiations lead to a time path of emissions that satisfies a constraint on concentrations or on temperature change. The model may also be operated in a 'benefit cost' mode — choosing a time path of emissions that maximizes the discounted utility of consumption, after making allowance for the disutility of climate change. Abatement choices are distinguished by 'where' (in which region?), 'when' (in which time period?) and 'what' (which greenhouse gas to abate?). There may be trade-offs between equity and efficiency in these choices.

The intertemporal consumption and savings choices assumes forward-looking behaviour. All prices and quantities are determined simultaneously. Outside the energy sector, output is aggregated into a single good, the numéraire.

Consumption is just one of the claimants upon total economic output, while in each region at time pp, some output is allocated to investment to build up the capital stock. Other output is employed to pay for energy costs, and some output is allocated to net exports of the numéraire. Gross output is defined so that there is a low elasticity of price response in the short run, but a much higher response over the longer term. That is, new output is responsive to current and expected future prices, but the economy is locked into the technology choices made in earlier years. With 10-year time intervals and 40% depreciation over a decade, we have two vintages in the economy. New output is based on an economy wide nested CES (constant elasticity of substitution) production function. The inputs to this production function are expressed as new capital, new labour, new electric, and new non-electric energy. These inputs are governed by transition equations like those that have just been written for gross output.

The production function is calibrated to allow for substitution: (1) capital-labour substitution, (2) interfuel substitution between electric and non-electric energy, and

(3) substitution between capital-labour and energy. The parameters adjust to reflect autonomous improvements in the productivity of labour and of energy.

International trade is expressed in terms of a limited number of tradeable goods, which assumes Heckscher-Ohlin trade, rather than Armington trade (region-specific heterogenous goods). Specifically, each region produces the numéraire good, which means that heterogenous categories outside the energy sector (e.g., foodgrains, medical services, haircuts and computers) are all aggregated into a single item called ‘U.S. dollars of 2000 purchasing power’. This simplifying assumption is inappropriate to describe short term balance-of-payments for countries. Each region may produce oil and gas (subject to resource exhaustion constraints), and these are tradeable. For each tradeable good and each projection period pp, there is a balance-of-trade constraint specifying that — at a global level — net exports from all regions must be balanced with net imports (there is a price). The prices can be described as ‘efficiency prices’.

Table 5 - Cost assumptions electricity taken from IEA ($/kW) and CO_2 coefficients (tC/KwH)

	2020	2050+	Emission Coefficient
Coal (Pulverized)	$ 2,100	$ 2,100	0.19
Coal Integrated Gasification Combined Cycle (IGCC)	$ 2,400	$ 2,200	0.19
Coal IGCC with CCS	$ 3,500	$ 2,700	0.02
Gas Single Cycle	$ 625	$ 625	0.14
Natural Gas Combined Cycle (NGCC)	$ 900	$ 900	0.09
NGCC with CCS	$ 1,620	$ 1,350	0.01
Nuclear (GEN III)	$ 4,000	$ 4,000	-
Nuclear (GEN IV)	N/A	$ 5,600	-
Biomass(No CCS)	$ 2,300	$ 2,100	0,03
BECCS	$ 3,400	$ 3,000	-0,25
Wind On-shore	$ 1,700	$ 1,500	-
Wind Off-shore	$ 2,500	$ 1,500	-
Solar PV	$ 2,000	$ 600	-

A.2.2 Climate policy baseline assumptions

In the base case policy scenario for Europe, we assume no BECCS and a limit on CCS in 2050 equal to 0.2 Gt C per year (equal to 15% of the reduction effort). As there are so little concrete climate policy plans worked out for Europe for the years beyond 2030 besides the net-zero emissions by 2050, we decided to use the model to simulate an efficient energy system fitting with that goal (a uniform carbon price over all sectors). So, these assumption results in the demand for biomass for both biofuel-blending outside ETS and some biomass-powered electricity production.

Minimal mitigation cost increases wind-energy to more than 55% of production in 2050 while nuclear’s role complements this large amount of wind energy. This means that nuclear’s role is pushed to maximal levels (compared to the other cases). Maximal means that the current nuclear capacity is maintained, i.e. it scrapped in line with economic considerations, while offset by investments in generation IV nuclear capacities. This may seem unrealistic, but we want to avoid too expensive energy systems for the EU. But we also highlight the uncertainty of our main finding (gains of CTBO) by exploring the impact of CTBO at higher levels of CCS.

