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Climate neutral energy carriers in the regulatory energy tax (REB)

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SUMMARY

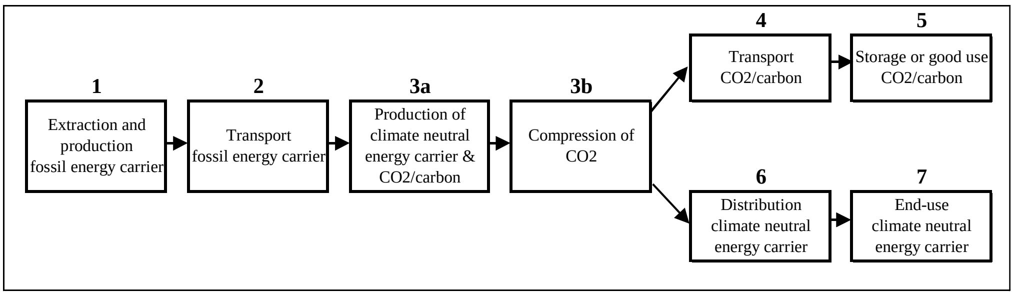
Introduction

The Dutch government is currently examining the possibilities to promote the production and use of <u>climate neutral energy carriers</u> (CNE) by including them in a regulation, which exempts specific environmental friendly energy carriers from the regulatory energy tax. An interdepartmental working group 'Regulation Climate Neutral Energy Carriers' has been formed with representatives from the Ministry of VROM, Finance and Economic Affairs, which has the task to prepare this regulation. Ecofys has been asked by RIVM to provide the working group with background information on avoided greenhouse gas emissions by application of climate neutral energy carriers and the associated costs.

Climate neutral energy carriers are defined as hydrogen and electricity produced by means of fossil fuels and by which (a substantial part of) the produced carbon dioxide is stored or put to good use. The term "<u>climate neutrality</u>" of an energy carrier refers to the share of the energy carrier that can be marked as climate neutral. The emission reduction is equal to the difference between the emissions in the (chosen) reference system and the emissions caused by the climate neutral energy carrier.

Concept

For sake of this study, we constructed a generic production chain for climate neutral energy carriers which is divided into seven steps (chain elements):



To judge whether a project qualifies for support within the new regulatory framework and to determine the level of financial support the <u>climate neutrality</u> and the <u>additional costs</u> of a climate neutral energy carrier need to be determined.

- In order to be able to calculate the climate neutrality of an energy carrier in principle <u>all changes</u> in the emissions of greenhouse gases in each chain element of the production chain must be determined. The emissions of production and application of an energy neutral energy carrier are therefore compared to the emissions in a reference system.

- The production costs of climate neutral hydrogen and electricity are compared to the current prices of natural gas and electricity for small consumers (excluding VAT). The production costs are calculated using a 15% discount rate.

Results

The 'climate neutrality' and additional costs are determined for five different production chains listed in table S-1. These production chains provide a good average of the possibilities for the production of climate neutral energy carriers. The main results of the analysis are summarised in table S-2.

Table S-1. Characterisation of five production chains for climate neutral energy carriers examined in this study.

Code	Production facility	Storage/use of CO_2/Carbon	Climate neutral energy carrier
PC1	Natural Gas Reforming + fuel gas recovery	Storage in coal layers by ECBM	Hydrogen
PC2	Coal gasification + fuel gas recovery	Storage in empty NG field	Hydrogen
PC3	Coal combustion with pure O_2	CO_2 used in production of methanol	Electricity
PC4a	Flue gas recovery of coal-fired power plant	CO_2 used in greenhouses + storage	Electricity
PC4b	Flue gas recovery of natural fired power plant	CO_2 used in greenhouses + storage	Electricity
PC5	Natural processing (recovery of abundant CO_2)	Storage in aquifer	Natural gas

Table S-2 Summary of the main results for the costs and climate neutrality of the five examined production chains.

Code	Emission Factor	Costs [a]	Reference	Climate neutrality [c]
PC1	17 $kgCO_2/GJ\ H_2$	13.5-16.2 euro/GJ H_2	Natural gas	71%
PC2	33 $kgCO_2/GJ\ H_2$	15 euro/GJ H_2	Natural gas	46%
PC3	0.2 $kgCO_2$/kWh	0.08 euro/kWh	Average park	77%
PC4a	0.5 $kgCO_2$/kWh	0.11 euro/kWh	Average park/gas engine[b]	21%
PC4b	0.2 $kgCO_2$/kWh	0.09 euro/kWh	Average park/gas engine[b]	63%
PC5	59 $kgCO_2$/GJ NG	11 euro/GJ NG	Natural gas	7%

a) for comparison: prices for small consumers including REB excluding VAT: natural gas 9.7 euro/GJ; electricity 0.14 euro/kWh.
b) 25% of the recovered CO_2 is used in greenhouses; 75% is stored underground.
c) Climate neutrality compared to the reference in the former column.

From our analysis it can be concluded that the emissions from the total production chain of climate neutral hydrogen ranges from 17 and 33 kg of carbon dioxide equivalents per gigajoule. For comparison the emission of natural gas for the whole production chain amount to 60 kg CO_2-eq/GJ. The climate neutrality of the hydrogen amounts to about 71% when natural gas is used as feedstock, and to about 46% when coal is used.

The emissions from the total production chain of climate neutral electricity amounts to between 0.2 and 0.5 kg of carbon dioxide equivalents per kWh. For comparison, the emissions of electricity production facilities currently in operation range from about 0.4 to 1.1 kgCO_2-eq/kWh. The climate neutrality ranges from 20% to 75%, depending on the application/storage of the recovered CO_2 and the electricity production reference used.

The calculated production costs for hydrogen ranges from 13 to 16 euro/GJ of hydrogen, whereas the current price for natural gas for end-users (including energy tax and excluding VAT) is approximately 10 euro/GJ.

The calculated production costs for electricity ranges from 8 to 11 euroct/kWh in the situation where the producer of the electricity delivers the CO_2 for free to the customer (either a methanol producer or a greenhouse grower). In case the customer of the CO_2 is willing to pay a price for the CO_2, equalling the marginal costs of the energy saved by the customer, the electricity price could drop to 5 to 9 euroct/kWh. For comparison the current price for electricity for end-consumers (including energy tax and excluding VAT) is approximately 14 euroct/kWh.

The specific reduction costs for climate neutral hydrogen (using a discount rate of 5%) ranges from 150-250 euro/Mg of CO_2. In the examined production chains the specific reduction costs for climate neutral electricity is very sensitive to the assumptions with regard to the energy price. The costs range from <0 – 30 euro/Mg of CO_2 avoided.

Sensitivity of results

Generally only emission changes in chain element 3 (production of the climate neutral energy carrier and compression of the CO_2) are substantial, and contribute up to 80% of the total emissions of the whole chain. Emission changes in element 1 (extraction and production of the fossil energy carrier) are only relevant when the (methane) emission factor of the fossil fuel used for the production of the climate neutral energy carrier differs substantially from the (methane) emission factor of the fossil fuel used in the reference systems. Emission changes due to storage can also be neglected. However, in cases where the CO_2 is applied in other production processes, e.g. in greenhouses, it has to be carefully analysed which part of the CO_2 is stored in the product and which part of the CO_2 is emitted to the atmosphere.

The costs for climate neutral energy carriers are sensitive to the scale of production. In our analysis we assumed an annual production of 5 million gigajoule of hydrogen or electricity. A production unit twice as large as assumed in this study, might lead to a cost reduction of 10 to 15%.

TABLE OF CONTENTS

SUMMARY III

TABLE OF CONTENTS VII

1 INTRODUCTION 1

1.1 Introduction 1
1.2 Aim of the project 1
1.3 Approach 2
1.4 Structure of the report 2

2 PRODUCTION CHAINS 3

2.1 Definition of 'climate neutral energy carriers' 3
2.2 Concept of the production chain 3
2.3 Energy saving versus CO_2 removal 4
2.4 Emission Reductions and Additional costs 6
2.5 Examples of Production Chains 7

3 REFERENCE SYSTEMS 9

3.1 Definition 9
3.2 Multi-project versus project specific approach 9
3.3 Static versus (Semi-) Dynamic approach 10
3.4 Conclusions 11

4 SYSTEM BOUNDARIES 13

4.1 Introduction 13
4.2 Key figures and assumptions 13
4.3 Changes in emissions per chain element 14
4.4 Uncertainty in the emission calculations 20
4.5 Conclusions 21

5 ADDITIONAL COSTS 23

5.1 Introduction 23
5.2 Starting point for the cost calculations 23
5.3 End-use costs of Climate Neutral Hydrogen and natural gas 25
5.4 End-use costs of Climate Neutral Electricity 28
5.5 Specific Reduction Costs 30
5.6 Conclusions 31

6 CONCLUSION 33

GLOSSARY 35

REFERENCES 37

1 ANNEX: DESCRIPTION OF PRODUCTION CHAINS 39

1.1 PC1: Hydrogen from NG and ECBM 39
1.2 PC2: Hydrogen from coal and storage in empty natural gas field 45
1.3 PC3: Electricity production from coal and storage in empty natural gas field 48
1.4 PC4: Electricity production from coal or natural gas and use of carbon dioxide in greenhouses and storage in natural gas field 52
1.5 PC5: Storage of carbon dioxide from natural gas processing 58
1.6 PC6: Hydrogen and carbon black production 62

2 ANNEX: COST CALCULATIONS FOR COMPRESSION AND TRANSPORT OF CARBON DIOXIDE 67

2.1 Compression of CO_2 67
2.2 Transport of carbon dioxide 68

REFERENCES ANNEX 69

1 INTRODUCTION

1.1 INTRODUCTION

The fourth National Environmental Policy Plan states that climate neutral energy carriers will play an important role in reducing the emissions of greenhouse gases. Climate neutral energy carriers are defined as energy carriers that emit none or hardly any greenhouse gases over the whole life-cycle. The Dutch government is currently examining the possibilities to promote the production and use of climate neutral energy carriers by including them in a regulation, which exempts specific environmental friendly energy carriers from the regulatory energy tax.

An interdepartmental working group 'Regulation Climate Neutral Energy Carriers' has been formed with representatives from the Ministry of VROM, Finance and Economic Affairs, which has the task to prepare this regulation. Extension of the regulatory energy tax, by including climate neutral energy carriers needs the formal approval of the European Commission. The plan is to submit a formal proposal for approval before the second half of 2002.

1.2 AIM OF THE PROJECT

RIVM commissioned Ecofys to conduct a study with the aim to:

- Provide the working group 'Regulation Climate Neutral Energy Carriers' with input for their discussion with the European Commission.
- Assist the RIVM in acquiring additional knowledge on climate neutral energy carriers.

To meet these objectives Ecofys has carried out the following tasks:

- Elaborate on the definition of 'climate neutral energy carriers'.
- Provide an overview of possible production chains of climate neutral energy carriers. Ecofys will focus on the production chains, which have the potential to be implemented on the short term or are already implemented abroad.
- Explore possibilities for the definition of system boundaries and references systems for climate neutral energy carriers.
- Quantify the additional costs and CO_2 reduction for five production chains of climate neutral energy carriers.
- Make an estimate of the reduction potential for the five production chains in the Netherlands.

1.3 APPROACH

The project roughly consisted of two phases:

1. In the *first* phase a discussion paper was drawn up. The paper held the definition of the research boundaries of the project, presented the concept of the production chain, included a long list of possible options for climate neutral energy carriers production chains and discusses aspects related to the definition of the system boundaries and the reference system. This paper was discussed at a workshop attended by members of the working group 'Regulation Climate Neutral Energy Carriers' and researchers of the RIVM. At this workshop the research boundaries of the project were further defined and five production chains for climate neutral energy carrier were selected for further quantitative elaboration.
2. In the *second* phase information was gathered on the five selected production chains for climate neutral energy carriers and the five chains were quantitatively elaborated with respect to emission reductions and additional costs. The information was gathered through literature research and by interviewing people who are currently developing projects in this field. On the basis of the quantitatively elaborated examples some general criteria were formulated regarding the choice of the system boundaries and the reference system.

1.4 STRUCTURE OF THE REPORT

- Chapter 2 starts with the definition of 'climate neutral energy carriers' used in this project, and introduces the concept of the production chain. Furthermore the chapters holds a brief description of the five examined production chains.
- Chapter 3 deals with the definition of reference systems and describes different applicable methods to determine the emissions in the reference system.
- Chapter 4 deals with the system boundaries of the examined production chains and analysis the contributions of each of the chain elements to the total changes in emissions compared to a chosen reference system.
- Chapter 5 analyses the costs of climate neutral energy carriers and compares them to the current prices of natural gas and electricity.
- Chapter 6 holds the conclusions.
- The annex includes an extensive overview of all the figures and assumptions used to execute the emission and cost calculations. Furthermore the annex provides an elaborated description of each of the production chains.

2 PRODUCTION CHAINS

2.1 DEFINITION OF 'CLIMATE NEUTRAL ENERGY CARRIERS'

The term "climate neutrality" of an energy carrier refers to the share of the energy carrier that can be marked as climate neutral. From the Terms of Reference for the project and the discussions at the workshop the following list of limiting conditions and definitions for climate neutral energy carriers was formulated. It was stated that the regulatory framework will apply to 'climate neutral' or 'climate extensive' energy carriers:

- Which are produced by means of fossil energy carriers in addition to which the CO_2 is stored or put to good use (no time limit has been set yet for the period the CO_2 should be stored or put to good use).
- Which are being delivered to end users to substitute energy carriers that fall under the regulatory energy tax. This means that a climate neutral energy carrier has to substitute either natural gas, electricity, domestic fuel oil, gasoline or LPG (the last ones as long as they are not used as transport fuel).
- Where CO_2 reductions resulting from the storage or use of the CO_2 are linked to the climate neutral energy carrier. This means e.g. that the CO_2 reduction may not be used to fulfil existing obligations or agreements.

These definitions and limiting conditions were the starting point for the construction and elaboration of the production chains for climate neutral energy carriers.

2.2 CONCEPT OF THE PRODUCTION CHAIN

Given the definition and limiting conditions listed in paragraph 2.1, seven chain elements can be distinguished in a production chain for climate neutral energy carriers. The different chain elements and their mutual dependence are displayed in Figure 1. The production chain includes:

1. *Extraction and production of the fossil energy carrier*. This means the extraction of coal, natural gas or oil.
2. *Transport of the fossil energy carrier*. This means the transport of coal, natural gas or oil.

3a. *Production of* two products a) the *climate neutral energy carrier* (e.g. hydrogen or electricity) and *CO_2 or carbon*. A variety of production technologies can be used to produce these two products simultaneously. For instance:

   - producing electricity with a coal-fired power plant and scrubbing the CO_2 from the flue gases,

- firing natural gas with pure oxygen in a gas turbine producing electricity and a pure CO_2 stream or reforming natural gas, and scrubbing the flue gas from a electricity or hydrogen production unit.

3.b *Compression of the CO_2*. In practise in all cases carbon dioxide needs to be transported and is required at high pressure.

4. *Transport* and/or distribution of the *CO_2 or carbon*.
5. *Storage of the CO_2 or carbon*. In this step the CO_2 is stored or put to good use. Examples are the use of CO_2 to extract methane from coal layers not economically accessible for coal mining through Enhanced Coal Bed Methane (ECBM), storage of CO_2 in aquifers and empty gas fields or the use of CO_2 for the production of methanol.
6. *Transport and distribution of the climate neutral energy carrier*.
7. *End-use of the climate neutral energy carrier*. This means the use of the climate neutral energy carrier by the end-user.

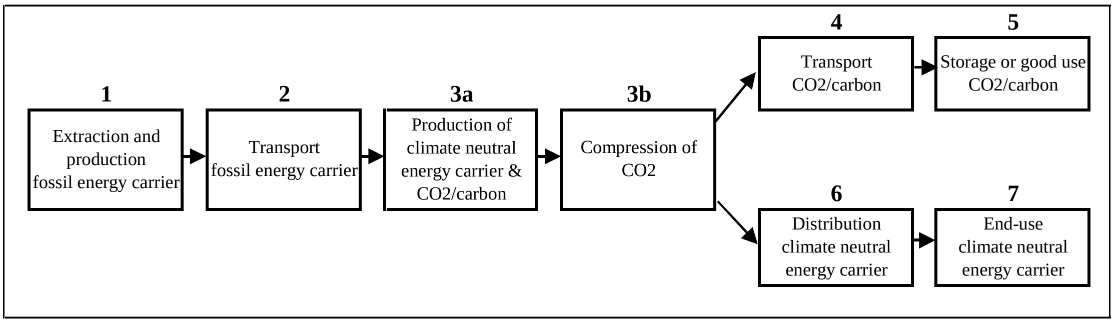


Figure 1: Chain elements in a production chain for climate neutral energy carriers

2.3 ENERGY SAVING VERSUS CO_2 REMOVAL

Applying energy saving and CO_2 removal are two ways to reduce emissions of CO_2 to the atmosphere. As energy saving projects in principle can not be applied[1] for support within the new regulation for climate neutral energy carriers it is important to make a clear distinction between energy saving and CO_2 removal. In some cases, however, it is not immediately clear whether a proposed "project" concerns a CO_2 removal project or that it should be considered an energy saving project. This paragraph presents a conceptual framework for classifying projects either as CO_2 removal or energy saving.

The principle of an energy saving project is that:

- after implementation of the project less energy is used to deliver the same amount of service.[2]

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[1] If the energy saving is already valued within the framework of other policy agreements such as the benchmark covenant or long term voluntary agreements a company may not be able to apply for support. In other cases this will be decided upon when the new regulation is drawn up (minutes Workshop 21 November 2001).

[2] Here the reference is project based. In chapter 3 other choices for reference are discussed. Also choices have to be made regarding system boundaries (further discussed in chapter 3).

Referring to Figure 2 this means that the amount of energy needed after implementation of the project to deliver a fixed amount of service (*energy_in(after))* is smaller than the amount of energy needed to deliver the same amount of service in the reference case (*energy_in(before)*). Assuming that the same fuel is used in both cases the CO_2 production after implementation of the project is smaller than in the reference case (i.e. *CO_2-production(after)* is smaller than *CO_2-production(before)*). Examples of energy saving projects are improving boiler efficiency, but also applying CO_2 from e.g. pure CO_2 sources as a fertiliser to reduce energy use in greenhouses.

The principle of a <u>CO_2 removal project</u> is that:

- less CO_2 is emitted after implementation of the project than before, and
- that the energy use after implementation of the project is larger than before implementation (i.e. *energy_in(after)* is larger than *energy_in(before)*) while generating the same amount of service).[3]

Assuming that in both cases the same fuel is used the CO_2 production in a CO_2 removal project is larger than in the reference case (i.e. *CO_2-production(after)* is larger than *CO_2-production(before)*). When the recovered CO_2 is <u>stored</u> (in any form) for a long-term[4], this results in an overall smaller emission (i.e. *CO_2-emission(after)* is smaller than *CO_2-emission(before)*). An example of a CO_2 removal projects is the recovery of CO_2 from a power plant and storage underground.

In some cases less energy is used (i.e. *energy_in(after)* is smaller than (*energy_in(before)*) and less CO_2 is emitted (i.e. *CO_2-emission(after)* is smaller than *CO_2-emission(before)*) <u>but</u> the reduction in CO_2 emissions is larger than would be expected from the decreased use in energy. Again under the assumption that the same type of fuel is used this means that two 'projects' are implemented at the same time: an energy saving and a CO_2 removal project. The boundaries of those two projects should be identified separately. An example is the use of a conventional power plant in the reference case and the application of a more efficient fuel cell power plant with CO_2 recovery in the project case.