We disregard BECCS in the EU in the base case, because there are also no concrete plans for BECCS (note that the CCS bound also limits the possibility to use BECCS). We think this is a realistic assumption because of EU's perception on potential other sustainability problems related to biomass (food prices and land-use changes). Nevertheless, we assume biomass to be used for biofuel-blending, while there are no restrictions on biomass and BECCS in other regions (besides the overall global sustainability cap of 150 EJ/year. So, in terms of the global numbers, we are in line with the assumptions of the global IEA NZ scenario.

Nevertheless our global scenario with a uniform carbon price in the rest-of-the-world may deviate from IEA's regional assumptions of the NZ strategies, which assumes many technology-specific stringent policy plans beyond the current existing policy plans or countries' pledges made for the Paris climate agreement. The differences of the two scenarios is beyond the scope of this project (focus is Europe).

B Detailed Results

In this annex we provide more detailed model results for both the Dutch and the European CTBO. Although the Dutch variant would probably have a relatively small fixed price (between € 0 and € 50), we here also present the outcomes for higher price ranges. In these ranges, CCS at gas fired plants — who cannot acquire

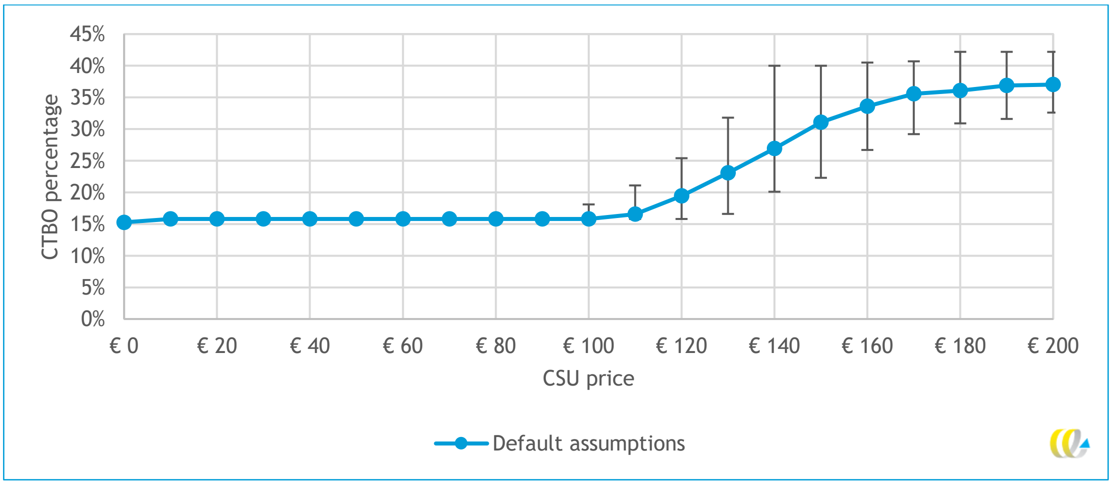
B.1 CTBO in the Netherlands

In this annex we provide more detailed model results for both the Dutch and the European CTBO. Although the Dutch variant would probably have a relatively small fixed price (between € 0 and € 50), we here also present the outcomes for higher price ranges. In these ranges, CCS at gas fired plants — who cannot acquire SDE++ subsidy — gradually becomes profitable. Note that negative emission sources are not included in the model, and could lead to (much) higher CTBO percentages at given CSU prices.

B.1.1 CTBO for gas

Figure 9 shows the relation between the CSU price and the CTBO percentage for a larger price range. As before, we see that the graph is flat for a relatively large price range. After € 100, CCS gradually becomes profitable for gas-powered plants. Small differences in CCS costs can largely influence the attained CTBO percentage in this range, as pictured by the error bars[50]. Adding to this uncertainty is that many gas-fired plant will operate more sparsely in 2030 (providing mostly flexible power). The smaller the number of operating hours a gas fired plant has, the more pressure fixed costs of a CCS installation will put on the business case.