[3] When the definition for a CO_2 removal project is restricted to the first bullet (using less energy), an energy saving project can be seen as a sub-category of CO_2 removal (in that case the carbon is/stays stored (underground) as e.g. natural gas or coal).

[4] The minimal period for storage is still under discussion.

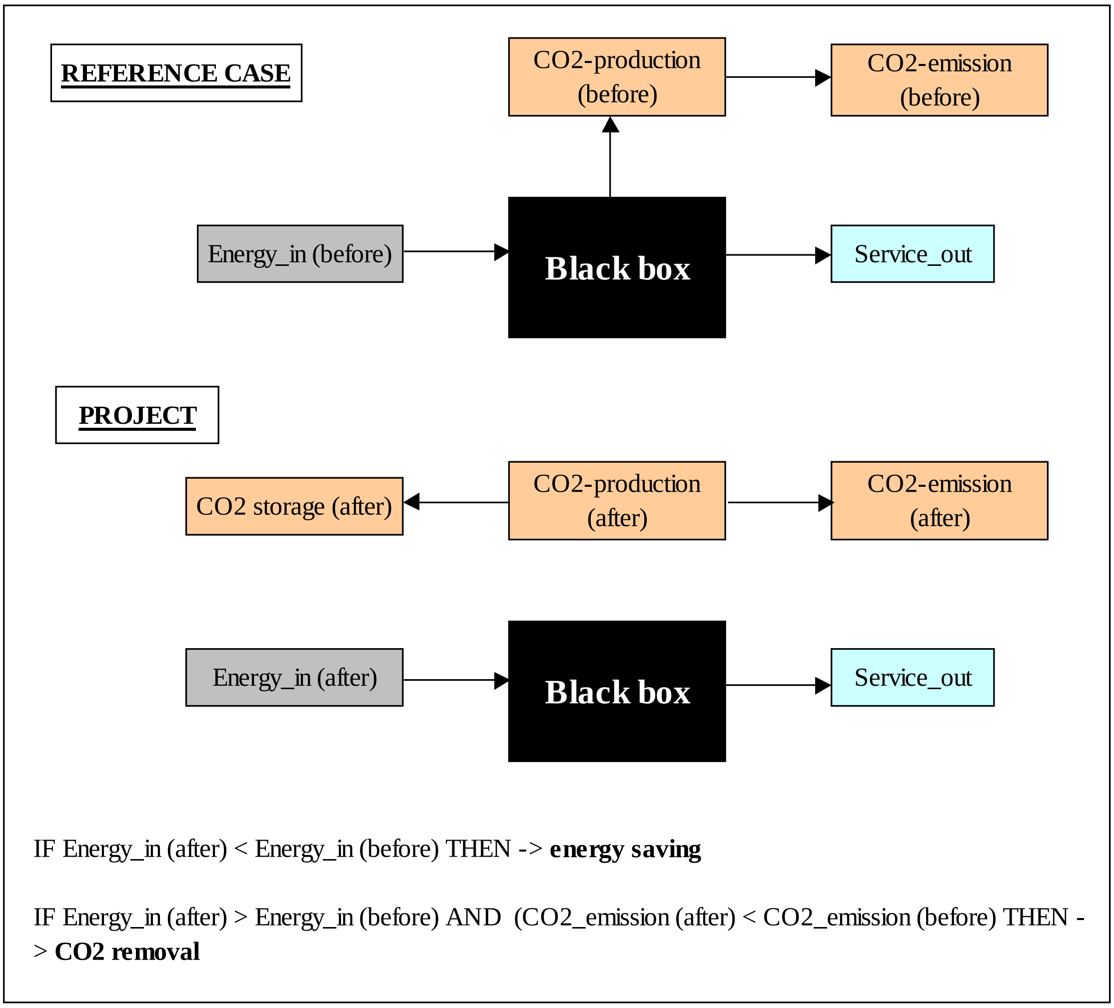

Figure 2: Outline of the difference between energy saving and CO_2 removal projects.

2.4 Emission Reductions and Additional costs

In order to be able to judge if a project qualifies for support within the new regulatory framework and determine the level of financial support the "climate neutrality" and the additional costs of a climate neutral energy carrier need to be determined.

The term "climate neutrality" of an energy carrier refers to the share of the energy carrier that can be marked as climate neutral. The "climate neutrality" is determined by the greenhouse gas emission reduction that can be obtained through application of a climate neutral energy carrier. The emission reduction is equal to the difference between the emissions in the (chosen) reference system[5] and the emissions of the production chain.

The additional costs of a climate neutral energy carrier are defined as the extra costs for the energy carrier compared to the costs for the fossil fuel (derived) energy carrier which is replaced by

[5] What is meant by reference system is explained in section 3.

the climate neutral energy carrier. The additional costs is the difference between the costs in the defined reference system and the costs for the project.

In order to be able to determine the absolute emission reductions and the additional costs choices have to be made with regard to:
- The reference system.
- The system boundaries.

2.5 Examples of Production Chains

Within this project five production chains (see Figure 1) were selected for further quantitative elaboration. A range of different techniques can represent the different elements in the production chain for a climate neutral energy carrier. Criteria for the selection of the chain elements were:
- Maturity of the applied technology both on the production and the consumption side. Only chain elements were selected which can make use of proven technologies and for which it can be expected that they can be implemented on the short term. This means that e.g. stationary fuel cells were not considered because large-scale implementation is not expected in the short term.
- Applicability and sufficient emission reduction potential for the Netherlands.

The final choice of the production chains for further elaboration was taken in close consultation with the RIVM and the working group on 'Regulation Climate Neutral Energy Carriers'. It must be stressed that in principle the chain elements can be chosen independently to put together the a complete production chain, i.e. that e.g. CO_2-storage in an aquifer in production chain #5 can easily be replaced by delivery of CO_2 for methanol production.

In the process of elaboration a few potential chains dropped out because it turned out that they did not fit within the framework of a climate neutral energy carrier. The C-fix[6] process of Shell was not further elaborated, because after consulting experts with Shell it turned out that no hydrogen is produced together with the C-fix, i.e. the carbon storage can not be linked to an energy carrier which can be supplied to end-consumers. Furthermore the carbon black process of Kvaerner has been analysed, but the results are only represented in the Annex (PC6). In order to be able to made calculations for this process many assumption had to be made, which makes this process unsuitable for drawing general conclusion on the criteria for climate neutral energy carriers.

Table 1 holds a brief description of the production chains (PC) which are quantitatively elaborated. A detailed description of each of the production chains is included in the **Annex**.

[6] C-fix is a product produced from heavy fraction of fuel oil. The material can be used as glue to form with sand and aggregate a product with properties between asphalt and concrete. The material fixes 1 kg CO2-equivalent in each 4 kilo material. CO2 emissions are avoided because the heavy oil fraction are normally combusted, e.g. in ships (http://www.eet.nl/projecten/index.htm)

Table 1: Short description of the examined production chains

<table>
<tr><th>Code</th><th>Production facility</th><th>Storage/use of CO_2/Carbon</th><th>Climate neutral energy carrier</th></tr>
<tr><td>PC1</td><td>Natural Gas Reforming + fuel gas recovery</td><td>Storage in coal layers combined with ECBM</td><td>Hydrogen (in NG-grid)</td></tr>
<tr><td colspan="4">➢ Reforming of the natural gas into hydrogen and carbon dioxide, including the recovery of the carbon dioxide from the fuel gases. This is in principle the concept ProtonChemie wants to apply in the former fertiliser factory in Rozenburg.
➢ The CO_2 is stored in coal layers, which are not profitable for coal mining, and simultaneously methane is produced from the coal layers.
➢ The produced hydrogen is put into the natural gas grid and delivered to the end-users.</td></tr>
<tr><td>PC2</td><td>Coal gasification + fuel gas recovery</td><td>Storage in empty NG field</td><td>Hydrogen (in NG-grid)</td></tr>
<tr><td colspan="4">➢ Coal is converted in a gasifier to synthesis gas of which the main components are hydrogen and carbon monoxide. The carbon monoxide is converted to carbon dioxide by the water-gas shift reaction and recovered from the fuel gases.
➢ The CO_2 is stored in an empty natural gas field.
➢ The produced hydrogen is put into the natural gas grid and delivered to the end-user.</td></tr>
<tr><td>PC3</td><td>Coal combustion with pure O_2</td><td>CO_2 used in production of methanol</td><td>Electricity</td></tr>
<tr><td colspan="4">➢ Combustion of coal with pure O_2 at high temperatures to produce electricity and delivering a concentrated stream of CO_2 (The concept of the ‘zero emission plant’ as developed by ZEST).
➢ The CO_2 is supplied to a methanol production plant, to replace part of the natural gas.
➢ The electricity is supplied to the grid and delivered to the end-users.</td></tr>
<tr><td>PC4a</td><td>Flue gas recovery of coal-fired power plant</td><td>CO_2 used in greenhouses + storage</td><td>Electricity</td></tr>
<tr><td>PC4b</td><td>Flue gas recovery of natural fired power plant</td><td>CO_2 used in greenhouses + storage</td><td>Electricity</td></tr>
<tr><td colspan="4">➢ Two cases are examined: a) combustion of coal in a conventional coal-fired power plant and b) combustion of natural gas in a combined cycle (STEG in Dutch). In both cases the CO_2 is recovered from the flue gases and the electricity is delivered to the grid.
➢ In the three summer months the CO_2 is delivered to greenhouses (25% of the recovered CO_2) and 75% of the CO_2 is stored in an empty gas field.
➢ The electricity is supplied to the grid and delivered to end-users.</td></tr>
<tr><td>PC5</td><td>Natural processing
(recovery of abundant CO_2)</td><td>Storage in aquifer</td><td>Natural gas</td></tr>
<tr><td colspan="4">➢ Processing of natural gas by removing CO_2 in order to meet the required specification, and recovery of the abundant CO_2.
➢ Storage of the CO_2 in an aquifer.
➢ Delivery of the natural gas to the end-user.
(This is the concept currently already operated by Statoil).</td></tr>
</table>

3 REFERENCE SYSTEMS

3.1 Definition

The main question is how much greenhouse gas emissions are reduced due to the production and use of a climate neutral energy carriers. The reduction can be calculated by comparing the climate neutral production chain by a reference system. The ‘reference system’ is defined as the amount of greenhouse gases that would have been emitted and the costs that would have been made in the absence of the project. The reduction of greenhouse gas emissions and additional costs due to the implementation of a production chain can be calculated by comparing the emission and costs of the production chain with the emission and costs in the reference system.

3.2 Multi-project versus project specific approach

Different methods and approaches can be applied to determine the emissions and costs in the reference systems. In principle two different approaches can be applied the multi-project approach and the project specific approach.

1. In the multi-project approach generic emissions factors and cost figures for a certain activity are used to calculate the emission and generated costs in the reference systems. These generic emission and cost factors are project independent and can e.g. be derived from benchmarks. This approach is e.g. applied in the CO_2 reductionplan[7], where generic CO_2 emission reduction factors are given for different types of projects
2. In the project specific approach the emissions and costs in the reference system are calculated with project specific assumptions or measurements for all important project parameters. E.g. emission factors of one specific electricity production plant are used because it can be argued that the project replaces electricity generated by that specific plant. This approach is e.g. applied for project within EruPT[8] and PCF[9] where reference systems have to be defined for JI and CDM projects.

[7] Uitvoeringsregeling subsidies CO_2 reductionplan (30 juni 1998/nr. WJA/JZ 98043171) (http://www.CO2reductie.nl/)
[8] EruPT: Emissions Reduction Unit Purchasing Tender (www.carboncredits.nl)
[9] PCF: Prototype Carbon Fund (Worldbank). (http://www.prototypecarbonfund.com/)

Applying different approaches

For the production of climate neutral electricity by means of a coal-fired power plant and storage of the CO_2 in empty gas fields roughly three different approaches can be applied to calculate the emissions in the reference system:

1. The electricity generated with the project replaces the average produced electricity in the grid (e.g. the Dutch grid or the European grid);
2. The electricity generated with the project replaces electricity produced by a specific technology mix (e.g. the average public mix, industrial power or a specific technology e.g. a combined cycle unit);
3. The electricity generated by the project replaces electricity generated by a specifically defined plant (e.g. due to the implementation of the project another (specific) power plant is closed down or not erected).

When applying the different methods for production chain #3 (Power production with the zero emission plant) (see **Annex**) the amount of achieved CO_2 reduction per kWh ranges from

- 0.2 kg CO_2-eq/kWh when using the combined cycle as a reference system,
- 0.4 kg CO_2-eq/kWh when using the average production mix in the Netherlands, and
- 0.7 kg CO_2-eq/kWh when applying the project specific approach,

For the production of climate neutral hydrogen by means of natural gas reforming and storage of the CO_2 in an aquifer the reference system is defined as th use of natural gas. The emissions in the reference system can be calculated by taking the emissions of greenhouse gases for the production of natural gas in the Netherlands. In this case only a multi-project approach can be applied and the emission reduction per GJ hydrogen ranges from 43 kg CO_2-eq /GJ for PC1 to 27 kg CO_2-eq /GJ for PC2 (for comparison natural gas has an emission factor of 60 kg CO_2-eq /GJ when including the emissions in all stages).

From practical experiences gained with the two approaches the following conclusions can be drawn:

- In general the project specific approach provides a better approximation of the emissions and costs in the reference systems than the multi-project approach.
- The transaction costs for the multi-project approach are lower than for the project specific approach, because less time is needed for data gathering.
- The consistency and transparency between different projects can be better guarded in the multi-project than in the project specific approach, because it is always clear which generic emission and cost factors have been used.

3.3 Static versus (Semi-) Dynamic approach

The emissions and costs in the reference system have to be determined for each year the project is in place, i.e. over the whole lifetime of the project. Three different approaches can be applied:

- Static approach: In the static approach the emission- and cost-factors (e.g. a benchmark) in the reference system stay on the same level over the lifetime of project or the regulation.
- Dynamic approach: In the dynamic approach the emission- and cost-factors in the reference

system changes depending on the autonomous technological development over the lifetime of the project or regulation.

- Semi-dynamic approach: In the semi-dynamic approach the emission and cost factors changes depending on the technological development, however, these factors are kept constant for a (certain period) for a specific project.

Advantages and disadvantages of the three approaches are:

- The advantage of the static approach is that the project developer has clarity on the amount of reductions that he can realise over the whole lifetime of the project, this is not the case in the dynamic approach.
- The disadvantage of the static approach is that after a certain period the reductions and costs can be overestimated, because current best available technology becomes standard technology after a certain period and costs may have decreased.
- The advantage of the dynamic approach is that it holds incentives for further research into technological improvements, because this will increase the amount of reductions that can be achieved. The environmental effectiveness of the dynamic approach is therefore larger then for the static approach.
- The disadvantage of the semi-dynamic approach is that for the same year and for the same technology (but implemented in another year) different costs and emission reductions can apply (which may lead to inequality of justice).

3.4 CONCLUSIONS

Table 2 provides a summary of possible approaches that can be applied to determine the emissions and costs for the reference system.

Table 2: Overview of possible approaches to determine the emissions and costs in the reference system. The approaches in the shaded areas are applied in this study.

	Project-specific	**Multi-project**
Static and semi-dynamic	➢ Project specific measurements and assumptions on costs and emissions ➢ Factors constant over lifetime project and/or regulation	➢ Generic emission and cost factors ➢ Factors constant over lifetime project and/or regulation
Dynamic	➢ Project specific measurements and assumptions on costs and emissions ➢ Factors change depending on autonomous development.	➢ Generic emission and cost factors ➢ Factors change depending on autonomous development.

It can be concluded that the multi-project approach provides the best opportunities for transparent calculations of the additional costs and emission reductions. Furthermore it was indicated in the workshop that clarity on the amount of supports is very important for the investors. This would mean that the static approach would have to be applied. We therefore applied the static multi- and project-specific approach in the elaboration of the five examined production chains. The results show that the degree of ‘climate neutrality’ can be strongly influenced by the choice of the reference system.

4 SYSTEM BOUNDARIES

4.1 INTRODUCTION

To determine the "climate neutrality" of a produced climate neutral energy carrier purchased by the end-user in chain element 7, in principle all changes in the emissions of greenhouse gases in each chain element of the production chain must be determined. This means that in principle the system boundary is drawn around all 7 chain elements (See Figure 1 in section 2.2).

Including all 7 chain elements within the system boundaries requires a lot of calculation work and will probably not lead to a very practicable regulation. By means of the elaborated examples included in the **Annex** this chapter analyses

- in which chain elements the largest changes in the emissions take place,
- under what circumstances certain changes in emissions can be neglected, i.e. under what circumstances can the system boundaries be simplified.

4.2 KEY FIGURES AND ASSUMPTIONS

Table 3 provides an overview of the key characteristics used for the emission calculations. The figures are derived from literature and collected within the framework of other project executed by Ecofys. References to the used literature sources are mainly included in the **Annex**.

Table 3: Summary of the key figures used for the emission calculations

	Coal	**Natural gas**	**Hydrogen**
Methane (kgCH4/GJ) [1]			
Extraction	0.38	0.02	n/a
Transport	0.00	0.00	n/a
Distribution	n/a	0.11	n/a
Energy use (MJ/GJ) [2]			
Extraction	10.0	20.0	n/a
Transport	17.2	10.0	n/a
Distribution	n/a	10.0	30.0
Combustion (kgCO2/GJ) [3]			
Coal	94		
Natural gas	56		
Methanol	61		

Electric efficiency power production	
Dutch park **[4]**	43%
Conventional coal-fired	42%
Conventional natural gas-fired	45%
Natural gas-fired combined cycle	55%
Gas engine	38%
Energy use [5]	
Compression of CO2 (MJe/kgCO2)	0.4
Transport of CO2 (kJe/kgCO2/km)	0.5
Storage of CO2 (kJe/kgCO2)	0
Transport of power (%)	5%
Lower heating value (MJ/m3)	
Natural gas	32
Hydrogen	10

[1] Hendriks and De Jager, 2001; **[2]** IVM, 1997; **[3]** VROM, 1997; **[4]** Novem, 1999; **[5]** Wildenborg et al, 1999

4.3 CHANGES IN EMISSIONS PER CHAIN ELEMENT

Figure 3 and Figure 4 show the contribution of each of the chain elements to the total achieved emission reduction when producing a climate neutral energy carrier. The figure shows the changes in emissions in each of the chain element of a production chain compared to (a) reference system(s) for each of the five elaborated production chains.

Figure 3 and Figure 4 show that the climate neutrality of the energy carriers lies in the range of 7% to 77% (black bars in the two figures). The figures show that the largest changes in emissions take place either in the stage of production (chain element 3) for projects where electricity is produced or at the end user (chain element 7) in cases where hydrogen is produced. Depending on the type of project and the reference used smaller or larger changes in emissions take place in other chain elements. This chapter will examine in which cases it is possible to neglect the changes in emissions in these chain elements.