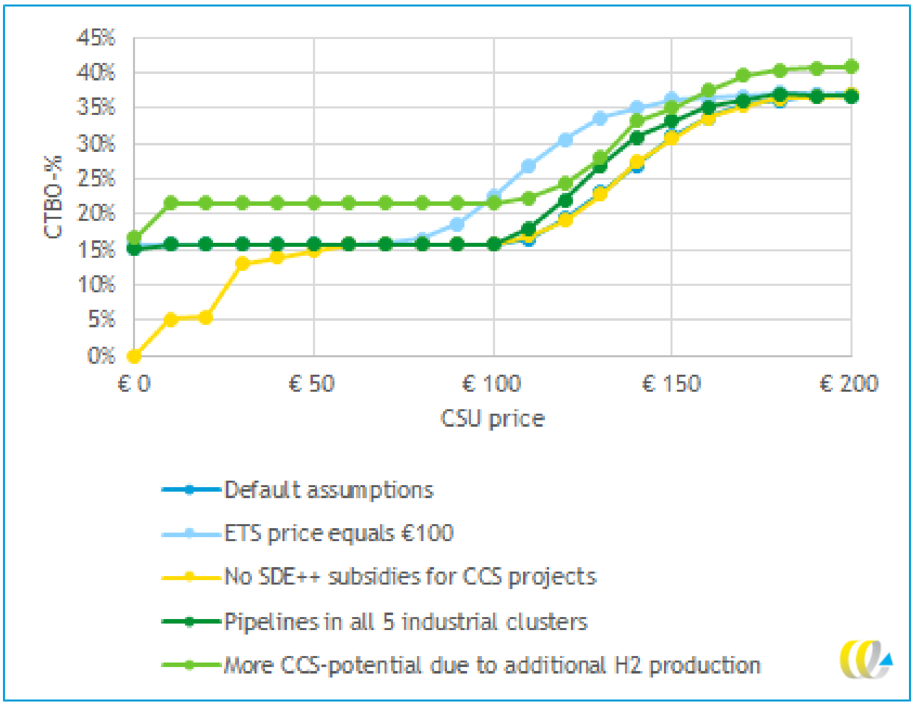
Figure 9 - Relation between the CSU price and the CTBO percentage for a Dutch gas-only CTBO



[50] The top and bottom of the error bars represent the largest and smallest output from the 100 runs, respectively.

Figure 10 presents the outcomes of four different sensitivity analyses: one in which we assume a higher ETS price, one in which we assume there is no SDE++ budget for CCS in 2030, one in which we assume there is CO_2 infrastructure present at all five large industrial clusters, and finally, one in which we add new fossil hydrogen production sites to the model (summing to 4 Mton CO_2/year).

Figure 10 - CSU price and CTBO percentage — Sensitivity analyses[51]



As becomes clear from Figure 9, a higher ETS price shifts the curve to the left. This makes sense: the larger the CO_2 price, the smaller the unprofitable top for abatement technologies. The addition of CO_2 infrastructure in four of the five industrial clysters also shifts the graph to the left. After all, transport per pipeline leads to lower variable costs for CCS and thus to earlier adoption.

Already presented in Chapter Figure 2, the removal of SDE++ subsidy for CCS projects causes a drastic change in the behavior at lower price ranges. Now, a small CSU price can increase the number of CCS projects, rather than only changing the financing scheme. Finally, the addition of new hydrogen production sites in the Netherland causes the graph to move upwards, starting at a CSU price of € 80/tCO_2. This is explained by the fact CCS costs for hydrogen production are small: starting at a CSU price of € 10, the new hydrogen sites no longer need SDE++ subsidy, making room for other CCS projects. The new hydrogen production also causes the national gas use to rise, but this effect is relatively weaker. The net effect is hence an increase in the CTBO percentage.

Note that that the CTBO% at 60€/ton is exactly the same as if there is only a pipeline in Rotterdam, because these projects are already profitable without CO_2 infrastructure (SDE

[51] Zeeland is a separate cluster with Yara and Dow.

amounts are, after all, higher for CCS without CO_2 infrastructure than for CCS-with-infra; with more infrastructure, the SDE expenditure per CCS project therefore mainly decreases).

Figure 11 shows the effect of a Dutch CTBO on energy prices for a larger price range. Notice that the gas price depends both on the CSU price (price effects) and on the CTBO percentage (volume effect). This dual dependency explains the nonlinear relation depicted in the graph. At relatively low CSU prices, the effects on gas and electricity prices are limited; at higher CSU prices, the increase in gas prices does however become substantial. The electricity price grows by a slower pace, since only a small percentage of electricity costs stem from gas expenditures in 2030.

Figure 11 – A Dutch CTBO's effect on energy prices in 2030

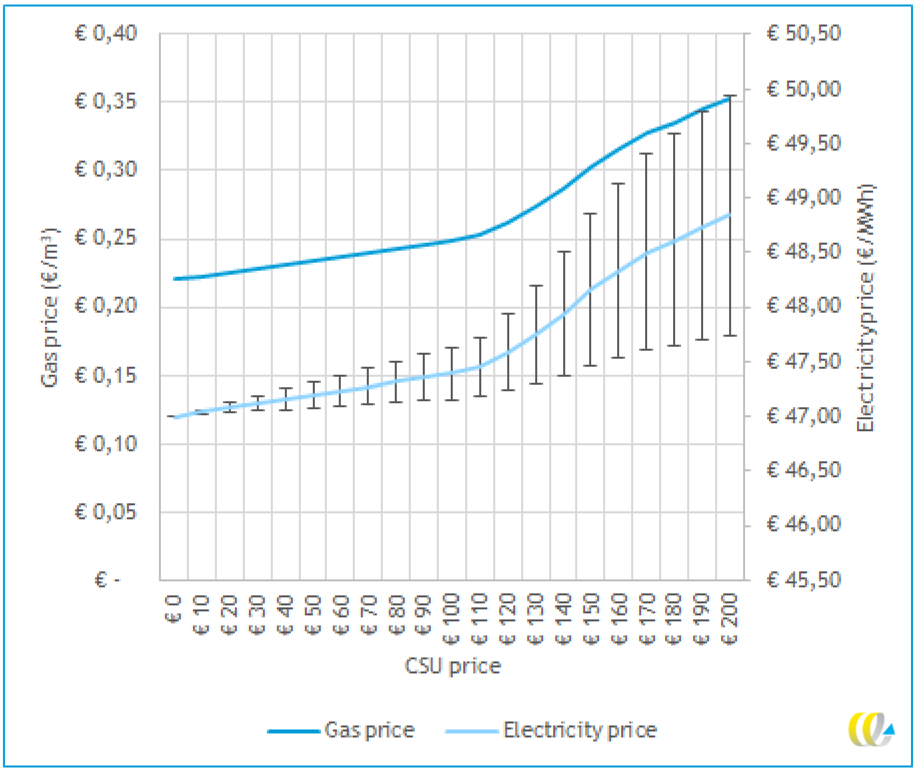


Figure 11 shows how the increase in energy prices translates to total yearly energy expenditures for an average Dutch household. The graph closely follows the path of the gas price and cost increases stay limited up until a CSU price of roughly € 100.