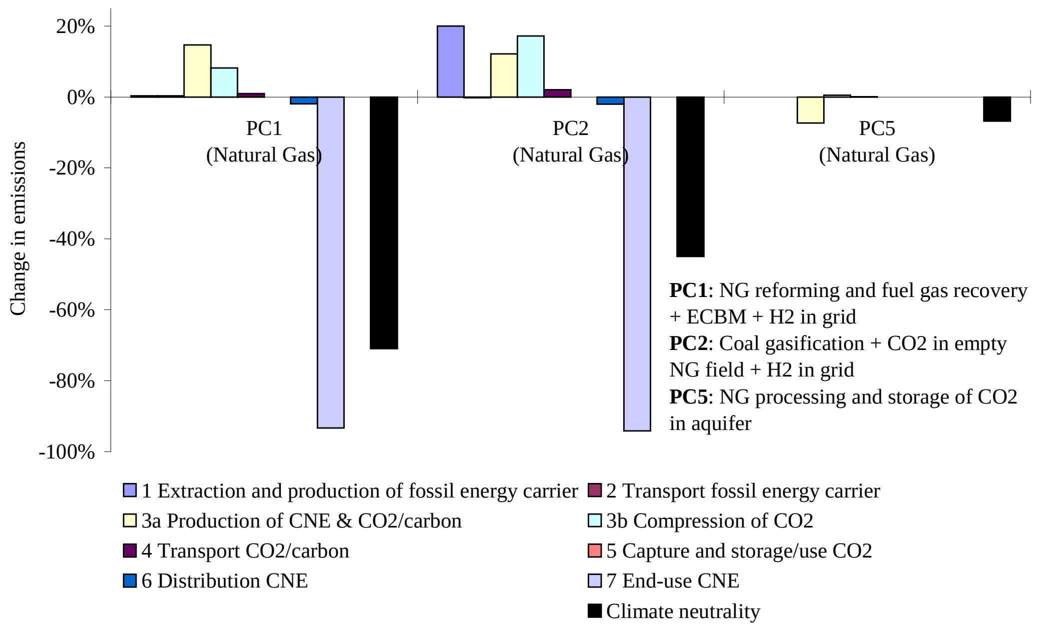

Figure 3: Changes in emission in each of the chain elements for the production chain where hydrogen or natural gas is produced (the reference system for each of the chain elements is included in brackets)

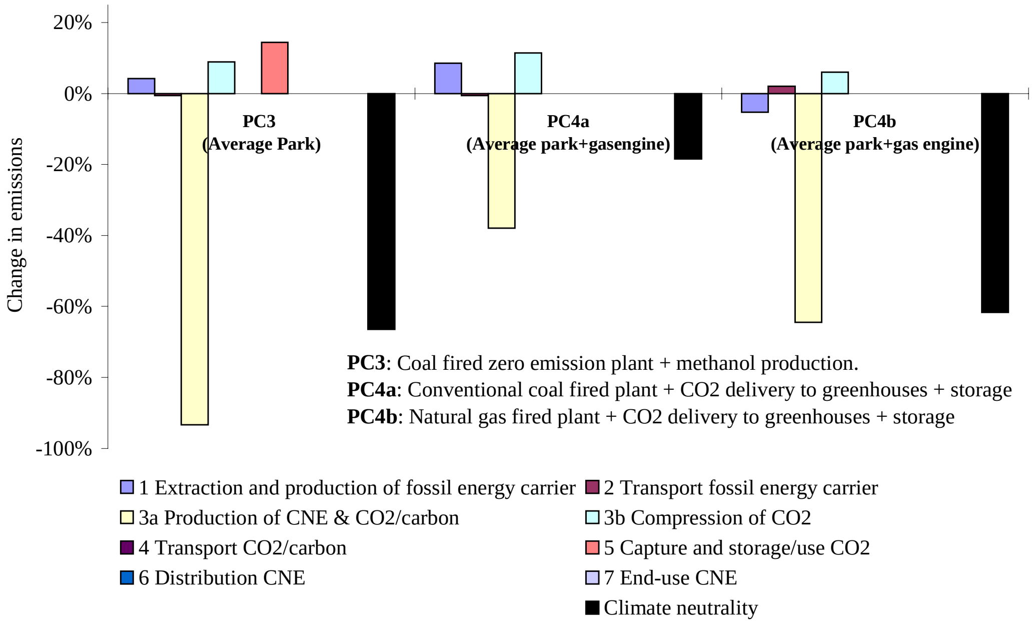

Figure 4: Changes in emission in each of the chain elements for production chains where electricity is produced (the reference system for each of the chain elements is included in brackets)[10].

4.3.1 Chain element #1 and chain element #2

- Chain element 1 (CE1): extraction and production of fossil energy carrier.
- Chain element 2 (CE2): transport of fossil energy carrier.

Application of CO_2 recovery requires additional input of fossil fuels, i.e. additional mining (CE1) and transport (CE2) of the energy carrier is needed compared to the situation where no climate neutral energy carrier is produced. The emissions of greenhouse gases in CE1 and CE2 mainly comprise emissions of methane. The emission of CO_2 resulting from the energy use for extraction and transport of the fossil energy carrier are negligible.

Table 4 shows the emission factors of methane for coal, oil and natural gas per GJ of fuel for the extraction and transport phase.

[10] For production chain #4 the cases are included in which most CO_2 is reduced the other cases will be discussed in section 4.3.3.

Table 4: Methane emission factors for extraction and transport for three different fossil fuels (Sources: [Hendriks, 2001], [Jager de, 1996])

Fuel	**Emission factor for extraction and production (chain element 1)**	**Emission factor transport (chain element 2)**
Coal	8.1 kg CO_2-eq/GJ of coal[1].	0.007 kg CO_2-eq/GJ of coal.km[5]
Natural gas	0.5 kg CO_2-eq/GJ of natural gas[2]	0.07 kg CO_2-eq/GJ of natural gas[3]
Oil	2.0 kg CO_2-eq/GJ of oil[4]	

[1] This is the average factor for Western European coal mining for all coal and lignite. Large variation exits. Emissions from deep coal mining may go up to over 25 kg of methane per Mega gram (tonne) of coal. Open cast mining generally causes very low methane emissions. Emissions from coal stock are relatively low and not included in the calculations (Hendriks et al, 2001).

[2] This is the average factor for the Netherlands. For natural gas this factor ranges from 1.5 kg CO_2-eq/GJ for offshore fields and 0.12 CO_2-eq/GJ for onshore fields. The factors can differ substantially on a country by country basis e.g. for the Russian Federation emission factors are estimated to be much higher up to 14 kg CO_2-eq/GJ of natural gas.

[3] Excluding the emissions in the distribution system.

[4] This is the average factor for the Netherlands.

[5] The indirect emissions from transport are low. Shipping over a distance of 5000 km contributes to less than 1% of the total greenhouse gas emissions of electricity production through a coal-fired power plant.

The methane emission factor can differ substantially between the different types of fossil fuels e.g. the emission factor for coal is 4 to 16 times higher than for natural gas and oil. The examined production chains show that in the cases where the type of fossil fuel for the production of the climate neutral energy carrier is the same as the type of fossil fuel used in the reference system, the changes in emission in the extraction phase due to the additional energy use.. For instance, in PC1 hydrogen is produced from natural gas. It is assumed that in the reference system natural gas would have been used. The increase in methane emissions in the extraction phase, due to the extra natural gas needed to produce the hydrogen and to recover the CO_2, contributes to less than 1% of the total changes in emissions. On the other hand in PC2 hydrogen is produced from coal but at the end-users' site replaces natural gas. In this case the increase in methane emissions in the in the extraction phase, due to the extra coal needed to produce the hydrogen and to recover the CO_2, can contribute up to 20% in the total change in emissions. This is caused by the fact that the methane emissions per GJ of coal exceeds the methane emission per GJ of natural gas by a factor of 16.

It can be concluded that when the type of fossil fuel used for the production of the climate neutral energy carrier differs from the fuel used in the reference system (fuel shift), changes in methane emissions in the extraction phase can not be neglected (see also Figure 3 and Figure 4).

Table 4 shows that the methane emissions in the transport phase (CE2) are very low, assuming that Dutch natural gas is used and not e.g. gas from the Russian Federation where the level of methane emissions in the transport phase can be much higher (de Jager *et al*, 1996). Figure 3 and Figure 4 show that the increase in methane emission in the transport phase due to the additional energy use for the production of a climate neutral energy carrier is very small compared to the total change in emissions (<1%).

4.3.2 Chain element #3a and chain element #3b

- Chain element 3a (CE3a): production of climate neutral energy carrier & CO_2/carbon
- Chain element 3a (CE3a): compression of the recovered CO_2

Without exception the bulk of additional energy needed for the production of a climate neutral energy carrier is required in chain element 3. The additional energy is needed to recover the CO_2 (CE3a) and to compress (CE3b) the recovered CO_2 to the transport pressure of about 12 MPa.[11]

For production of hydrogen (PC1 and PC2) 30% to 50% additional energy is needed for the recovery of the CO_2 compared to the reference system in which natural gas in used. In case of the production of climate neutral electricity (PC3 and PC4) the electrical efficiency decreases with 5% to 7%-points compared to the project specific reference case where the CO_2 is not recovered (i.e. an additional energy use of 11%-16%).

The electricity needed for the compression of the CO_2 leads to a CO_2 emission of 0.07 kg CO_2 per kg of CO_2 compressed. The increase of the CO_2 emission due to the compression energy is between 4% and 18% compared to the reference system.[12]

4.3.3 Chain element #4

- Chain element 4 (CE4): transport of recovered CO_2/carbon.

Pipeline transport of CO_2 requires about 1 kJe/km.kgCO_2. In the examined production chains it was assumed that the transport distance is 100 km (except for PC5 (natural gas processing) where a distance of 20 km is assumed) and the electricity is obtained from the grid. In that case the changes in CO_2 emission due to the energy needed for the transport of CO_2 is smaller than 2%.

4.3.4 Chain element #5

- Chain element 5 (CE5): storage or use of the CO_2 or carbon.

The changes in emissions in this chain element depend on the assumptions made with regard to the application of the CO_2 or carbon:

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[11] 1 MPa = 10 bars.

[12] Assuming the electricity is derived from the grid (using average emission factor for Dutch power generation).

- PC1, PC2 and PC5: Injecting CO_2 in an empty gas field or aquifer requires relatively little energy and the contribution to changes in the total greenhouse gas emissions are typically less than 1%.
- PC3: When using the CO_2 in the methanol production only 88% of the CO_2, which is recovered in chain element #3, is stored effectively in the methanol[13]. Depending on the choice of the reference system this emission contributes between 12% (in the project specific reference system) and 26% (in case the combined cycle is the reference system) to the total changes in greenhouse gas emissions.
- PC4: For this production chain it is assumed that the CO_2 will be delivered to greenhouse horticulture in the summer months (25% of the recovered CO_2) and that the remaining part of the CO_2 will be stored in an empty gas field. When using the recovered CO_2 in greenhouses this CO_2 is taken up by the crops and emitted after the crops have been consumed, i.e. the crops can not be considered as a long-term carbon sink. CO_2 emission reduction can be achieved because the gas engine or boiler does not need to operate during periods CO_2 is required when there is no good use for the heat.[14] The analysis shows that the choice of the power production facility (natural gas-fired or coal-fired) and especially, the choice of the reference system at the greenhouse (gas engine or boiler) determines the change in the level of greenhouse gas emissions between the production chain and the reference system. In some cases even a negative emission reduction is obtained, i.e. the production chain emits <u>more</u> CO_2 than in the reference system.[15] Table 5 shows that changes in CO_2 emissions highly dependent on the choice of the reference system and the type of fossil fuel that is used to produce the electricity and CO_2.

[13] In this case the use of the methanol was kept outside the system boundaries, i.e. the emission of methanol in a later stage where not considered.

[14] According to the concept presented in 2.3 this project is an ‘energy saving’ project.
[15] Within the Dutch OKEP project possibilities to deliver CO_2 from the Shell Pernis refineries has been examined. In this project the same reference is used as ref 5 in Table 5.

Table 5: Greenhouse gas emissions per unit of delivered electricity for production chain # 4 and for different reference systems. The grey shaded areas mark the cases in which the greenhouse gas emission in the production chain are lower than in the reference case.

	CO_2 emissions (kg CO_2-eq/kWh)			
	PC4a Coal-fired		PC4b Natural-gas fired	
Emission in the **production chain**	0.49		0.23	
Emission in the different **reference systems**: [Reference for Electricity production + Reference for CO_2 prod. at greenhouse]				
Ref 1: Coal fired power plant + gas engine	0.80	39%	0.86	73%
Ref 2: Coal fired power plant + boiler	1.15	58%	1.04	78%
Ref 3: Average park + gas engine	0.62	21%	0.62	63%
Ref 4: Average park + boiler	0.86	43%	0.75	69%
Ref 5: Combined cycle + gas engine	0.46	-5%	0.43	47%
Ref 6:Combined cycle + boiler	0.62	22%	0.51	55%
PC4a: Power production with a conventional **coal-**fired plant (efficiency 35%), with flue gas recovery and part (25%) CO_2 delivery to greenhouses and part (75%) storage in empty gas field **PC4b**: Power production with a conventional **natural gas-fired** plant (efficiency 40%), with flue gas recovery and part CO_2 delivery to greenhouses and part storage in empty gas field				

4.3.5 CHAIN ELEMENT#6

- Chain element 6 (CE6): distribution climate neutral energy carrier

For the examined production chains the changes in the emissions in the distribution system contribute up to 5% to the total emission reduction. For the production chains where hydrogen is produced it is assumed that three times as much energy is needed for the distribution of hydrogen than for natural gas[16]. The increase in CO_2 emissions due to extra energy use is however offset by the reduction of methane emissions in the distribution system, leading to a net decrease of the emissions in the distribution system compared to the reference system.

4.3.6 CHAIN ELEMENT#7

- Chain element (CE6): end-use climate neutral energy carrier

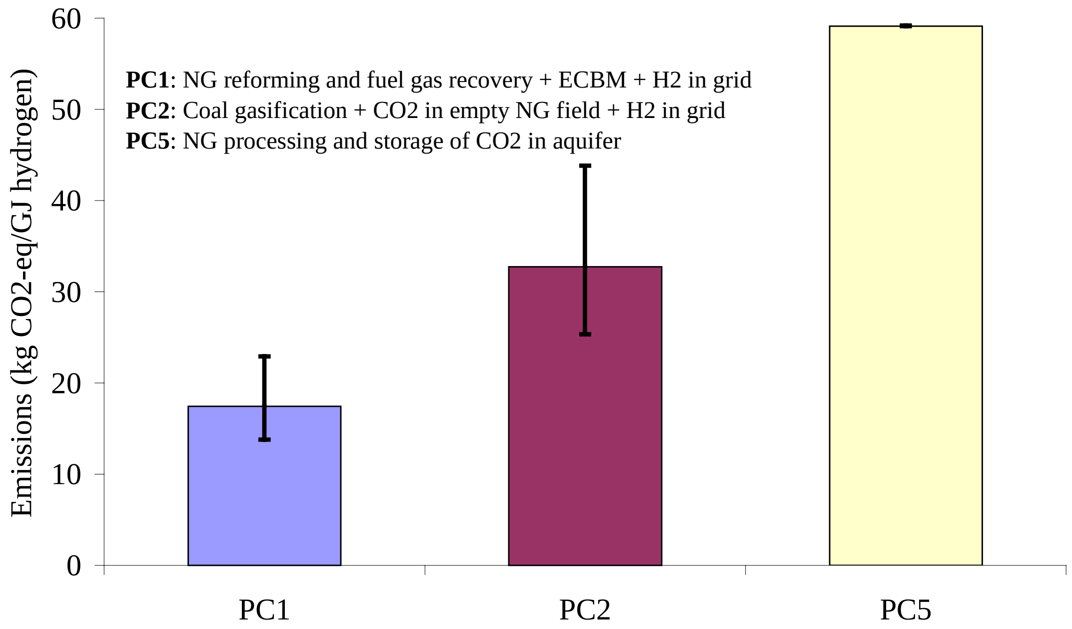
For the production chains where hydrogen is produced the largest contribution to the total change in emission takes place in this chain element (because hydrogen replaces natural gas). For the production chains where electricity is produced no change in emission occur (because electricity

[16] The energy content (GJ/m^3) of natural gas is about three times higher than the energy content of hydrogen.

replaces electricity). It is assumed that the hydrogen is applied by the end-user with the same efficiency as natural gas. This means that no *additional* changes in emissions will be achieved in this chain element[17]..

4.4 UNCERTAINTY IN THE EMISSION CALCULATIONS

In the examined production chains sometimes a 'best-guess' has been made with regard to efficiencies, additional energy use and emission factors. The outcome of the calculations are most sensitive to the values taken for the efficiency of the production facility (either the efficiency of the reforming process, the power production or the gasification) and the recovery rate of the CO_2. Therefore an analyses was carried out in order to determine the range in resulting greenhouse gas emissions per unit of delivered energy carrier for the 5 production chains, when varying the efficiency of the production facility (either 20% above of below the best guess level) and the recovery rate (either 2%-points above or below the best guess level). The results in Figure 5 show that with these assumptions the emission factors are 20% above or below the 'best-guess' levels.



[17] Additional emission reductions can be obtained when hydrogen is used more efficiently e.g in a fuel cell.

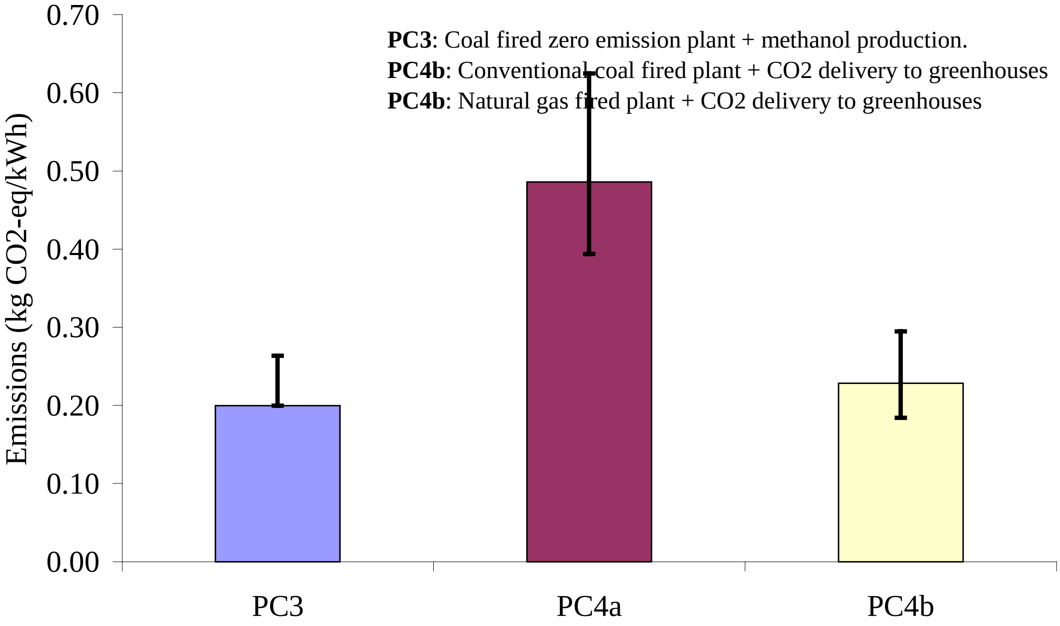


Figure 5: Greenhouse gas emission per unit of delivered energy carrier in the 'best guess' case and when assuming either a higher or a lower production efficiency and recovery rate.

4.5 Conclusions

- The emissions from the total production chain of climate neutral hydrogen ranges from 17 to 33 kg of carbon dioxide equivalents per gigajoule. For comparison, the emissions of natural gas amount to 60 kgCO_2-eq/GJ. Assuming that the hydrogen replaces natural gas, the climate neutrality amounts to about 71% when natural gas is used as feedstock, and amounts to about 46% when coal is used.
- The greenhouse emissions from the total production chain of climate neutral electricity amounts to between 0.2 and 0.5 kg of carbon dioxide equivalents per kWh. For comparison, the emissions of electricity production facilities currently in operation range from 0.4 to 1.1 kgCO_2/kWh. The climate neutrality ranges from 20% to 75%, depending on the storage/application of the CO_2 and the assumed reference for electricity production.

In principle in each chain element changes in emissions take place due to the production of a climate neutral energy carrier. Our analysis shows that:

- Changes in emissions in chain element 2 (transport of the energy carrier), chain element 4 (transport of the CO_2/carbon) and chain element 6 (distribution of the energy carrier) together contributes less then 2% to the total changes in emissions compared to the reference system. By neglecting changes in these chain elements, the 'climate neutrality' of the energy carrier would be affected (either an increase or decrease) by a maximum of 2%-points.
- Changes in emissions in chain element 1 (extraction of the energy carrier) due to the additional energy needed for the production of a climate neutral energy carrier is very small in

those cases where both in the production chain and in the reference system the same fossil fuel is used. By neglecting these changes the climate neutrality of the energy carrier would increase with a maximum of 1-% points. However if the methane emission factor of the fossil fuel used for the production of the climate neutral energy carrier differs substantially from the methane emission factor of the fossil fuel used in the reference systems (e.g. coal compared to natural gas) the contribution to the total change in emission can amount to 20%.

- Chain element 3 (production of the energy carrier) is the most important element to consider with respect to additional energy use to recover the carbon dioxide or carbon. In case of production of hydrogen the additional energy use can contribute up to 30% of the total changes in greenhouse gas emissions. In case of electricity production the additional energy use very much depends on the choice of the efficiency in the reference system. In the examined production chains the minimum additional energy use amounts to 20%.
- The storage of CO_2 in the underground (aquifer, gas field or coal field) in chain element 4 requires little energy, the contribution of the CO_2 emissions deriving from this energy use to the total changes in emission can be neglected (<1%). In cases where the CO_2 is applied in other production processes it has to be carefully analysed, which part of the CO_2 is stored in the product and which part of the CO_2 is emitted to the atmosphere.
- The outcomes of the emission calculations are mainly sensitive to assumptions with regard to the efficiency of the production installation and the recovery rate of the CO_2.

5 ADDITIONAL COSTS

5.1 INTRODUCTION

The additional costs for a climate neutral energy carrier are the difference in production costs for the climate neutral energy carrier and the conventional energy carrier. The production costs for a climate neutral energy carrier can be split into three parts:

- Investments: once-only costs for the production facility, the CO_2 storage facility and the infrastructure.
- Operation and maintenance costs (O&M).
- Energy costs

By choosing the appropriate technical lifetime and discount rate the costs for the production of one unit of climate neutral energy carrier is determined by:

$$cost^{CNE} = \frac{(annuity\ factor \times investments) + O\&M + energy\,cost}{delivered\,energy} \quad \left[\frac{Euro}{GJ}\,or\,\frac{Euro}{kWh}\right] \quad \text{Eq. 5.1}$$

The discount rate and the depreciation period determine annuity factor.

The costs of the reference system might be the average costs of the production of the energy carrier in the Netherlands, but also the costs for a specific project (e.g. the same type of technology but without CO_2 removal).

The specific emission reduction costs expressed in euro/Mg CO_2 avoided can be determined by:

$$specific\,reduction\,cost = \frac{cost^{CNE} - cost^{ref}}{emission\ factor^{CNE} - emission\ factor^{ref}} \quad \left[\frac{Euro}{Mg\,CO_2}\right] \quad \text{Eq. 5.2}$$

5.2 STARTING POINT FOR THE COST CALCULATIONS

End-user and national cost method

The costs are presented according to two different methods described in VROM (1998):

1. End-user costs: The aim of this method is to determine the costs of the energy carrier for the end-user (in our case end-user that has to pay the regulatory energy tax). In this method calculations are made with energy prices including RET and excluding VAT[18] and the annuity factor is calculated by using an 8% discount rate for investment done by the government and 15% for companies.
2. National costs: The aim of this method is to determine the costs for the Netherlands as a whole. This method is applied in order to make different type of reduction options in different sectors comparable (e.g. the in order to be able to compare the reduction costs of PV panels with the reduction costs when applying climate neutral energy carriers). In this method calculations are made with energy prices excluding energy tax and VAT. Furthermore a social discount rate is applied in our case 5%.

The first method was used to calculate the costs of the climate neutral energy carrier (in euro/unit of energy delivered). The second method was used to calculate the specific reduction costs (in euro/Mg CO_2 avoided).

Lifetime of the investments

The investments are depreciated over the lifetime of the investments. It is assumed that installations will be depreciated in 25 years and infrastructure in 50 years. Furthermore it is assumed that a company will make the investment in infrastructure (i.e. not the government). In the end-cost method it is therefore assumed that all investments are depreciated with a discount rate of 15%.

Energy prices

Table 6 provides an overview of the energy prices used in the cost calculations.

Table 6 Energy prices used for the cost calculations (EnergieNed, 2000)

Prices (excluding VAT)		
Coal (for industry and power production)	1.70	euro/GJ
Natural gas (for industry and power production)	2.80	euro/GJ
Natural gas (for greenhouses)	5.26	euro/GJ
Electricity (for industry)	0.04	euro/kWh
Prices Consumers (excluding VAT)		
	Total	of which distribution
Natural gas (euro/m3)		
incl. Reg. Energy Tax	0.31	n/a
excl. Reg. Energy Tax	0.19	0.026
Electricity (euro/kWh)		
incl. Reg. Energy Tax	0.14	n/a
excl. Reg. Energy Tax	0.08	0.033

[18] The price also includes all kinds of other taxes that do not have to be paid by the end-consumer but ar e have to be paid by e.g. the producers or distributors.

5.3 End-use costs of Climate Neutral Hydrogen and natural gas

Table 7 provides an overview of the investment costs for the production facilities and infrastructure of the five production chains. The total investment costs for the production chains in which hydrogen or electricity is produced is in de range of 200 to 400 million euro. For the production chain where natural gas with a low carbon dioxide content is produced is about 45 million euro.

Table 7 Estimated absolute investments cost for the five examined production chains (for the assumed production volumes) differentiated between investments in the production facility and the infrastructure.

		Production facility	**Infra structure**	**Total**
		Meuro	Meuro	Meuro
PC1a	NG reforming and fuel gas recovery + ECBM + H_2 in grid*)	116	101	218
PC1b		204	101	306
PC2	Coal gasification + CO_2 in empty NG field + H_2 in grid	167	114	282
PC3	Coal-fired zero emission plant + methanol production.	157	47	204
PC4a	Conventional coal-fired plant + CO_2 delivery to greenhouses + storage	330	53	384
PC4b	Natural gas-fired plant + CO_2 delivery to greenhouses	173	38	211
PC5	NG processing and storage of CO_2 in aquifer	39	6	45

*) upper line in case use can be made of an existing production facility and lower line in case of investements in a new

Figure 6 provides an overview of the resulting costs for hydrogen and natural gas produced by means of the examined production chains. The costs are split into energy costs, capital costs and operation and maintenance costs. The calculated costs of hydrogen range from 13 to 16 euro/GJ of hydrogen, whereas the current price for natural gas for end-users (including energy tax and excluding VAT) is approximately 10 euro/GJ.

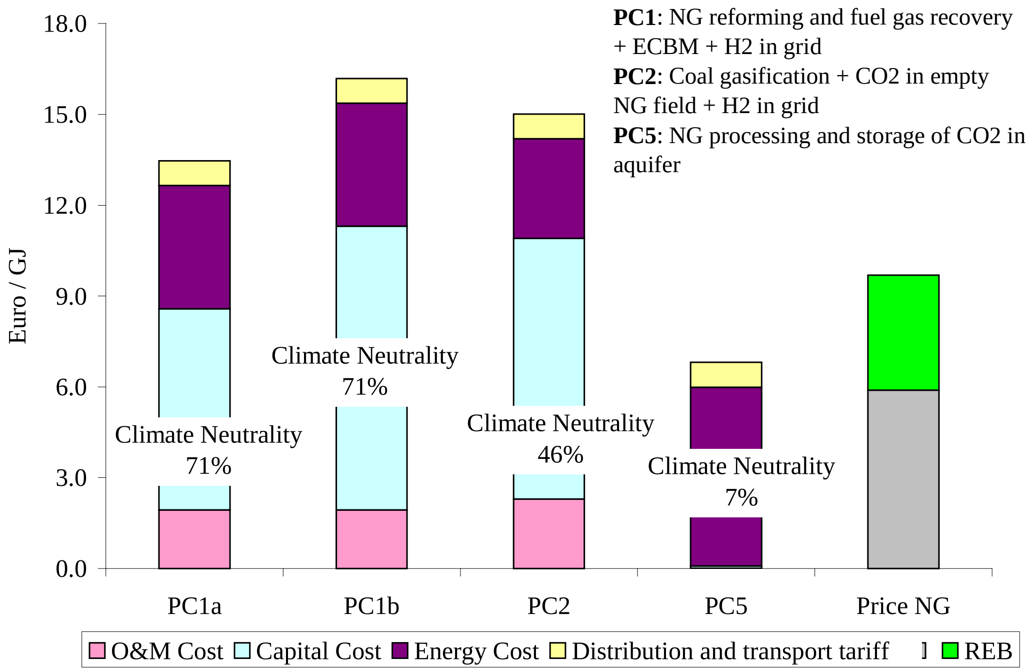


Figure 6: End-use costs for climate neutral hydrogen compared to the current end-user prices for natural gas (including energy tax and excluding VAT, i.e. approximately 30 euroct/m3)[19]

5.3.1 Production chain #1

The total costs for the production of hydrogen through production chain #1 are between 13-16 euro/GJ of hydrogen.

The energy costs in the total end-costs of hydrogen for production chain #1 are approximately 6.5 euro/GJ of hydrogen, this mainly includes the purchase of natural gas for the production in chain element #3.

The capital costs for production chain #1 include investments in

- the production facility. For production chain #1 two case have been examined:
  a) PC1a is the production chain in which use can be made of an existing production facility for the production of hydrogen. In this case 'limited' investments are needed at the production facility itself in order to get the production started.
  b) PC1b is the production chain for which it is assumed that investment have to be made in a complete new hydrogen production facility.
- compressors to compress the CO_2

[19] The cost calculations presented in the figure for PC1a (the ProtonChemie case) are based on the interview Ecofys had with two representatives of Proton Chemie. The cost figures will be updated after Proton Chemie has sent their business plan with more detailled figures to Ecofys.

- the infrastructure to distribute the hydrogen to a place where it can be put into the natural gas grid,
- the infrastructure to distribute the CO_2 to a place where it can be stored or used
- storage facility of the CO_2 in an empty coal field.

The total capital costs are 4.2 euro/GJ of hydrogen in case use can be made of an existing production facility and 7.0 euro/GJ of hydrogen in case of a newly built hydrogen plant. In both cases approximately 3 euro/GJ of hydrogen of these capital costs exist of investment in the infrastructure for the distribution of hydrogen and CO_2.

It must be stressed that the investment costs for the hydrogen transport system are surrounded by large uncertainties. Factors that determine the costs are e.g. transport distance and the possibility to situate the hydrogen transport lines close to existing natural gas transport systems. In case the hydrogen production facility is located downstream in the natural gas grid and the hydrogen has to be transported upstream in order to be able to mix it in the natural grid the costs for the infrastructure are substantial. In case of a newly built plant (part of) these costs can be avoided when the new production facility is build upstream (i.e. in the North of the Netherlands). The currently used figure was provided by Proton Chemie, and reflects the situation that the hydrogen has to be transported from Rozenburg to Beverwijk, a intensively used area.

The cost calculation are also sensitive to the assumptions made with regard to the scale of production of the hydrogen. For the calculation in Figure 6 we took the cost figures for a medium size hydrogen plant (annual production of 5 million GJ of hydrogen). If in case PC1b we assume large scale production (annual production of 10 million GJ of hydrogen) the investment costs of the hydrogen plant go down by 20 to 30% and the investment costs for the infrastructure increase but not proportional to the amount hydrogen produced. In the case of large scale production for PC1b the hydrogen price goes down to approximately 14.5 euro/GJ of hydrogen instead of 16 euro/GJ of hydrogen (doubling of the production leads to 10 to 15% lowering of the costs).

5.3.2 Production chain #2

The total costs for the production of hydrogen through production chain #2 is approximately 15 euro/GJ of hydrogen.

The energy costs (coal) in the total end-costs of hydrogen for production chain #2 are approximately 3.3 euro/GJ of hydrogen, mainly including the purchase of coal to produce hydrogen.

The capital costs for production chain #2 include the same items mentioned for production chain #1 with the exception that in this case

- the investment in the production facility consist of a coal gasifier.
- the CO_2 is stored in an empty gas field

The total capital costs are approximately 9 euro/GJ of hydrogen, this is higher than in production chain #1. This is caused by the fact that the investments to produce the same amount of hydrogen through coal gasification are higher than for the same amount of hydrogen by means of the natural gas shift reaction. Furthermore more CO_2 has to be recovered with the production of the same amount of hydrogen leading to higher costs for recovery, compression, transport and storage compared to production chain #1.

5.3.3 Production chain #5

The additional production costs for natural gas where the surplus of CO_2 is stored in a aquifer is approximately 0.1 euro/GJ of natural gas. This means that the price for the end-user only goes up marginally. The additional costs mainly consist of capital costs for the investments in hardware in order to be able to compress the CO_2 and investments for the transport and storage.

The additional costs are very sensitive to assumptions with regard to the scale of production. In our case we assumed an annual production of natural gas of 100 million GJ and an annual stored amount of 0.5 million kg of CO_2. In case the production is lowered by a factor of 10 the costs (per unit of natural gas) increase with a factor of 2.

5.4 End-use costs of Climate Neutral Electricity

Figure 7 provides an overview of the resulting costs for the climate neutral electricity by means of the examined production chains. The costs are split into energy costs, capital costs and operation and maintenance costs. The calculated costs of electricity range from 8 to 11 euroct/kWh. This is in the situation where the producer of the electricity delivers the CO_2 for free to the customer (either a methanol producer or a greenhouse grower). In case the customer of the CO_2 is willing to pay a price for the CO_2, equalling the marginal costs of the energy saved by the customer, the electricity price could drop to 5 to 9 euroct/kWh. For comparison the current price for electricity for end-consumers (including energy tax and excluding VAT) is approximately 14 euroct/kWh.

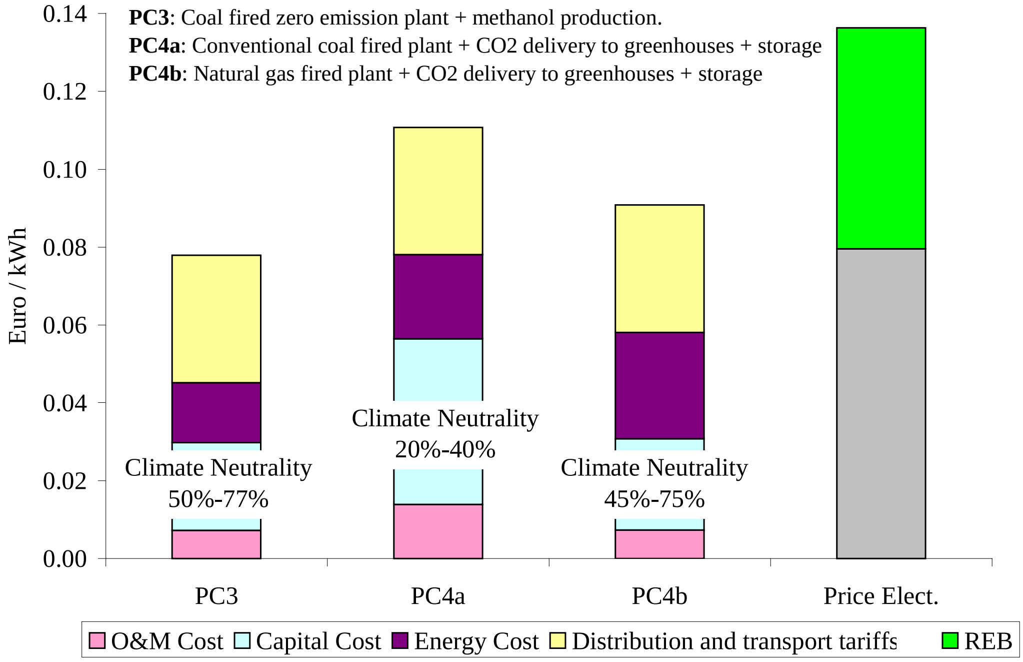


Figure 7: End-use costs for climate neutral electricity compared to the current end-consumer prices for electricity (including energy tax and excluding VAT, i.e. approximately 14 euroct/kWh).

5.4.1 Production chain #3

The total costs for the production of electricity by means of production chain #3 are approximately 8 euroct/kWh (in case the CO_2 is delivered for 'free' to the methanol producer).

The energy costs in the total end-costs of electricity for production chain #3 are approximately 1.5 euro/kWh, this mainly includes the purchase of coal for the production of electricity in chain element #3.

The capital costs for production chain #3 include investments in:

- the zero emission production plant. This includes investments in the production unit as well as the oxygen factory[20].
- compressors to compress the CO_2
- the infrastructure to distribute the CO_2 to the methanol producer.

The total capital costs are 2.3 euroct/kWh and the operation and maintenance costs amount to 0.7 euroct/kWh.

[20] The costs and efficiency of the zero emission plant is based on studies and seems to be optimistic. Currently a pilot/demo plant is planned in the USA.

If it is assumed that the methanol producer is willing to pay 50 euro/Mg of CO_2 (equalling his saving on energy costs), the electricity price could drop with 2.6 euroct/kWh leading to a price of 5 euroct/kWh.

5.4.2 PRODUCTION CHAIN #4

The total annual costs for the production of electricity by means of production chain #4 are between 10 euroct/kWh (in case of a coal-fired plant) and 11 euroct/kWh (in case of a natural gas-fired plant). In both cases it is assumed that the CO_2 is delivered for ‘free’ to the greenhouse growers.

The energy costs in the total end-costs of electricity for production chain #4 are approximately 2.2-2.9 euro/kWh, this mainly includes the purchase of coal or natural gas for the production of electricity in chain element #3.

The capital costs for production chain #3 include investments in:
- either a conventional coal fired power plant or a conventional natural gas fired power plant.
- investment in the recovery unit,
- compressors to compress the CO_2,
- the infrastructure to distribute the CO_2 to the greenhouses and the empty gas field.

The total capital costs amount to 4.3 euroct/kWh for the coal fired unit and 3.0 euroct/kWh for the natural gas fired unit.

If it is assumed that the greenhouse grower is willing to pay 92 euro/Mg CO_2 (equalling his saving on energy costs for a boiler)[21], the electricity price could drop with approximately 2 euroct/kWh leading to a price between 8.5 and 9 euroct/kWh.

5.5 SPECIFIC REDUCTION COSTS

The specific reduction costs (euro/Mg CO_2) are calculated using the national cost method, i.e.
- that the investments are depreciated with a discount rate of 5% and,
- that the saving on energy costs with the purchaser of the CO_2 (either the methanol producer or the greenhouse grower) are included in the calculations.