Figure 12 - Yearly cost increase average Dutch household as result of a CTBO

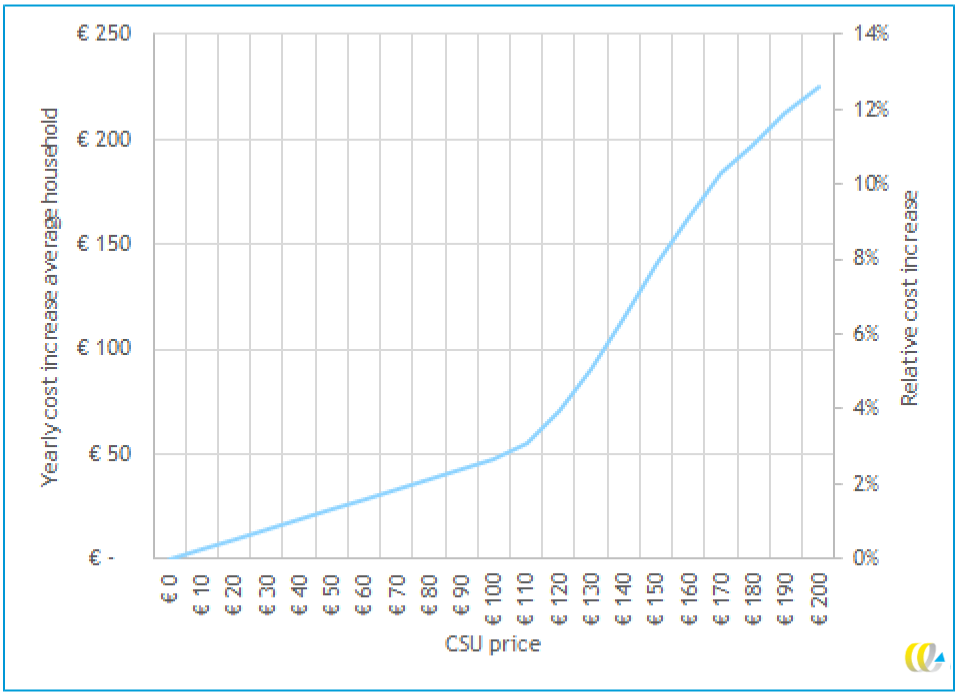
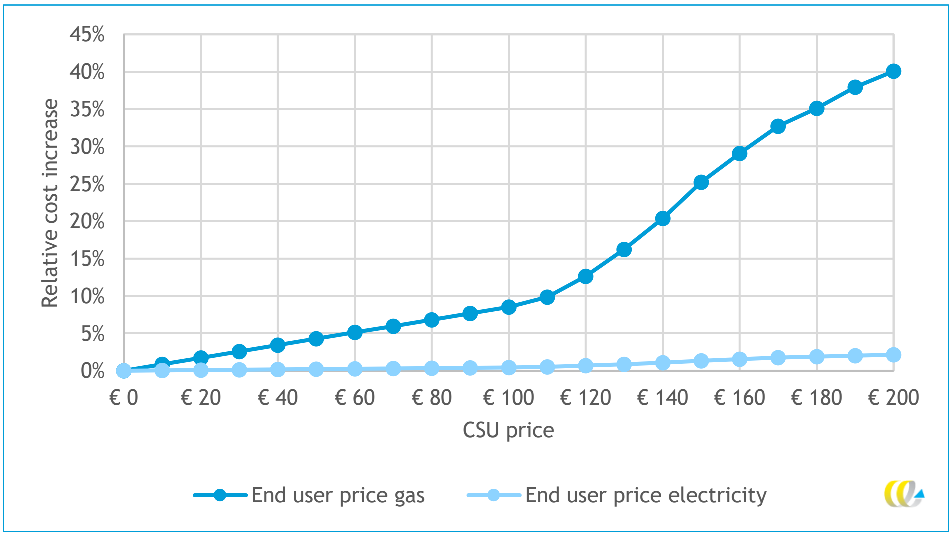


Figure 12 shows how the elevated energy prices that result from the introduction of a CTBO translate to end user energy prices at an average firm[52]. Since firms generally pay less energy taxes as a share of their end user costs, end user prices are more sensitive to energy price changes. We hence see a larger relative cost increase than witnesses by households.

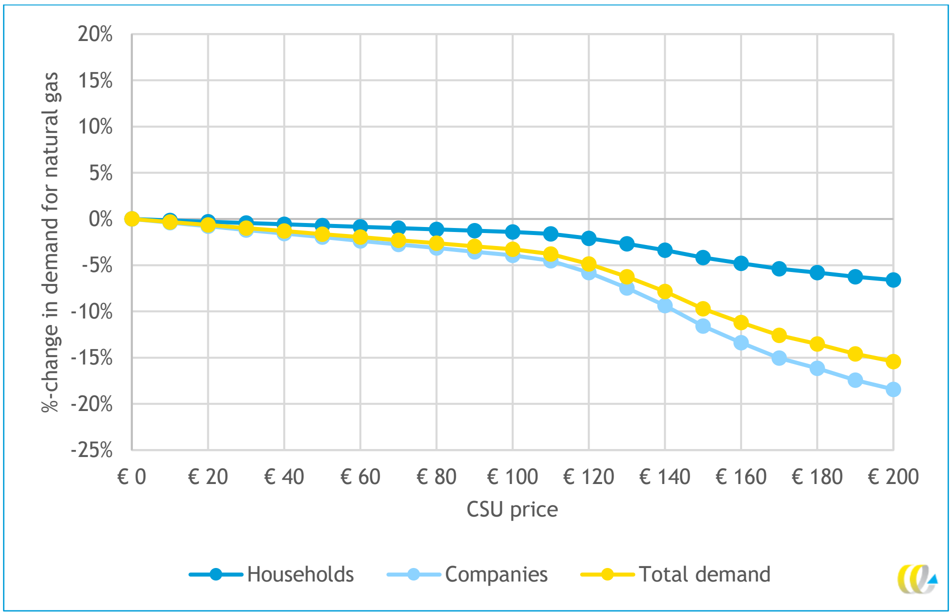
Figure 13 - Effect of a Dutch gas-only CTBO on energy costs at firms