In order to be able to calculate the specific reduction costs (see formula 5.2 in section 5.1), the production costs for the energy carriers in the reference case were determined. The following reference prices for the different reference systems were calculated:
- Production of natural gas: 2.8 euroct/GJ
- Electricity production conventional coal fired power plant: 3.1 euroct/kWh
- Electricity production combined cycle: 3.2 euroct/kWh

[21] Assumed that 1 kg of CO_2 delivered to the greenhouse replaces 1 kg of CO_2 generated in a gas turbine; assuming a natural gas price of 0.165 euro/m^3.

- Electricity production average park: 3.1 euroct/kWh

Table 8 provides an overview of the specific reduction costs (euro/Mg of CO_2 avoided) for the five examined production chains in the different reference systems.

Table 8: Specific emission reduction costs for each of the production chains for different reference systems (euro/Mg of CO_2-eq.)

	Specific CO_2 emission reduction cost (Euro/Mg CO_2)		
	Low	**Average**	**High**
PC1: NG reforming and fuel gas recovery + ECBM + H_2 in grid	173	144	
PC2: Coal gasification + CO_2 in empty NG field + H_2 in grid		239	
PC3: Coal-fired zero emission plant + methanol production.	< 0	< 0	< 0
PC4a: Conventional coal plant + CO_2 greenhouses + storage	13	16	28
PC4b: Natural gas-fired plant + CO_2 delivery to greenhouses	5	9	16
PC5: NG processing and storage of CO_2 in aquifer		16	

The table shows that the specific reduction for the production chains where hydrogen is produced ranges from 150 to 250 euro/Mg CO_2-eq. The specific reduction costs for the production of climate neutral electricity depends on the choice of the reference system (i.e. on the climate neutrality of the energy carrier) and ranges from 30 euro/Mg CO_2-eq (when comparing the gas fired power plant with CO_2 removal with a combined cycle for electricity production and the delivery of CO_2 to a greenhouse grower with a gas engine) to < 0 euro/Mg CO_2-eq (when comparing the zero emission plant to a conventional coal fired power plant and delivery of the CO_2 to a methanol producer).

It must be stressed that the specific reduction costs for the examined production chains where electricity is produced are very sensitive to assumption regarding a) the energy prices in the reference system and b) the energy prices paid by the either the methanol producer and the greenhouse grower. E.g. when assuming that the energy prices in the reference system and the price paid by the consumer of the CO_2 are 20% lower than the ‘base case’, the specific reduction costs for production chain 4a and 4b go up with a factor 3 to 4. If the energy prices are assumed to be 20% higher than the ‘base case’ the specific costs are lower than 0 euro/Mg CO_2-eq.

5.6 CONCLUSIONS

The following conclusions can be drawn with respect to the costs for climate neutral energy carriers for the examined production chains:

- The production costs for climate neutral hydrogen (using a discount rate of 15%) range from 13 to 16 euro per gigajoule. This means that costs for producing climate neutral hydrogen (end-use costs, without REB) are between 30% and 40% higher than the current natural gas price of 9.7 euro/GJ paid by the small consumers (including energy tax and excluding VAT). Investment costs in the production facility and the infrastructure make up the largest share of the additional costs. Part of the investment costs for the infrastructure can be avoided in case a newly built plant is sited in such a way that the hydrogen can be mixed in the natural gas grid right away.

- The production costs for climate neutral electricity (using a discount rate of 15%) range from 5 to 11 eurocents per kWh. This means that costs for producing climate neutral electricity (end-use costs, without REB) are between 20% and 60% lower than the current electricity price of about 0.14 euro/kWh for small consumers (including REB, excluding VAT). The higher cost range (8-11 eurocents/kWh refers to the situation that the CO_2 is delivered for 'free' to the customers of the CO_2 (either a methanol producer or a greenhouse grower). If the customers are willing to pay a price for the CO_2 equal to the price of the energy that is being saved, the lower cost range applies, i.e. from 5 to 9 eurocents per kWh.
- The production costs are sensitive for the assumptions regarding the scale of production. In our analysis we assumed an annual production of 5 million gigajoule of hydrogen (equivalent to 158 million m^3 natural gas) or electricity (1390 million kWh). In case twice as much hydrogen is produced, the costs might drop by 10 to 15%.
- The specific reduction costs for climate neutral hydrogen range from 150 to 250 euro/Mg of CO_2 The specific reduction costs for climate neutral electricity is very sensitive to assumptions with regard to the energy price. The costs range from <0 – 30 euro/Mg of CO_2 avoided. However when assuming a 20% lower or higher energy price the costs range from <0 – 150 euro/Mg
- Based on the results of the examined production chains no clear relationship could be found between the climate neutrality and the production costs per unit of energy.

6 CONCLUSION

Main conclusions on emissions

- The emissions from the total production chain of climate neutral hydrogen amounts to between 17 and 33 kg of carbon dioxide equivalents per gigajoule. For comparison, the emissions of natural gas amount to 60 kgCO_2/GJ. The climate neutrality amounts to about 71% when natural gas is used as feedstock, and to about 46% when coal is used.
- The emissions from the total production chain of climate neutral electricity amounts to between 0.2 and 0.5 kg of carbon dioxide equivalents per kWh. For comparison, the emissions of electricity production facilities currently in operation amount to 0.4 and 1.1 kgCO_2/kWh. The climate neutrality ranges from 20 to 75%, depending on the technology and reference used.

Main conclusions on costs

- The production costs for climate neutral hydrogen (using a discount rate of 15%) range from 13 to 16 euro per gigajoule. This means that costs for producing climate neutral hydrogen (end-use costs, without REB) are between 30% and 40% higher than the current natural gas price of 9.7 euro/GJ paid by the small consumers (including energy tax and excluding VAT). The investments in the production facility and the infrastructure make up the largest share of the additional costs. Part of the investment costs for the infrastructure can be avoided in case a newly built plant is sited in such a way that the hydrogen can be mixed in the natural gas grid right away.
- The production costs for climate neutral electricity (using a discount rate of 15%) range from 5 to 11 eurocents per kWh. This means that costs for producing climate neutral electricity (end-use costs, without REB) are between 20% and 60% lower than the current electricity price of about 0.14 euro/kWh for small consumers (including REB, excluding VAT). The higher cost range (8-11 eurocents/kWh refers to the situation that the CO_2 is delivered for 'free' to the customers of the CO_2 (either a methanol producer or a greenhouse grower). If the customers are willing to pay a price for the CO_2 equal to the price of the energy that is being saved, the lower cost range applies, i.e. from 5 to 9 eurocents per kWh.
- The production costs are sensitive for the assumptions regarding the scale of production. In our analysis we assumed an annual production of 5 million gigajoule of hydrogen (equivalent to 158 million m^3 natural gas) or electricity (1390 million kWh). In case twice as much hydrogen is produced, the costs might drop by 10 to 15%.
- The specific reduction costs for climate neutral hydrogen lie in the range of 150-250 euro/Mg of CO_2. The specific reduction costs for climate neutral electricity is very sensitive to the assumptions with regard to the energy price. The costs range from <0 – 30 euro/Mg of CO_2 avoided.
- Based on the results of the examined production chains no clear relationship could be found between the climate neutrality and the production costs per unit of energy.

Sensitivity of results

- Emissions in chain element 1 and 2 can in most cases be neglected. However if the methane emission factor of the fossil fuel used for the production of the climate neutral energy carrier differs substantially from the methane emission factor of the fossil fuel used in the reference systems (e.g. coal compared to natural gas) the contribution to the total change in emission can amount to 20%.
- Chain element 3 (production of the energy carrier) is the most important element to consider with respect to additional energy use to recover the carbon dioxide or carbon. In case of production of hydrogen the additional energy use can contribute up to 30% of the total changes in greenhouse gas emissions. In case of electricity production the additional energy use very much depends on the choice of the efficiency in the reference system. In the examined production chains the minimum additional energy use amounts to 20%.
- The storage of CO_2 in the underground (aquifer, gas field or coal field) in chain element 4 requires very little energy, the contribution of the CO_2 emissions deriving from this energy use to the total changes in emission can be neglected (<1%). In cases where the CO_2 is applied in other production processes it has to be carefully analysed, which part of the CO_2 is stored in the product and which part of the CO_2 is emitted to the atmosphere.
- The total investment costs for the production chains in which in which 5 million gigajoule of hydrogen or electricity is produced is in de range of 200 to 400 million euro. For the production chain where 100 million gigajoule natural gas with a low carbon dioxide content is produced the total investment costs is about 45 million euro.

GLOSSARY

English	Dutch
Climate neutral energy carriers	Klimaatneutrale energiedragers
Decarbonization	Ontkoling
Enhanced Coal Bed Methane (ECBM)	Secundaire methaan winning uit kolenvelden
Enhanced Oil Recovery (EOR)	Secundaire oliewinning
Fuel gas	Stookgas
Flue gas	Rook
Production chain	Productie keten
Reference systems	Referentiesystemen
Regulation Climate Neutral Energy Carriers	Regeling klimaat neutrale energie dragers
Regulatory Energy Tax	Regulerende Energy Belasting (REB)
System boundaries	Systeemgrenzen

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1 ANNEX: DESCRIPTION OF PRODUCTION CHAINS

In this annex six different production chains (PC) of climate neutral energy carriers are discussed. The discussion comprises a description of the chain elements. For all PC's a detailed table about costs and tables on the basic assumptions are presented. Furthermore the cost methodology for compression and transport of carbon dioxide is presented in section ***2****.*

1.1 PC1: Hydrogen from NG and ECBM

- Steam reforming of natural gas followed by carbon dioxide recovery from synthesis gas Produced hydrogen is added to the natural gas grid
- Recovered carbon dioxide is stored in coal bed layers while producing natural gas

PC1: production of the climate neutral energy carrier.
Natural gas is reformed to a mixture of carbon monoxide and hydrogen. In a second step the carbon monoxide is shifted further with water to carbon dioxide and an extra amount of hydrogen. In a CO_2 recovery unit, the carbon dioxide is separated from the hydrogen.
Various processes have been developed and are commercially in use to produce hydrogen. Hydrogen is a major intermediate in the production of ammonia. In the conventional hydrogen production process, the natural gas is desulphurized. The conventional catalysts (e.g. based on iron-chromium or nickel-chromium) used in the steam process are highly sensitive to any sulphur compound. Alternatively, sulphur-tolerant catalysts (e.g. based on cobalt and molybdenum) can be used, although some of them require a minimum concentration of sulphur in the gas. In the next step natural gas is mixed with steam and heated to 500-600 °C. In two reactors (the primary and secondary reforming step), the hydrocarbon conversion is almost complete. The heat is supplied by burning natural gas in burners. The outlet temperature is about 1000 °C. The carbon monoxide content (12-15%) is converted in a shift reactor to carbon dioxide. The CO_2 is removed by a solvent which has chemical and/or physical absorption characteristics. Generally, chemical solvents remove CO_2 to a higher extend but require more energy than physical solvents. The solvents used in chemical absorption processes are mainly aqueous amine solutions with special promoters. Physical solvents are for instance glycol dimethylethers (Selexol) and propylene carbonate. Some solvents, like activated methyldiethanolamine are intermediate in their behaviour. The scrubbing is performed in packed columns in countercurrent with the gas stream. The carbon dioxide is recovered in almost pure form and normally vented or used in other production processes, e.g. urea production. Another emerging process is the Pressure Swing Adsorption (PSA). In that case, the recovered CO_2 is not pure.
An alternative concept for the ammonia production process is the heat exchange primary reformer. In this concept heat is supplied by the hot process gas exiting the secondary reformer. To

achieve a good heat balance excess air has to be supplied to the secondary reformer. However, to avoid contamination of the hydrogen with nitrogen, purified oxygen has to be used. Examples are ICI's Gas Heated Reforming (GHR), Kellog's Reformer Exchange System (KRES) and UHDE's Combined Autothermal Reforming (CAR). The advantage of the alternative partial oxidation concept is that there are no external burners required, thus close to 100% of the produced CO_2 can be recovered.[22]

PC1: application of the climate neutral energy carrier

The produced hydrogen is transported and added to the natural gas in the grid. Studies have showed that up to 17% (on volume base) or 5% (on energy base) content of hydrogen in the natural gas is possible without creating difficulties at the end-use site. To avoid exceeding this limits, the natural gas capacity should be high enough. Recent results of a TNO/Gasunie [Vrom, 2001] study showed that part of the high-pressure transport pipelines (the A55 pipes) may be affected by the hydrogen. The consequence may be that the hydrogen has to be mixed with the natural gas in low-pressure transport lines or in the distribution section. This is technically spoken not a problem.

PC1: compression of the recovered carbon dioxide

Recovered carbon dioxide needs to be compressed before it can be transport through a pipeline and injected into coal bed layers. A minimal transport pressure of 8 MPa is required. To overcome (initial) pressure drop during transport, compression to 12 MPa is assumed. The compression is most effectively achieved by alternate compression and cooling of the CO_2 flow. A four-stage compression process tuns out to be adequate. Possible water vapour in the CO_2 is separated in a knock out drum between the third and the fourth stage. Depending on the specifications of the carbon dioxide required, additional drying can be done by a glycol-based system.

PC1: transport of the recovered carbon dioxide

The compressed carbon dioxide can be transported, if required, by pipelines. Transport by pipelines is established technology. Assumed is a transport distance of 100 km from recovery site to storage site.

PC1: storage of the recovered carbon dioxide

Carbon dioxide is used to produce natural gas trapped in economically unminable coal layers (also called coal bed methane – CBM). The technical potential of CBM in the Dutch underground is significant: a maximum reserve of about 60 EJ is stored in coal layers up to a depth of 2000 metre. These reserves are concentrated in four main areas: Zuid Limburg, the Peel area, the Achterhoek area and Zeeland. The storage potential could be about 8 Tg of carbon dioxide.[23] However, it is still uncertain to what extent these reserves can be accessed. With conservative assumptions the 'proven' reserves is limited to 0.3 EJ and the 'possible' reserves to about 3.9 EJ. The accompanying CO_2 that can be sequestrated amounts than to between 54 Gg and 600 Gg.

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[22] Further advangtages are reduced soot and no NOx formation. However, mixing oxygen with natural gas can cause explosions. In addition an air separation plant is needed.

[23] The current annual Dutch energy consumption is about 3 EJ. The current CO_2 emission about 180 Gg.

If the produced CBM is used on top of the CBM field, the resulting CO_2 can be injected in the coal directly (thereby eliminating CO_2 transport costs).

PC1: Example projects:

- Proton Chemistry.
- Hydrogen fuelled combined cycle power station.

Proton Chemistry

Proton Chemistry wants to convert a currently closed ammonia factory into a hydrogen factory. The produced hydrogen should be mixed with natural gas in the network grid. This project is the base for our calculations.

Project: Hydrogen fuelled combined cycle power station

In 1998/1999 Norsk Hydro developed a plan to build a 1300 MWe hydrogen fuelled combined cycle power station. The hydrogen had to be produced through reforming of natural gas. The re-covered CO_2 would be used for enhanced oil recovery (EOR). The estimated cost for the project were 30 Euro/Mg of CO_2. Due to the recovery of CO_2 the production costs of electricity increase with approximately 45% (excluding the positive income from EOR). The plan was not realised because the cost were considered to high.

PC1: cost calculations

Two PC1 projects are presented. The first one (PC1a) is based on the design and cost estimates of ProtonChemie. For the second one (PC1b) a newly build hydrogen production plant is assumed.
The net costs of storage of carbon dioxide in coal bed, i.e. resulting costs of injecting the CO_2 and benefits of produced natural gas are taken from Novem [2001]. The costs taken are average costs for the Netherlands (presented as euro per GJ natural gas recovered).

Table 9 gives an overview of the emissions of carbon dioxide in the production of hydrogen for all chain elements. The overall resulting emission reduction amounts to 71%.
Table 10 shows the main figures used for the cost calculations. In Table 11 and Table 12 both the end-user costs and the national costs are presented per GJ of H_2 produced. For the calculation of the end-user costs a discount factor of 15% is used. For the national costs 5% is used.

Table 9. Emission balance for project PC1 and reference system for all chain elements

Emission (Gg/y)	PC1	Reference
1. Extraction fossil fuel production	3.2	8.0
2. Transport fossil fuel production	4.2	3.1
3a. Production energy carrier	44.1	0.0
3b. Compression recovered carbon dioxide	24.5	0.0
4. Transport recovered carbon dioxide	2.9	0.0
5. Storage/use recovered carbon dioxide	0.0	0.0
6. Distribution energy carrier	8.4	14.4
7. Application energy carrier	0.0	280.0
Total CO2-eq. emission	87.2	305.5
Emission reduction (%)		71%

Table 10. Main figures for cost calculations

Assumptions regarding costs	PC1A	PC1B
Hydrogen produced (GJ/y)	5,000,000	5,000,000
Load (h/y)	8,000	8,000
Production H2 (GJ H2/GJ NG)	75%	75%
Recovered CO2 (Gg/y)	329	-
Recovery CO2 (%)	88%	88%
Transport distance CO2 (km)	100	100
Investment H2 plant (euro/(GJ NG/y))	5	23
Investment H2 distribution system (MEuro)	75	75
Investment CO2 compression (euro/(MgCO2/y))	36	36
Investment CO2 transport (euro/(MgCO2/km/y))	0.8	0.8
Investment CO2 storage (euro/(MgCO2/y))	-	-
O&M complex installations	6.0%	6.0%
O&M other (pipelines etc.)	2.5%	2.5%

Table 11. Cost calculations for PC1. The investment costs are based on the ProtonChemie business case (own estimated currently).

Investment costs								
	Production energy carrier			kEuro	25000	Euro/(GJ H2/y)	5.00	
	Distribution energy carrier			kEuro	75000	Euro/(GJ H2/y)	15.00	
	Compression CO2	Euro/(MgCO2/y)	35.7	kEuro	13076	Euro/(GJ H2/y)	2.62	
	Transport CO2	Euro/(MgCO2/y/km	0.80	kEuro	26480	Euro/(GJ H2/y)	5.30	
	Use/storage CO2	Euro/(MgCO2/y)	-	kEuro	-	Euro/(GJ H2/y)	0.00	
O&M costs								
	Production energy carrier		6.0%	kEuro/y	6784	Euro/GJ H2	1.36	
	Distribution energy carrier		2.5%	kEuro/y	1875	Euro/GJ H2	0.38	
	Compression CO2		2.5%	kEuro/y	327	Euro/GJ H2	0.07	
	Transport CO2		2.5%	kEuro/y	662	Euro/GJ H2	0.13	
	Use/storage CO2		2.5%	kEuro/y	0	Euro/GJ H2	0.00	
Energy costs								
	Production energy carrier			kEuro/y	18667	Euro/GJ H2	3.73	
	Distribution energy carrier			kEuro/y	140	Euro/GJ H2	0.03	
	Compression CO2			kEuro/y	1555	Euro/GJ H2	0.31	
	Transport CO2			kEuro/y	0	Euro/GJ H2	0.00	
	Use/storage CO2			kEuro/y	12113	Euro/GJ H2	2.42	
	Use/storage CO2			*kEuro/y*	*12113*	*Euro/GJ H2*	*2.42*	
Depreciation costs							End_user	National cost
	Production energy carrier					Euro/GJ H2	0.77	0.35
	Distribution energy carrier					Euro/GJ H2	2.25	1.06
	Compression CO2					Euro/GJ H2	0.40	0.19
	Transport CO2					Euro/GJ H2	0.80	0.38
	Use/storage CO2					Euro/GJ H2	0.00	0.00
Total Annual costs							End_user	National cost
	Production energy carrier					Euro/GJ H2	5.86	5.44
	Distribution energy carrier					Euro/GJ H2	2.66	1.47
	Compression CO2					Euro/GJ H2	0.78	0.56
	Transport CO2					Euro/GJ H2	0.93	0.51
	Use/storage CO2					Euro/GJ H2	2.42	2.42
Total O&M costs						Euro/GJ H2	1.93	1.93
Total Energy costs						Euro/GJ H2	6.49	6.49
Total Depreciation						Euro/GJ H2	4.23	1.98
Total production costs						Euro/GJ H2	12.65	10.40
Distribution and transport costs						Euro/GJ H2	0.81	0.81
Total costs (production and distribution costs)						Euro/GJ H2	13.46	11.22
Comparison						Euro/GJ NG	9.69	9.69

Table 12. Cost calculations for PC1. The investment costs are based on a newly build hydrogen production plant.

							End_user	National cost
Investment costs								
	Production energy carrier			kEuro	113067	Euro/(GJ H2/y)	22.61	
	Distribution energy carrier			kEuro	75000	Euro/(GJ H2/y)	15.00	
	Compression CO2	Euro/(MgCO2/y)	35.7	kEuro	13076	Euro/(GJ H2/y)	2.62	
	Transport CO2	Euro/(MgCO2/y/k	0.80	kEuro	26480	Euro/(GJ H2/y)	5.30	
	Use/storage CO2	Euro/(MgCO2/y)	-	kEuro	0	Euro/(GJ H2/y)	0.00	
O&M costs								
	Production energy carrier		6.0%	kEuro/y	6784	Euro/GJ H2	1.36	
	Distribution energy carrier		2.5%	kEuro/y	1875	Euro/GJ H2	0.38	
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	Transport CO2		2.5%	kEuro/y	662	Euro/GJ H2	0.13	
	Use/storage CO2		2.5%	kEuro/y	0	Euro/GJ H2	0.00	
Energy costs								
	Production energy carrier			kEuro/y	18667	Euro/GJ H2	3.73	
	Distribution energy carrier			kEuro/y	140	Euro/GJ H2	0.03	
	Compression CO2			kEuro/y	1555	Euro/GJ H2	0.31	
	Transport CO2			kEuro/y	0	Euro/GJ H2	0.00	
	Use/storage CO2			kEuro/y	12113	Euro/GJ H2	2.42	
	Use/storage CO2			*kEuro/y*	*12113*	*Euro/GJ H2*	*2.42*	
Depreciation costs							End_user	National cost
	Production energy carrier					Euro/GJ H2	3.50	1.60
	Distribution energy carrier					Euro/GJ H2	2.25	1.06
	Compression CO2					Euro/GJ H2	0.40	0.19
	Transport CO2					Euro/GJ H2	0.80	0.38
	Use/storage CO2					Euro/GJ H2	0.00	0.00
Total Annual costs							End_user	National cost
	Production energy carrier					Euro/GJ H2	8.59	6.69
	Distribution energy carrier					Euro/GJ H2	2.66	1.47
	Compression CO2					Euro/GJ H2	0.78	0.56
	Transport CO2					Euro/GJ H2	0.93	0.51
	Use/storage CO2					Euro/GJ H2	2.42	2.42
Total O&M costs						Euro/GJ H2	1.93	1.93
Total Energy costs						Euro/GJ H2	6.49	6.49
Total Depreciation						Euro/GJ H2	6.95	3.23
Total production costs						Euro/GJ H2	15.37	11.65
Distribution and transport costs						Euro/GJ H2	0.81	0.81
Total costs (production and distribution costs)						Euro/GJ H2	16.19	12.47
Comparison						Euro/GJ NG	9.69	9.69

1.2 PC2: Hydrogen from coal and storage in empty natural gas field

- Partial oxidation of coal followed by carbon dioxide recovery from synthesis gas
- Produced hydrogen is added to the natural gas grid
- Recovered carbon dioxide is stored in empty natural gas field

PC2: production of the climate neutral energy carrier.
Coal is converted in a gasifier to synthesis gas of which the main components are hydrogen and carbon monoxide. The heat of the reaction is supplied by partial oxidation of the carbon. Therefore oxygen is added (either by adding air or by adding pure oxygen). The carbon monoxide is converted to carbon dioxide by the water-gas shift reaction. The carbon dioxide is recovered by means of a physical absorption process, with e.g. Selexol as absorbent, followed by compression and possible drying. The carbon dioxide is released typically at higher pressures (e.g. 0.4 MPa) than by amine-based or PSA-based processes (0.1 to 0.2 MPa). Compression is done in the same way as described in PC1.

PC2: application of the climate neutral energy carrier
See PC1: application of the climate neutral energy carrier.

PC2: compression of the recovered carbon dioxide
See PC1: compression of the recovered carbon dioxide.

PC2: transport of the recovered carbon dioxide
See PC1: transport of the recovered carbon dioxide.

PC2: storage of the recovered carbon dioxide in empty natural gas field
The CO_2 is stored in an empty natural gas field.[24] Natural gas fields are or will become available mainly in the North of the Netherlands and offshore. Although not all effects about storage in natural gas fields are known, it is expected that this concept is feasible. Depending on the size of the CO_2 flow and the properties of the natural gas field, one or more wells are required to inject the carbon dioxide.

PC2: cost calculations
Table 13 gives an overview of the emissions of carbon dioxide for the production of hydrogen for all chain elements The overall resulting emission reduction amounts to 45%.
Table 14 shows the main figures used for the cost calculations. In Table 15 both the end-user costs and the national costs are presented per GJ of H_2 produced. For the calculation of the end-user costs a discount factor of 15% is used. For the national costs 5% is used. See main report for a discussion of the results.

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[24] Enhanced recovery of natural gas from a field is also suggested. To date, little is known about the feasibility of such an approach. Dilution of natural gas by CO_2 may be of a smaller problem when the natural gas is used for methanol production, or, more speculative, used in a recycle loop in a O_2/CO_2 generation system.

Table 13. Emission balance for project PC2 and reference system for all chain elements

Emission (Gg/y)	PC2	Reference 1
Extraction fossil fuel production	62.0	8.0
Transport fossil fuel production	0.0	3.14
Production energy carrier	36.2	0.0
Distribution energy carrier	8.4	14.4
Application energy carrier	0.0	280.0
Compression recovered carbon dioxide	51.1	0.0
Transport recovered carbon dioxide	6.0	0.0
Storage/use recovered carbon dioxide	0.0	0.0
Total CO2-eq. emission	163.6	305.5
Emission reduction (%)		46%

Table 14. Main figures for cost calculations

Assumptions regarding costs	PC2
Hydrogen produced (GJ/y)	5,000,000
Load (h/y)	8,000
Production H2 (GJ H2/GJ coal)	65%
Recovered CO2 (Gg/y)	687
Recovery CO2 (%)	95%
Transport distance CO2 (km)	100
Investment coal gasifier (euro/(GJ H2))	625
Investment CO2 recovery unit (euro/(GJ H2))	104
Investment CO2 compression (euro/(MgCO2/y))	23
Investment CO2 transport (euro/(MgCO2/km/y))	0.6
Investment CO2 storage (euro/(MgCO2/y))	36
O&M complex installations	6.0%
O&M other (pipelines etc.)	2.5%

Table 15. Cost calculations for PC2.

							End-user	National cost
Investment costs								
	Production energy carrier			kEuro	126476	Euro/(GJ H2/y)	25.30	
	Distribution energy carrier			kEuro	75000	Euro/(GJ H2/y)	15.00	
	Compression CO2	Euro/(MgCO2/y)	22.9	kEuro	15742	Euro/(GJ H2/y)	3.15	
	Transport CO2	Euro/(MgCO2/y/k	0.57	kEuro	39408	Euro/(GJ H2/y)	7.88	
	Use/storage CO2	Euro/(MgCO2/y)	36.36	kEuro	24979	Euro/(GJ H2/y)	5.00	
O&M costs								
	Production energy carrier		6.0%	kEuro/y	7589	Euro/GJ H2	1.52	
	Distribution energy carrier		2.5%	kEuro/y	1875	Euro/GJ H2	0.38	
	Compression CO2		2.5%	kEuro/y	394	Euro/GJ H2	0.08	
	Transport CO2		2.5%	kEuro/y	985	Euro/GJ H2	0.20	
	Use/storage CO2		2.5%	kEuro/y	624	Euro/GJ H2	0.12	
Energy costs								
	Production energy carrier			kEuro/y	13077	Euro/GJ H2	2.62	
	Distribution energy carrier			kEuro/y	140	Euro/GJ H2	0.03	
	Compression CO2			kEuro/y	3244	Euro/GJ H2	0.65	
	Transport CO2			kEuro/y	0	Euro/GJ H2	0.00	
	Use/storage CO2			kEuro/y	0	Euro/GJ H2	0.00	
	Use/storage CO2			*kEuro/y*	*0*	*Euro/GJ H2*	*0.00*	
Depreciation costs							End-user	National cost
	Production energy carrier					Euro/GJ H2	3.91	1.79
	Distribution energy carrier					Euro/GJ H2	2.25	1.06
	Compression CO2					Euro/GJ H2	0.49	0.22
	Transport CO2					Euro/GJ H2	1.18	0.56
	Use/storage CO2					Euro/GJ H2	0.77	0.35
Total Annual costs							End-user	National cost
	Production energy carrier					Euro/GJ H2	8.05	5.93
	Distribution energy carrier					Euro/GJ H2	2.66	1.47
	Compression CO2					Euro/GJ H2	1.21	0.95
	Transport CO2					Euro/GJ H2	1.38	0.76
	Use/storage CO2					Euro/GJ H2	0.90	0.48
Total O&M costs						Euro/GJ H2	2.29	2.29
Total Energy costs						Euro/GJ H2	3.29	3.29
Total Depreciation						Euro/GJ H2	8.61	4.00
Total production costs						Euro/GJ H2	14.19	9.58
Distribution and transport costs						Euro/GJ H2	0.81	0.81
Total costs (production and distribution costs)						Euro/GJ H2	15.01	10.40
Comparison						Euro/GJ NG	9.69	9.69

1.3 PC3: Electricity production from coal and storage in empty natural gas field

- Partial oxidation of coal followed by electricity production in steam turbine cycle
- Produced carbon dioxide is pure, only water has to be separated
- Carbon dioxide is used in methanol synthesis to replace natural gas

PC3: production of the climate neutral energy carrier.
Coal is combusted by (pure) oxygen. Additional water is evaporated in the hot gases. The mixture is delivered to three turbines to produce electricity. After leaving the low-pressure turbine, the gaseous mixture will be cooled in a condenser where the carbon dioxide is separated from the steam. The water is recycled. An outline of the so-called Zero-emission steam technology (ZEST) is given in Figure 8 [Anderson, year unknown; Smith, year unknown].

PC3: application of the climate neutral energy carrier
The produced electricity is added to the grid. No differences compared to not-climate neutral produced electricity is assumed.

PC3: compression of the recovered carbon dioxide
See PC1: compression of the recovered carbon dioxide.

PC3: transport of the recovered carbon dioxide
See PC1: transport of the recovered carbon dioxide. Assumed is a transport distance of 100 km.

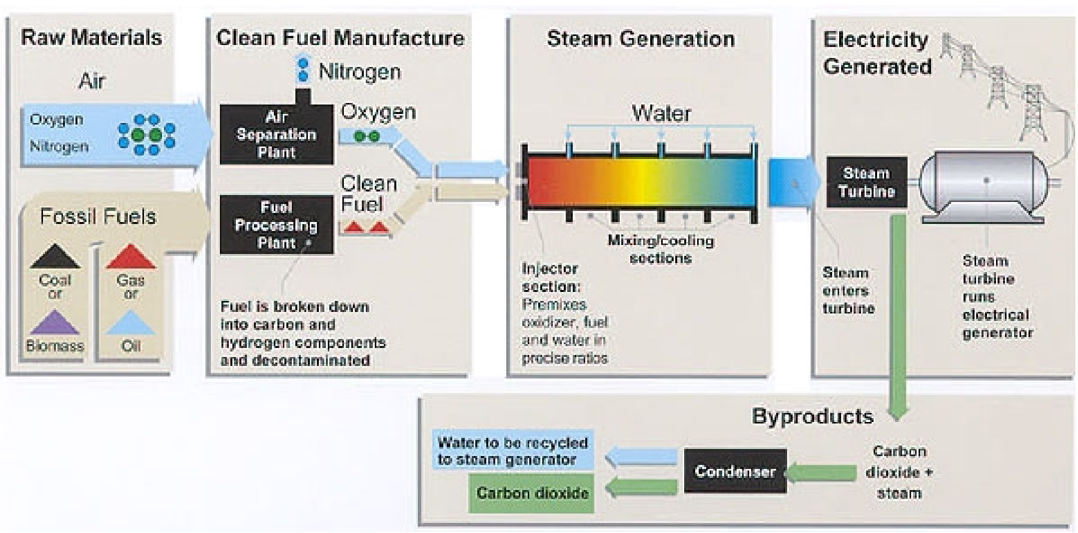


Figure 8 Outline of the ZEST technology [www.cleanenergy.com, 2001].

PC3: use/storage CO_2: application of the recovered carbon dioxide in methanol production.
CO_2 can be used as base material to produce methanol. A methanol production process based on natural gas only, creates a H_2/CO ratio which is too high for efficient use. The surplus of hydrogen is normally combusted. By adding CO_2 to the process the hydrogen can be used more efficiently, leading to a reduction in the use of natural gas (for the same methanol output).
Figure 9 shows the energy balance and CO_2 balance for the methanol production without and with external input of CO_2 (e.g. recovered from a power plant).

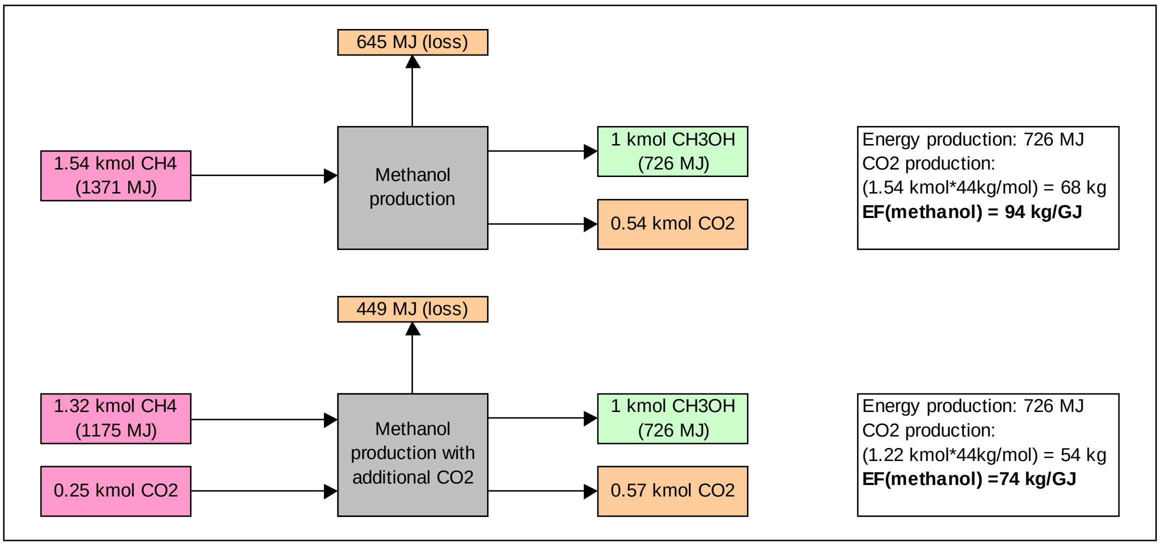


Figure 9. Simplified methanol production scheme without and with external CO_2 input.

The calculation shows that with external CO_2 the emission factor of methanol decreases from 94 to 74 kg per GJ of fuel input. The methanol production process is energetically more efficient when external CO_2 is added (assuming no extra energy use for the production of the external CO_2). The starting point in the calculation is pure methane. When natural gas with CO_2 is assumed, the emission reduction that can be obtained by adding CO_2 to the methanol synthesis will be less. How much less depends on the composition of the natural gas used.

According to Methanor (the only Dutch manufacturer of methanol) the current emission of CO_2 amounts to 2.05 kg per kg methanol (= 90 kg/GJ; in scheme in Figure 9: 94 kg/GJ). This could be reduced to 1.94 kg/kg methanol (= 85 kg/GJ in scheme in Figure 9: 74 kg/GJ) [Methanor, 2001]. Methanor informed us that 1.5 GJ natural gas per Mg methanol can be saved by applying external carbon dioxide.

PC3: cost calculations
Table 16 gives an overview of the emissions of carbon dioxide in the production of electricity for all chain elements. The project emissions are compared with three reference systems; production of electricity by a coal-fired power plant, by the average Dutch production park and by a natural gas-fired power plant. The overall resulting emission reduction vary from 49% to 77%.
Table 17 shows the main figures used for the cost calculations. In Table 18 both the end-user costs and the national costs are presented per GJe of electricity produced. For the calculation of the end-

user costs a discount factor of 15% is used. For the national costs 5% is used. See main report for a discussion of the results.

Table 16. Emission balance for project PC3 and three reference systems for all chain elements

Emission (Gg/y)	PC3	Reference Coal-fired plant	Reference Average park	Reference Combined cycle
Extraction fossil fuel production	80.5	89.50	50.1	4.37
Transport fossil fuel production	0.0	0.0	4.9	5.4
Production energy carrier	0.0	1044.4	774.6	509.1
Distribution energy carrier	0.0	0.0	0.0	0.0
Application energy carrier	0.0	0.0	0.0	0.0
Compression recovered carbon dioxide	69.9	0.0	0.0	0.0
Transport recovered carbon dioxide	0.0	0.0	0.0	0.0
Use carbon dioxide in methanol (extra emis	112.8	0.0	0.0	0.0
Total CO2-eq. emission	263.3	1133.9	829.6	518.9
Emission reduction (%)		77%	68%	49%

Table 17. Main figures for cost calculations

Assumptions regarding costs	PC3
Power produced (GJe/y)	5,000,000
Load (h/y)	8,000
Production efficiency (GJe/GJ coal)	50%
Recovered CO2 (Gg/y)	940
Recovery CO2 (%)	100%
Transport distance CO2 (km)	100
Investment power plant (euro/kWe)	803
Investment CO2 compression (euro/(MgCO2/y))	19
Investment CO2 transport (euro/(MgCO2/km/y))	0.5
Investment CO2 storage (euro/(MgCO2/y))	-
Saved NG in methanol production (GJ/Mg)	13.6
O&M complex installations	6.0%
O&M other (pipelines etc.)	2.5%

Table 18. Cost calculations for PC3.