52 Average in terms of energy use.

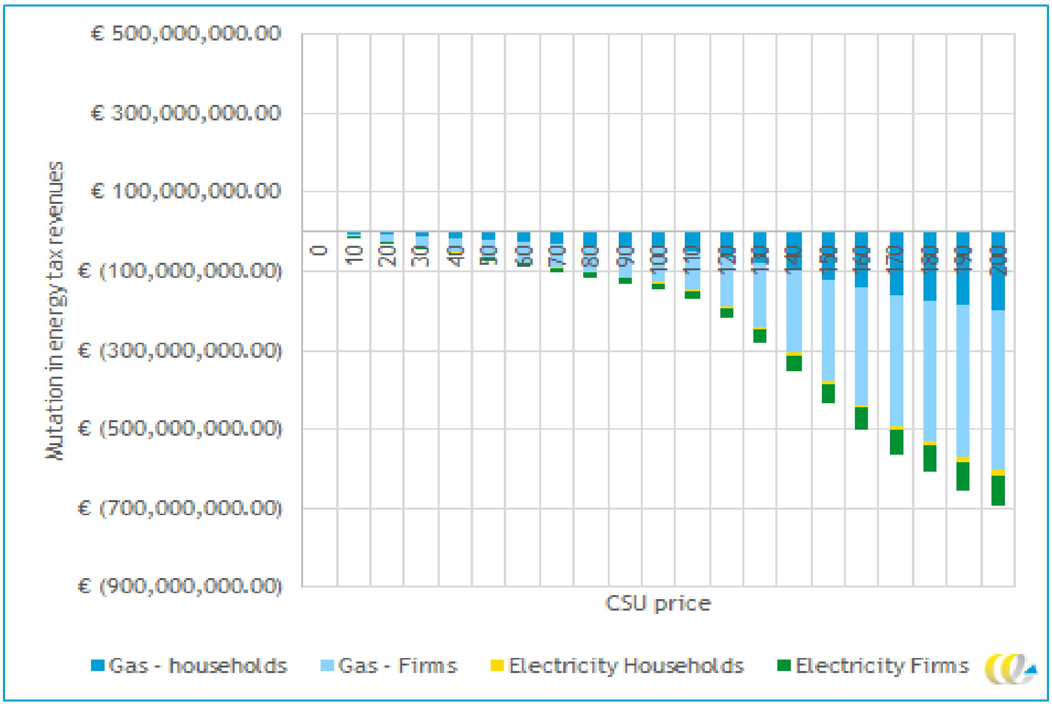
Figure 13 presents the influence a Dutch gas only CTBO has on the demand for natural gas. Underlying the presented relationship are demand elasticities taken from (CE Delft, 2021). At the lower price ranges, the change in demand is relatively small, but at higher price ranges the demand effect becomes very substantial.

Figure 14 – Change in demand for gas as result of a CTBO



Finally, Figure 14 presents how the demand effect translates to lower energy tax revenues for the Dutch government. At a CSU price of € 40/tonne CO_2, the loss in energy tax revenues equals roughly € 60 million a year. At the same time, notice that this second order effect also entails second-order CO_2 abatement (after all, less fossil energy is used).

Figure 15 - A Dutch gas-only CTBO's effect on energy tax incomes



A Dutch CTBO and the accompanying rise in energy prices have different effects on different groups. In Table 6 these effects are quantified. Households and gas-intensive firms see their energy bills slightly rise, while gas producers/supplier can expect a modest reduction in sales due to lower demand for natural gas. The effect of a Dutch CTBO on companies with CCS installations varies. Companies with low CCS costs (see Annex A.1 for an overview) can make economic profits because of the introduction of a CTBO[53]. The rise in energy prices is not large enough to cancel out the profits they make through the CTBO. In Figure 16 the economic profits made by a hypothetical hydrogen producer are also displayed.