							End-user	National cost
Investment costs								
	Production energy carrier			kEuro	139374	Euro/(GJe/y)	27.87	
	Distribution energy carrier			kEuro		Euro/(GJe/y)	0.00	
	Compression CO2	Euro/(MgCO2/y)	19.0	kEuro	17839	Euro/(GJe/y)	3.57	
	Transport CO2	Euro/(MgCO2/y/k	0.50	kEuro	46691	Euro/(GJe/y)	9.34	
	Use/storage CO2	Euro/(MgCO2/y)	-	kEuro	0	Euro/(GJe/y)	0.00	
O&M costs								
	Production energy carrier		6.0%	kEuro/y	8362	Euro/GJe	1.67	
	Distribution energy carrier		2.5%	kEuro/y	0	Euro/GJe	0.00	
	Compression CO2		2.5%	kEuro/y	446	Euro/GJe	0.09	
	Transport CO2		2.5%	kEuro/y	1167	Euro/GJe	0.23	
	Use/storage CO2		2.5%	kEuro/y	0	Euro/GJe	0.00	
Energy costs								
	Production energy carrier			kEuro/y	17000	Euro/GJe	3.40	
	Distribution energy carrier			kEuro/y		Euro/GJe	0.00	
	Compression CO2			kEuro/y	4439	Euro/GJe	0.89	
	Transport CO2			kEuro/y	0	Euro/GJe	0.00	
	Use/storage CO2			kEuro/y	0	Euro/GJe	0.00	
	Use/storage CO2			*kEuro/y*	*-35891*	*Euro/GJe*	*-7.18*	
Depreciation costs							End-user	National cost
	Production energy carrier					Euro/GJe	4.31	1.98
	Distribution energy carrier					Euro/GJe	0.00	0.00
	Compression CO2					Euro/GJe	0.55	0.25
	Transport CO2					Euro/GJe	1.40	0.66
	Use/storage CO2					Euro/GJe	0.00	0.00
Total Annual costs							End-user	National cost
	Production energy carrier					Euro/GJe	9.38	7.05
	Distribution energy carrier					Euro/GJe	0.00	0.00
	Compression CO2					Euro/GJe	1.53	1.23
	Transport CO2					Euro/GJe	1.64	0.90
	Use/storage CO2					Euro/GJe	0.00	0.00
Total O&M costs						Euro/GJe	2.00	2.00
Total Energy costs						Euro/GJe	4.29	4.29
Total Depreciation						Euro/GJe	6.27	2.89
Total production costs						Euro/GJe	12.55	9.18
Distribution and transport costs						Euro/GJe	9.09	9.09
Total costs (production and distribution costs)						Euro/GJe	21.64	18.27
Comparison						Euro/GJe	37.88	22.10

1.4 PC4: Electricity production from coal or natural gas and use of carbon dioxide in greenhouses and storage in natural gas field

- Electricity production by either a conventional coal-fired or a conventional natural gas fired-power plant.
- Recovery of carbon dioxide by amine-based chemical absorption process.
- Carbon dioxide is partly used in greenhouses and is partly stored in an empty natural gas field.

PC4: production of the climate neutral energy carrier.
Electricity is produced by a conventional coal-fired power plant (based on boiler and steam turbines) (project PC4a) or by a conventional natural gas-fired power plant (project PC4b). The flue gases of the plant are directed through an absorber. The absorbent, often an amine-based substance, reacts chemically with the carbon dioxide. The CO_2-lean gases are vented to the atmosphere. The CO_2-rich solution is regenerated (i.e. the CO_2 is liberated) and re-directed to the absorber. To improve the energy efficiency of the installation, the heat is extracted from the low-pressure steam of the plant's steam turbines. To avoid high losses of the absorbent, the gases should be sufficiently cleaned from particulates, SO_2, and NO_x.

PC4: application of the climate neutral energy carrier
Electricity is added to the grid. No differences compared to not-climate neutral produced electricity is assumed.

PC4: compression of the recovered carbon dioxide
See PC1: compression of the recovered carbon dioxide.

PC4: transport of the recovered carbon dioxide
See PC1: transport of the recovered carbon dioxide. A transport distance of 100 km is assumed.

PC4: application of the recovered carbon dioxide in greenhouses and storage in empty natural gas field
Carbon dioxide fertilising is commonly applied in greenhouses. The carbon dioxide in most cases is fed to greenhouses by leading the cleaned flue gases of a boiler or gas engine into the greenhouses. In warm periods, the heat is not required and wasted. By using CO_2 from external sources, natural gas can be saved. Care should be taken about the impurities in the CO_2. Impurities may harm the growth and yield of the crop.
In this study it is assumed that about 3 months per year carbon dioxide is required in greenhouses without need for additional heat. In the remaining months the carbon dioxide (75% of the recovered CO_2) is stored in empty natural gas fields.[25]

[25] Alternatively it could be assumed that all CO_2 is used in greenhouses. This is economically unattractive because then there is need for an expensive storage facility for carbon dioxide.

PC4: cost calculations

Two PC4 projects are presented. In the first one (PC4a) the carbon dioxide is recovered from a conventional coal-fired. In the second one (PC4b) the CO_2 is recovered from a conventional natural gas-fired power plant. The emissions are compared with six reference cases (three types of power production plants, i.e. same type of power plant as in project case PC3 (conventional coal-fired plant, average Dutch park, and natural gas-fired combined cycle) and two types of CO_2 production facilities in the greenhouses (by boiler and by gas engine).

Table 19 gives an overview of the emissions of carbon dioxide in the production of electricity for all chain elements for PC4a. The overall resulting emission reduction varies considerably depending on reference case chosen. Comparing with electricity production of an average park the emission reduction is 18% (replacing gas engine) and 41% (replacing boiler).

Table 22 gives an overview of the emissions of carbon dioxide in the production of electricity for all chain elements for PC4b. The overall resulting emission reduction varies considerably depending on the reference case chosen. Comparing with electricity production of an average park the emission reduction is 38% (replacing gas engine) and 54% (replacing boiler).

Table 20 and Table 23 show the main figures used for the cost calculations. In Table 21 and Table 24 both the end-user costs and the national costs are presented per GJe of power produced. For the calculation of the end-user costs a discount factor of 15% is used. For the national costs 5% is used.

Table 19. Emission balance for project PC4a and reference system for all chain elements

Emission (Gg/y)	PC4a	Reference	Reference	Reference	Reference	Reference	Reference
		Project specific Gas engine	Project specific Boiler	Average park Gas engine	Average park Boiler	Combined cycle Gas engine	Combined cycle Boiler
Extraction fossil fuel production	115.1	95.89	95.9	50.09	50.09	4.4	4.37
Transport fossil fuel production	0.0	0.0	0.0	4.9	4.9	5.4	5.4
Production energy carrier	134.3	660.2	1119.0	457.0	774.6	300.3	509.1
Distribution energy carrier	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Application energy carrier	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Compression recovered carbon dioxide	89.9	0.0	0.0	0.0	0.0	0.0	0.0
Transport recovered carbon dioxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Storage/use recovered carbon dioxide	302.1	302.1	302.1	302.1	302.1	302.1	302.1
Total CO2-eq. emission	641.4	1058.2	1517.1	814.1	1131.7	612.2	821.0
Emission reduction (%)		39%	58%	21%	43%	-5%	22%

Table 20. Main figures for cost calculations

Assumptions regarding costs	PC4a
Power produced (GJe/y)	5,000,000
Load (h/y)	8,000
Production efficiency (GJe/GJ coal)	35%
Recovered CO2 (Gg/y)	1,209
Recovery CO2 (%)	90%
CO2 delivered to greenhouses (Gg/y)	302
CO2 stored in empty NG fields (Gg/y)	906
Transport distance CO2 (km)	100
Investment power plant (euro/kWe)	1,000
Investment recovery plant (Meuro/(MgCO2/y))	2.23
Investment CO2 compression (euro/(MgCO2/y))	16
Investment CO2 transport (euro/(MgCO2/km/y))	0.44
Investment CO2 storage (euro/(MgCO2/y))	36.36
Saved NG (GJ/MgCO2)	17.9
O&M complex installations	6.0%
O&M other (pipelines etc.)	2.5%

Table 21. Cost calculations for PC4a.

Investment costs								
	Production energy carrier			kEuro	277462	Euro/(GJe/y)	55.49	
	Distribution energy carrier			kEuro		Euro/(GJe/y)	0.00	
	Compression CO2	Euro/(MgCO2/y)	16.3	kEuro	19718	Euro/(GJe/y)	3.94	
	Transport CO2	Euro/(MgCO2/y/k	0.44	kEuro	53487	Euro/(GJe/y)	10.70	
	Use/storage CO2	Euro/(MgCO2/y)	36.36	kEuro	32961	Euro/(GJe/y)	6.59	
O&M costs								
	Production energy carrier		6.0%	kEuro/y	16648	Euro/GJe	3.33	
	Distribution energy carrier		2.5%	kEuro/y	0	Euro/GJe	0.00	
	Compression CO2		2.5%	kEuro/y	493	Euro/GJe	0.10	
	Transport CO2		2.5%	kEuro/y	1337	Euro/GJe	0.27	
	Use/storage CO2		2.5%	kEuro/y	824	Euro/GJe	0.16	
Energy costs								
	Production energy carrier			kEuro/y	24286	Euro/GJe	4.86	
	Distribution energy carrier			kEuro/y		Euro/GJe	0.00	
	Compression CO2			kEuro/y	5707	Euro/GJe	1.14	
	Transport CO2			kEuro/y	0	Euro/GJe	0.00	
	Use/storage CO2			kEuro/y	0	Euro/GJe	0.00	
	Use/storage CO2			*kEuro/y*	*-28357*	*Euro/GJe*	*-5.67*	
Depreciation costs							End-user	National cost
	Production energy carrier					Euro/GJe	8.58	3.94
	Distribution energy carrier					Euro/GJe	0.00	0.00
	Compression CO2					Euro/GJe	0.61	0.28
	Transport CO2					Euro/GJe	1.61	0.76
	Use/storage CO2					Euro/GJe	1.02	0.47
Total Annual costs							End-user	National cost
	Production energy carrier					Euro/GJe	16.77	12.12
	Distribution energy carrier					Euro/GJe	0.00	0.00
	Compression CO2					Euro/GJe	1.85	1.52
	Transport CO2					Euro/GJe	1.87	1.03
	Use/storage CO2					Euro/GJe	1.18	0.63
Total O&M costs						Euro/GJe	3.86	3.86
Total Energy costs						Euro/GJe	6.00	6.00
Total Depreciation						Euro/GJe	11.82	5.44
Total production costs						Euro/GJe	21.68	15.30
Distribution and transport costs						Euro/GJe	9.09	9.09
Total costs (production and distribution costs)						Euro/GJe	30.77	24.39
Comparison						Euro/GJe	37.88	37.88

Table 22. Emission balance for project PC4b and reference system for all chain elements

Emission (Gg/y)	PC4	Reference Conv. Coal fired Gas engine	Reference Conv. Coal fired Boiler	Reference Average park Gas engine	Reference Average park Boiler	Reference Combined cycle Gas engine	Reference Combined cycle Boiler
Extraction fossil fuel production	6.0	95.89	95.9	50.09	50.09	4.4	4.37
Transport fossil fuel production	21.0	0.0	0.0	4.9	4.9	5.4	5.4
Production energy carrier	70.0	879.9	1119.0	609.1	774.6	400.3	509.1
Distribution energy carrier	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Application energy carrier	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Compression recovered carbon dioxide	46.9	0.0	0.0	0.0	0.0	0.0	0.0
Transport recovered carbon dioxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Storage/use recovered carbon dioxide	157.5	157.5	157.5	157.5	157.5	157.5	157.5
Total CO2-eq. emission	301.4	1133.2	1372.4	821.5	987.1	567.5	676.4
Emission reduction (%)		73%	78%	63%	69%	47%	55%

Table 23. Main figures for cost calculations

Assumptions regarding costs	PC4b
Power produced (GJe/y)	5,000,000
Load (h/y)	8,000
Production efficiency (GJe/GJ coal)	40%
Recovered CO2 (Gg/y)	1,058
Recovery CO2 (%)	90%
CO2 delivered to greenhouses (Gg/y)	264
CO2 stored in empty NG fields (Gg/y)	793
Transport distance CO2 (km)	100
Investment power plant (euro/kWe)	500
Investment recovery plant (Meuro/(MgCO2/y))	2.23
Investment CO2 compression (euro/(MgCO2/y))	18
Investment CO2 transport (euro/(MgCO2/km/y))	0.47
Investment CO2 storage (euro/(MgCO2/y))	36.36
Saved NG (GJ/MgCO2)	17.9
O&M complex installations	6.0%
O&M other (pipelines etc.)	2.5%

Table 24. Cost calculations for PC4b.

Investment costs								
	Production energy carrier			kEuro	177675	Euro/(GJe/y)	35.54	
	Distribution energy carrier			kEuro		Euro/(GJe/y)	0.00	
	Compression CO2	Euro/(MgCO2/y)	18	kEuro	18696	Euro/(GJe/y)	3.74	
	Transport CO2	Euro/(MgCO2/y/k	0.47	kEuro	49762	Euro/(GJe/y)	9.95	
	Use/storage CO2	Euro/(MgCO2/y)	36.36	kEuro	28841	Euro/(GJe/y)	5.77	
O&M costs								
	Production energy carrier		6.0%	kEuro/y	10661	Euro/GJe	2.13	
	Distribution energy carrier		2.5%	kEuro/y	0	Euro/GJe	0.00	
	Compression CO2		2.5%	kEuro/y	467	Euro/GJe	0.09	
	Transport CO2		2.5%	kEuro/y	1244	Euro/GJe	0.25	
	Use/storage CO2		2.5%	kEuro/y	721	Euro/GJe	0.14	
Energy costs								
	Production energy carrier			kEuro/y	35000	Euro/GJe	7.00	
	Distribution energy carrier			kEuro/y		Euro/GJe	0.00	
	Compression CO2			kEuro/y	4994	Euro/GJe	1.00	
	Transport CO2			kEuro/y	0	Euro/GJe	0.00	
	Use/storage CO2			kEuro/y	0	Euro/GJe	0.00	
	Use/storage CO2			*kEuro/y*	*-24812*	*Euro/GJe*	*-4.96*	
Depreciation costs							End-user	National cost
	Production energy carrier					Euro/GJe	5.50	2.52
	Distribution energy carrier					Euro/GJe	0.00	0.00
	Compression CO2					Euro/GJe	0.58	0.27
	Transport CO2					Euro/GJe	1.49	0.71
	Use/storage CO2					Euro/GJe	0.89	0.41
Total Annual costs							End-user	National cost
	Production energy carrier					Euro/GJe	14.63	11.65
	Distribution energy carrier					Euro/GJe	0.00	0.00
	Compression CO2					Euro/GJe	1.67	1.36
	Transport CO2					Euro/GJe	1.74	0.95
	Use/storage CO2					Euro/GJe	1.04	0.55
Total O&M costs						Euro/GJe	2.62	2.62
Total Energy costs						Euro/GJe	8.00	8.00
Total Depreciation						Euro/GJe	8.46	3.90
Total production costs						Euro/GJe	19.08	14.52
Distribution and transport costs						Euro/GJe	9.09	9.09
Total costs (production and distribution costs)						Euro/GJe	28.17	23.61
Comparison						Euro/GJe	37.88	22.10

1.5 PC5: STORAGE OF CARBON DIOXIDE FROM NATURAL GAS PROCESSING

Recovered carbon dioxide from natural gas processing is stored in an aquifer.

PC5: production of the climate neutral energy carrier.
Natural gas is extracted from hydrocarbon fields. The CO_2 content of natural gas is reduced by recovering the carbon dioxide. Depending of the gas field, the CO_2 content may vary from zero to 100%. The carbon dioxide is recovered using a chemical absorption process following the same principles as described in PC4.

PC5: application of the climate neutral energy carrier
The natural gas produced is added to the grid. No differences compared to not-climate neutral produced natural gas is assumed.

PC5: compression of the recovered carbon dioxide
See PC1: compression of the recovered carbon dioxide.

PC5: transport of the recovered carbon dioxide
See PC1: transport of the recovered carbon dioxide. A transport distance of 20 km is assumed.

PC5: storage of the recovered carbon dioxide in an aquifer
The carbon dioxide is stored in an aquifer (water containing layer). Aquifers are widespread available in the Netherlands, both onshore and offshore. Feasibility of injection of carbon dioxide in aquifers is being demonstrated by the project of Statoil in the Sleipner field. However, the properties and accessibility of aquifers may differ considerable from location to location. Substantial research and demonstration is required before aquifer storage will be a proven technology.

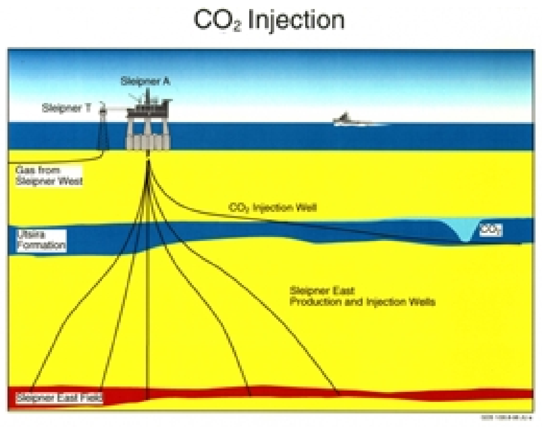
PC5: Example projects:
Sleipner gas field project.
Natuna gas field project.

Project: Sleipner gas field project
Statoil developed in the beginning of the nineties two gas fields, Sleipner East and Sleipner West. Gas from the Sleipner West field has a high carbon dioxide content, which must be reduced from roughly ten per cent to less than 2.5 percent to meet sales specifications. This is achieved in two 20-metre high absorption column installed on the platform Sleipner-T. Carbon dioxide from the gas is absorbed in the columns by an amine fluid and then removed from the amine in a regeneration plant (see photo and scheme below). The separation module includes pressure/storage tanks, heat exchangers, gas turbines and compressors and filters in addition to the columns. The installation weights about 8500 tonne and costs about 250 million Euro. Cleaned gas is sent for export. The carbon dioxide is injected into the water-filled Utsira sandstone formation about 1000 metres

beneath the seabed. The Utsira formation is a 200 meter massive sandstone located at a depth of 800 – 1000 meter. The CO_2 is injected into a small structural closure north-east of the injection platform. Roughly a million tonnes of carbon dioxide is deposited since 1996 annually as long as production of Sleipner West lasts, up to 2012.

<u>Project: Natuna gasfield project (Indonesia)</u>

The Norwegian project will probably be followed by a project developed by Exxon and Pertamina for the Natuna gas field in Indonesia. This gas field holds the same amount of natural gas as the Slochteren field in Groningen. However the CO_2 content of the Natuna gas field is 71%. In order to be able to use the gas from this field the CO_2 has to be separated. The planning is to inject the recovered CO_2 in two nearby aquifers, which amounts to about 100 million tonnes per year. Storage instead of emitting the CO_2 will decrease the global CO_2 with approximately 0.5% per year. It is unknown if or when this project will be executed, among others this will depend on the possibilities to sell the extracted natural gas to Japan.



PC5: cost calculations

Table 25 gives an overview of the emissions of carbon dioxide in the production of natural gas (complying carbon dioxide content specifications) for all chain elements. Table 26 shows the main figures used for the cost calculations. In Table 27 both the end-user costs and the national costs are presented per GJ of H_2 produced. For the calculation of the end-user costs a discount factor of 15% is used. For the national costs 5% is used. See main report for a discussion of the results

Table 25. Emission balance for project PC5 and reference system for all chain elements

Emission (Gg/y)	PC5	Reference
Extraction fossil fuel production	160.1	160.1
Transport fossil fuel production	62.7	62.7
Production energy carrier	0.0	468.8
Distribution energy carrier	0.0	0.0
Application energy carrier	5600.0	5600.0
Compression recovered carbon dioxide	34.9	0.0
Transport recovered carbon dioxide	0.8	0.0
Storage/use recovered carbon dioxide	0.0	0.0
Total CO2-eq. emission	5858.5	6291.6
Emission reduction (%)		7%

Table 26. Main figures for cost calculations

Assumptions regarding costs	PC5
Natural gas produced (GJ/y)	100,000,000
CO2 content in NG (%)	10%
CO2 content in NG (specification (%)	0
Recovered CO2 (Gg/y)	469
Recovery CO2 (%)	100%
Transport distance CO2 (km)	20
Investment CO2 recovery plant (additional) (MEuro/(kgCO2/s))	0.5
Investment CO2 compression (euro/(MgCO2/y))	29
Investment CO2 transport (euro/(MgCO2/km/y))	0.7
Investment CO2 storage (euro/(MgCO2/y))	36
O&M complex installations	6.0%
O&M other (pipelines etc.)	2.5%

Table 27. Cost calculations for PC5.

Investment costs								
	Production energy carrier			kEuro	8138	Euro/(GJ NG/y)	0.08	
	Distribution energy carrier			kEuro		Euro/(GJ NG/y)	0.00	
	Compression CO2	Euro/(MgCO2/y)	29	kEuro	13519	Euro/(GJ NG/y)	0.14	
	Transport CO2	Euro/(MgCO2/y/k	0.68	kEuro	6410	Euro/(GJ NG/y)	0.06	
	Use/storage CO2	Euro/(MgCO2/y)	36	kEuro	17045	Euro/(GJ NG/y)	0.17	
O&M costs								
	Production energy carrier		6.0%	kEuro/y	488	Euro/GJ NG	0.00	
	Distribution energy carrier		2.5%	kEuro/y	0	Euro/GJ NG	0.00	
	Compression CO2		2.5%	kEuro/y	338	Euro/GJ NG	0.00	
	Transport CO2		2.5%	kEuro/y	160	Euro/GJ NG	0.00	
	Use/storage CO2		2.5%	kEuro/y	426	Euro/GJ NG	0.00	
Energy costs								
	Production energy carrier			kEuro/y	0	Euro/GJ NG	0.00	
	Distribution energy carrier			kEuro/y		Euro/GJ NG	0.00	
	Compression CO2			kEuro/y	2214	Euro/GJ NG	0.02	
	Transport CO2			kEuro/y	0	Euro/GJ NG	0.00	
	Use/storage CO2			kEuro/y	0	Euro/GJ NG	0.00	
	Use/storage CO2			*kEuro/y*	*0*	*Euro/GJ NG*	*0.00*	
Depreciation costs							End-user	National cost
	Production energy carrier					Euro/GJ NG	0.01	0.01
	Distribution energy carrier					Euro/GJ NG	0.00	0.00
	Compression CO2					Euro/GJ NG	0.02	0.01
	Transport CO2					Euro/GJ NG	0.01	0.00
	Use/storage CO2					Euro/GJ NG	0.03	0.01
Total Annual costs							End-user	National cost
	Production energy carrier					Euro/GJ NG	0.02	0.01
	Distribution energy carrier					Euro/GJ NG	0.00	0.00
	Compression CO2					Euro/GJ NG	0.05	0.04
	Transport CO2					Euro/GJ NG	0.01	0.01
	Use/storage CO2					Euro/GJ NG	0.03	0.02
Total O&M costs						Euro/GJ NG	0.01	0.01
Total Energy costs						Euro/GJ NG	0.02	0.02
Total Depreciation						Euro/GJ NG	0.07	0.03
Total production costs						Euro/GJ NG	0.11	0.07
Distribution and transport costs						Euro/GJ NG	0.81	0.81
Total costs (production and distribution costs)						Euro/GJ NG	0.92	0.88
Comparison						Euro/GJ NG	9.69	9.69

1.6 PC6: HYDROGEN AND CARBON BLACK PRODUCTION

- Hydrogen and carbon black are produced by converting natural gas using electricity.
- Electricity is produced by using (part of) the hydrogen produced.
- Carbon black is applied in industry, replacing other carbon-containing products.

PC6: production of the climate neutral energy carrier.

Natural gas or other carbon containing feedstock is converted into hydrogen and carbon black. In a high-temperature reactor a plasma torch supplies the necessary energy to pyrolyse the feedstock. Separation of hydrogen and carbon black proceeds by conventional cyclones and filters. In addition a small amount of heat is produced.

Since 1990, a process is being developed by the Swedish engineering office Kvaerner. In a plasma reactor natural gas is converted to hydrogen and carbon black at a temperature of 1600 °C by a high voltage current. It is claimed that no by-products are formed. In addition steam is generated, which can be used to produce power. In principle also other carbon containing material can be converted.

PC6: application of the climate neutral energy carrier

A part of the hydrogen is used to produce the electricity required for the conversion processes. The electricity is produced in a combined cycle. An alternative could be that the total amount of hydrogen produced is added to the grid to replace natural gas, and that instead natural gas is used to produce electricity.

PC6: transport of the carbon

In this process, solid carbon is formed. This can be transported by trucks or ships.

PC6: use or storage of the carbon black

The carbon black is used to replace other carbon containing feedstock. Alternatively, carbon black can be stored for longer time to avoid that the carbon enters the atmosphere as carbon dioxide.

Currently the world wide production of carbon black is 6 million tonnes, where the capacity in Western Europe amounts to some 1 million tonnes. About 90% of produced carbon black is utilised within the rubber industry. The metallurgical industry could be a new market for carbon black. Applications could be

- as reduction material in the production of e.g. silicium carbide (SiC). In the production of SiC all or part of other carbon source (e.g. petrol coke) can be replaced. According to Kvaerner [2001], application of carbon black reduces the electricity consumption by about 15%. This is equivalent to 3.25 kWh per kg carbon black. In addition 15% feedstock for SiC production can be saved.
- as carbon additive to the steel and foundry industry (total consumption in Europe approximately 300.000 tonnes per year), replacing petroleum type coke or metallurgical coke.

It is argued that application of carbon black reduces the net power input in the metallurgical industry [Kvaerner, 1996].

Alternative hydrogen and carbon black production process

Another process is described by Steinberg [Steinberg, 2000]. In this process methane is decomposed to hydrogen and carbon in a thermal reactor. According to the author, 2 mole of hydrogen is produced from 1 mole of natural gas. The energy required is about 0.33 mole of hydrogen. To produce 1 GJ H_2 about 1.8 GJ natural gas is required. It is not clear whether thermal decomposition reactors are commercially available.

PC6: cost calculations

In contrast to the other climate neutral energy carrier production route, this process route is mainly for the production of carbon black with hydrogen as by-product. The resulting emission factor of carbon dioxide depends strongly on the configuration of the total concept and on the assumptions made to the use of the carbon black. For instance, in order to have a high emission reduction it is necessary that produced hydrogen is used as fuel for electricity production instead of natural gas. As the lion part of the hydrogen is used for power production (about 80%), the production of hydrogen is rather small per kg carbon black produced.

In our calculations we depart from the following starting points:

Project:

- Natural gas is used for production of H_2 and carbon black (with small amount of heat).
- H_2 is used for production of electricity.[26]
- Carbon black saves electricity and feedstock in industrial production process compared to other carbon containing feedstock.

Reference:

- Natural gas as alternative for hydrogen that is delivered to the end-user.
- Power production (to compensate saved power by application of CB in 'project').
- Additional feedstock use (to compensate for 'project' may save emission of CO_2 by production and transport).

Table 28 gives an overview of the emissions of carbon dioxide in the production of hydrogen for all chain elements. The overall resulting emission reduction amounts to 97%. When the power compensation in the reference case is not taken into account, the emission reduction amounts to 87%.

Table 29 shows the main figures used for the cost calculations. In Table 30 both the end-user costs and the national costs are presented per GJ of H_2 produced. For the calculation of the end-user costs a discount factor of 15% is used. For the national costs 5% is used. See main report for a discussion of the results.

[26] Alternatively natural gas can be used to produce power for the carbon black process and hydrogen is fed into the grid.

Table 28. Emission balance for project PC6 and reference system for all chain elements

Emission (Gg/y)	PC6	Reference	Reference
	Part H2 used for power for CB prod.	NG in grid	NG in grid; Power compensation for CB use
Extraction fossil fuel production	4	3.8	3.8
Transport fossil fuel production	3.5	3.5	3.5
Production energy carrier	0.0	0.0	0.0
Distribution energy carrier	1.7	0.0	0.0
Application energy carrier	0.0	56.0	232.5
Compression recovered carbon dioxide	0.0	0.0	0.0
Transport recovered carbon dioxide	0.0	0.0	0.0
Storage/use recovered carbon dioxide	0.0	0.0	0.0
Total CO2-eq. emission	9.1	63.4	239.9
Emission reduction (%)		86%	96%

Table 29. Main figures for cost calculations

Assumptions regarding costs PC1	PC6
Hydrogen produced (GJ/y)	1,000,000
Carbon black produced (Mg/y)	86,217
Gross production H2 (GJ H2/GJ NG)	64%
Net production H2 (GJ H2/GJ NG)	18%
Transport distance CO2 (km)	100
Investment CO2 recovery plant (additional) (Euro/(MgCB/y))	2,200.0
Saved power by applying carbon black (GJe/MgCB)	12
O&M complex installations	6.0%
O&M other (pipelines etc.)	2.5%

Table 30. Cost calculations for PC6.

Investment costs								
	Production energy carrier			kEuro	189677	Euro/(GJ H2/y)	189.68	
	Distribution energy carrier			kEuro		Euro/(GJ H2/y)	0.00	
	Compression CO2	Euro/(MgCO2/y)	-	kEuro	0	Euro/(GJ H2/y)	0.00	
	Transport CO2	Euro/(MgCO2/y/k	-	kEuro	0	Euro/(GJ H2/y)	0.00	
	Use/storage CO2	Euro/(MgCO2/y)	-	kEuro	0	Euro/(GJ H2/y)	0.00	
O&M costs								
	Production energy carrier		6.0%	kEuro/y	11381	Euro/GJ H2	11.38	
	Distribution energy carrier		2.5%	kEuro/y	0	Euro/GJ H2	0.00	
	Compression CO2		2.5%	kEuro/y	0	Euro/GJ H2	0.00	
	Transport CO2		2.5%	kEuro/y	0	Euro/GJ H2	0.00	
	Use/storage CO2		2.5%	kEuro/y	-25865	Euro/GJ H2	-25.87	
Energy costs								
	Production energy carrier			kEuro/y	15806	Euro/GJ H2	15.81	
	Distribution energy carrier			kEuro/y	28	Euro/GJ H2	0.03	
	Compression CO2			kEuro/y	0	Euro/GJ H2	0.00	
	Transport CO2			kEuro/y	0	Euro/GJ H2	0.00	
	Use/storage CO2			kEuro/y	0	Euro/GJ H2	0.00	
	Use/storage CO2			*kEuro/y*	*0*	*Euro/GJ H2*	*0.00*	
Depreciation costs							End-user	National cost
	Production energy carrier					Euro/GJ H2	29.34	13.46
	Distribution energy carrier					Euro/GJ H2	0.00	0.00
	Compression CO2					Euro/GJ H2	0.00	0.00
	Transport CO2					Euro/GJ H2	0.00	0.00
	Use/storage CO2					Euro/GJ H2	0.00	0.00
Total Annual costs							End-user	National cost
	Production energy carrier					Euro/GJ H2	56.53	40.65
	Distribution energy carrier					Euro/GJ H2	0.03	0.03
	Compression CO2					Euro/GJ H2	0.00	0.00
	Transport CO2					Euro/GJ H2	0.00	0.00
	Use/storage CO2					Euro/GJ H2	-25.87	-25.87
Total O&M costs						Euro/GJ H2	-14.48	-14.48
Total Energy costs						Euro/GJ H2	15.83	15.83
Total Depreciation						Euro/GJ H2	29.34	13.46
Total production costs						Euro/GJ H2	30.69	14.81
Distribution and transport costs						Euro/GJ H2	0.81	0.81
Total costs (production and distribution costs)						Euro/GJ H2	31.51	15.62
Comparison						Euro/GJ NG	9.69	9.69

2 ANNEX: COST CALCULATIONS FOR COMPRESSION AND TRANSPORT OF CARBON DIOXIDE

The specific costs of compressing and transporting carbon dioxide (euro per Mg CO_2) depends (strongly) on the amount of carbon dioxide processed. In the next sessions the cost calculation methodology is presented.

2.1 COMPRESSION OF CO_2

Investment costs for compression depends on the compression ratio and the (peak) flow. Reported costs on compression of carbon dioxide vary significantly. Figure 10 (left figure) gives an impression of the range of the specific investment costs. The figure is based on reported information provided by manufacturers and information found in literature. In this study, the compression costs used for the cost calculations are depicted in Figure 10.

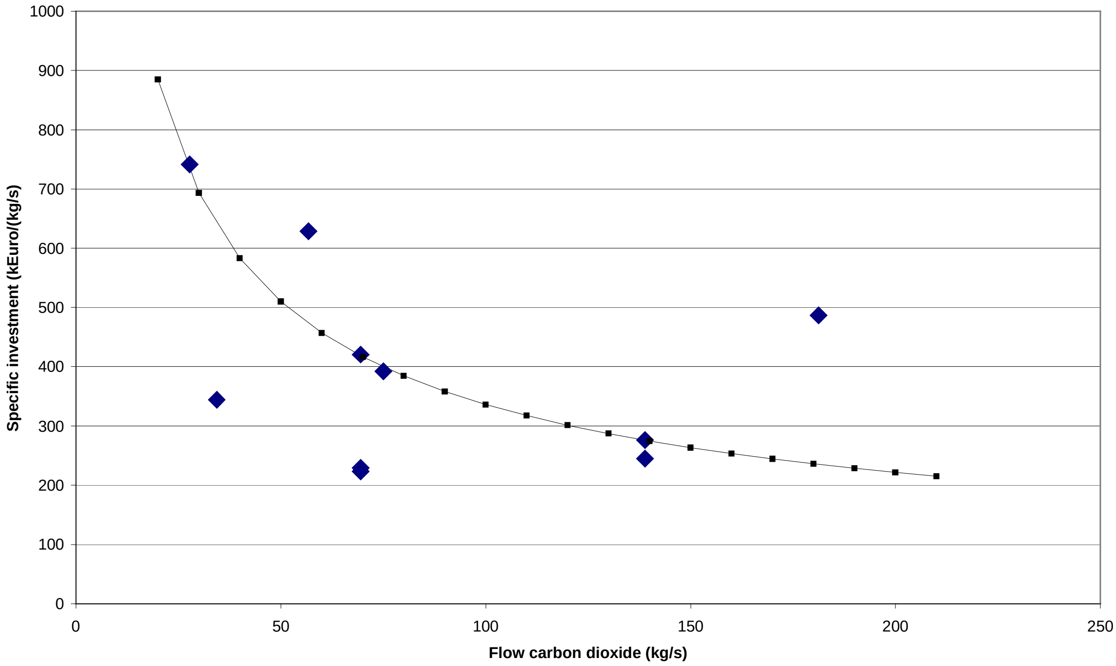


Figure 10 Compression costs from literature (dots) and used in this study (solid line).

2.2 TRANSPORT OF CARBON DIOXIDE

The investment costs of pipelines comprise of costs for material and construction. The costs depend on the diameter and length of the line, and on possible crossings (freeways and water crossings). The information on transport costs supplied by the Gasunie [1999] and Jole [1999] is presented in Figure 11.

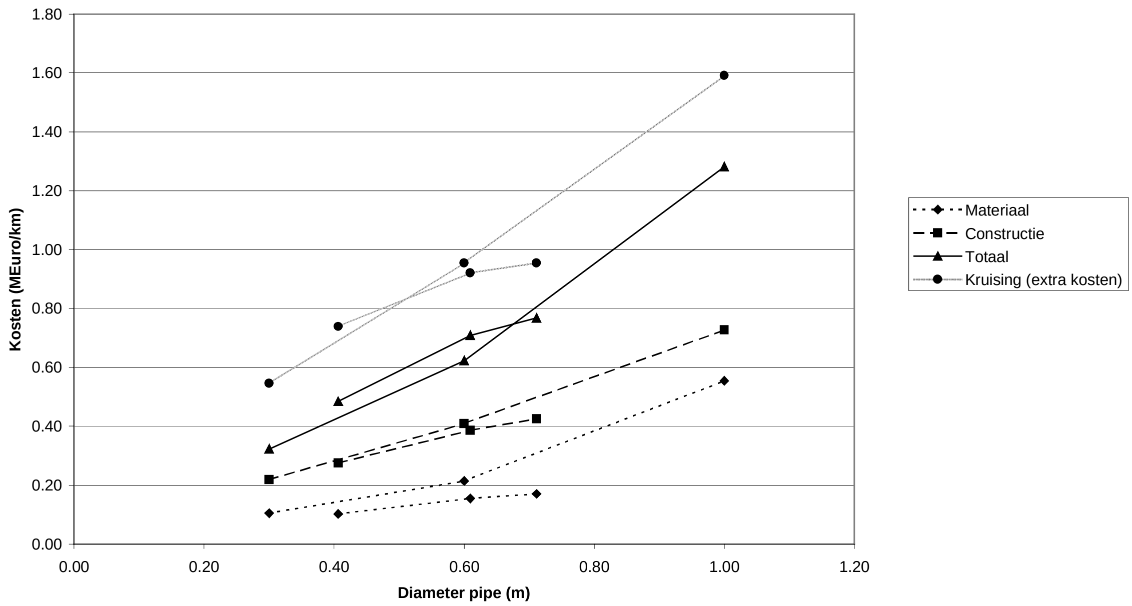


Figure 11. Investment costs pipelines. Indication provided by Gasunie (short lines) and Jole (long lines).

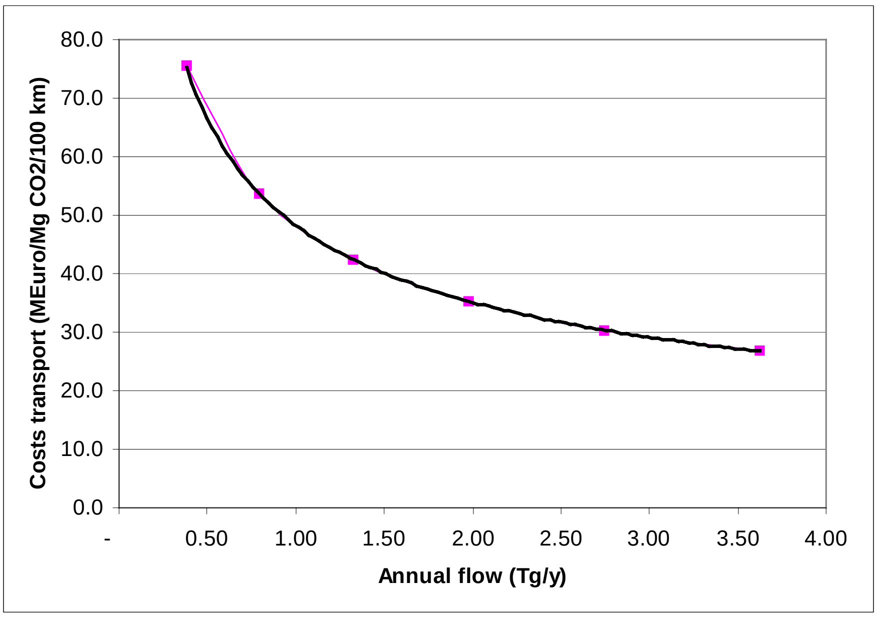


Figure 12. Investment costs for transport of CO_2 over a distance of 100 km used in this study (based on costs in Figure 11).

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