Table 6 - Effect of a Dutch CTBO different groups

CSU price (€/ton CO_2)	Average Households: increase in energy costs (%)	Average gas-intensive firm: Increase in energy costs (%)	Gas producer/ suppliers: mutation in sales average (%)	Government: Loss in tax revenues (€/year)	Economic profits average hydrogen producer (€/year)
0	0.0%	0.0%	0.0%	-	-
10	0.3%	0.9%	-0.3%	-14,801,231	2,109,282
20	0.5%	1.7%	-0.7%	-29,319,650	9,382,668
30	0.8%	2.6%	-1.0%	-44,120,880	16,656,054
40	1.1%	3.4%	-1.3%	-58,922,111	23,929,440
50	1.3%	4.3%	-1.6%	-73,723,342	31,202,826

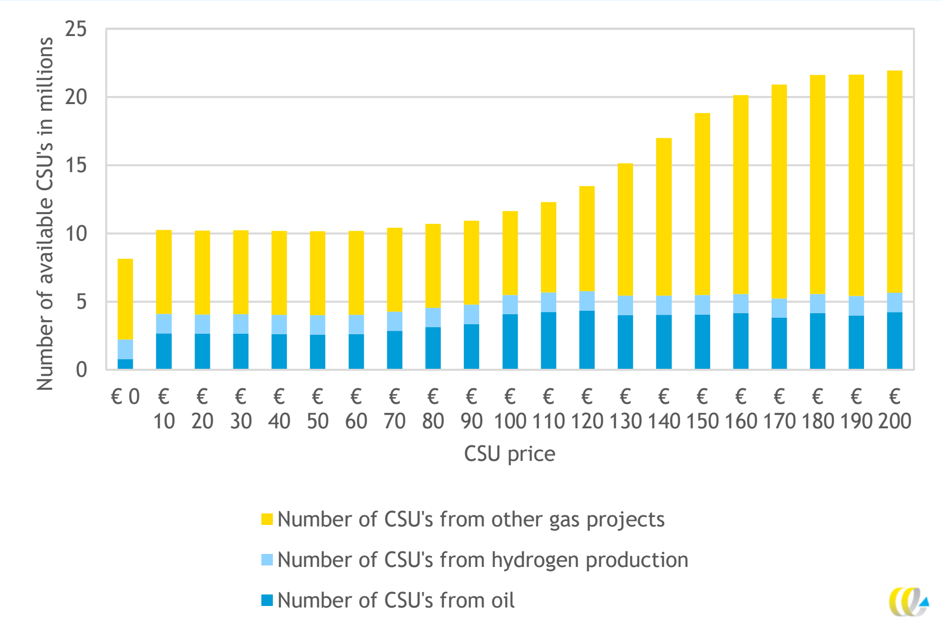
53 Note that the CSU price is either fixed or determined by the most expensive project necessary to hit the CTBO target percentage. This means that companies whose unprofitable top is lower than the CSU price + the ETS price, can make economic profits.

B.1.2 CTBO for oil and gas

A CTBO for both oil and gas yields result similar to a gas-only CTBO. This is because the number of domestic oil-related CCS projects is limited in the Netherlands. Figure 15 shows how many CSU's are available from oil and gas-related CCS projects at given CSU prices. Gas-related projects are separated into hydrogen production and other gas-related projects.

It is no coincidence that the there is a flat outcome at 10 Mt/yr, because CTBO mainly replaces the financing method (SDE becomes CTBO) and only ensures a limited increase in the CCS volume. The increase in the SDE ceiling for CCS seems to be enough to allow all low-cost projects to go ahead. If we only look at the existing point sources, the model simulations show that the SDE++ ceiling is not met. New blue hydrogen production could ensure that the ceiling is reached. Oil CCS only accounts for a small portion of CCS because a relatively large part of the CO_2 emissions comes from gas use (oil is used as a raw material, gas is often used to make hydrogen). The classification in the graph is based on the energy carrier that causes the CO_2 emissions, not on the basis of total inputs. So, although oil is by far the largest input for these companies, still oil only makes up a relatively small share of the total CCS volume.

Figure 16 - Number of CSU's from oil and gas projects[54]



[54] Example projects of non-H2 gas at a CSU price of 30 €/t projects are fertilizer production at Chemelot, Refining Shell, Yara, Refining ESSO, Refining BP, Refining ExxonMobile, Biomethanol production (and the hydrogen factories).