



Impact of international climate policies on CO₂ capture and storage deployment Illustrated in the Dutch energy system

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ABSTRACT

A greenhouse gas emission trading system is considered an important policy measure for the deployment of CCS at large scale. However, more insights are needed whether such a trading system leads to a sufficient high CO₂ price and stable investment environment for CCS deployment. To gain more insights, we combined WorldScan, an applied general equilibrium model for global policy analysis, and MARKAL-NL-UU, a techno-economic energy bottom-up model of the Dutch power generation sector and CO₂ intensive industry. WorldScan results show that in 2020, CO₂ prices may vary between 20 €/tCO₂ in a GRAND COALITION scenario, in which all countries accept greenhouse gas targets from 2020, to 47 €/tCO₂ in an IMPASSE scenario, in which EU-27 continues its one-sided emission trading system without the possibility to use the Clean Development Mechanism. MARKAL-NL-UU model results show that an emission trading system in combination with uncertainty does not advance the application of CCS in an early stage, the rates at which different CO₂ abatement technologies (including CCS) develop are less crucial for introduction of CCS than the CO₂ price development, and the combination of biomass (co-)firing and CCS seems an important option to realise deep CO₂ emission reductions.

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1. Introduction

The Fourth Assessment report of the IPCC published in 2007 (IPCC, 2007a) as well as other recent publications like the synthesis report of the scientific congress “Climate change: Global Risks, Challenges & Decisions” (Climate congress, 2009) underpin the necessity to limit the human induced increase of the mean

Abbreviations: CBS, statistics Netherlands; CCS, carbon dioxide capture and storage; CGE, computable general equilibrium; CHP, combined heat and power production; COE, cost of electricity; CPB, Netherlands Bureau for Economic Policy Analysis; CRRF, capture ready retrofit; ETS, greenhouse gas emission allowance trading scheme; EU, European Union; GHG, greenhouse gas; IEA, International Energy Agency; IGCC, Integrated gasification combined cycle power plant on coal (and biomass); IPCC, Intergovernmental Panel on Climate Change; MARKAL, (acronym for Market Allocation), a linear optimisation energy bottom-up model; NGCC, natural gas combined cycle power plant; NL, the Netherlands; NPV, net present value; O&M, operating and maintenance; PC, ultra supercritical pulverised coal (and biomass) fired power plant; ppm, parts per million; PV, photovoltaic systems; RES, reference energy system; RF, retrofit; SE, strong Europe scenario; TCR, total capital requirement; WEO, World Energy Outlook, published by IEA; WLO, Welfare and Environmental Quality report, published by ECN

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temperature on earth to maximum 2 °C or even stricter.¹ These studies also show the tremendous effort which is needed to reach this goal of limiting greenhouse gas (GHG) emissions. This is illustrated by the fact that human induced CO₂ emissions (excluding CO₂ emissions due to deforestation) were increasing by 0.8% on average in the period 1990–2000, while they increased with 3.3% on average over the period 2000–2006 (Boden et al., 2009). As a consequence the CO₂ emissions are at the high end of the range of the IPCC emission scenarios (Weyant et al., 2006; IPCC, 2007b). In a recent publication by Meinshausen et al. (2009) it is argued that diminishing the annual global CO₂ emissions to 50% of the 2000 level in 2050, is not sufficient to keep global warming below 2 °C. Instead they state that the cumulative amount of CO₂ emitted in the period 2009–2050 should not be more than about 700 GtCO₂ to have a 75% probability to stay below 2 °C. According to them, this probably cannot be achieved without short term actions that limits CO₂ emissions to less than 25% above 2000 levels in 2020.

It is expected that CO₂ capture and storage (CCS) will play an important role in realising the necessary emission reductions. In

¹ This scientific view is also recognised by the international political arena (COP15, 2009).

the Energy Technology Perspectives (ETP) study of the International Energy Agency (IEA, 2008), CCS is one of the key technologies in the Blue Map scenario,² contributing for 19% to the total CO₂ emission reduction in 2050. Development and implementation of capital-intensive technologies with a long life span such as CCS require a stable long-term investment environment. At present, however, such a stable investment environment is lacking because of inadequate international cooperation on climate change policy and uncertainty about future emission reduction targets. This can have major consequences for investments in CCS and the planning of CCS deployment activities, and also on the CO₂ emission reduction potential and costs on a national scale. The research question addressed in this paper is: what could be the impact of different international climate policy frameworks on the implementation of CCS in a national energy system such as the energy system of the Netherlands? The Netherlands is chosen, because it is an interesting country for CCS deployment with good CO₂ storage possibilities, and relatively short distances between large point sources and potential sinks for CO₂ (Broek et al., 2010a). We will consider the following climate policy features which might affect the implementation of CCS:

- *Insufficient international coordination of climate policy*

In an optimal trading scheme,³ all GHG emissions will be included and long-term targets will be set such that welfare is maximised by realising emission reductions at the lowest possible cost. To obtain a carbon price in all major emitting countries, an effective international coalition is needed. So far, such a coalition has not materialised and it is uncertain whether this coalition will ever be formed. The United Nations Climate Change conference in Copenhagen (COP15) in December 2009 also failed to produce an effective international agreement on further emission reductions (COP15, 2009). And even if an agreement will be successfully negotiated in Mexico in 2010, it remains to be seen whether this is sufficient to meet the 2 °C target as no restrictions on cumulative CO₂ emissions have been proposed so far (IISD, 2010). Countries are unwilling to implement stringent climate policies if other countries do not agree to do the same, because of fear of loss of competitiveness. With less ambitious targets, there is less incentive for investment in technologies such as CCS.

- *Uncertainty about long-term emission caps and allowance prices*
Emissions from the electricity sector in the EU are regulated by the European greenhouse gas emission allowance trading scheme (ETS). The expected price of allowances during the lifetime of a CCS installation is therefore an important factor for the investment in CCS, especially when the demonstration phase is over in which additional funding is available for the development of CCS.⁴ Uncertainty about the emission target of the EU for 2020, which depends on the outcome of an international agreement on climate change policy, increases the risks of investing in CCS.⁵ Moreover, for the period after

2020, a cap has not yet been set and a long-term goal such as the 2 °C target is not specific enough to formulate expectations about future caps. Consequently, it is difficult for firms to formulate expectations about the post-2020 price of GHG allowances, which will also influence the investment decisions of firms. Especially for long-term capital intensive emission reduction options such as CCS, the lack of a long-term ceiling will reduce their attractiveness vis-à-vis emission reduction options which have a shorter time horizon.

- *Uncertainty about the role of CDM*

From 2012, it is still unknown to what extent certified emission reductions (CERs), which can be obtained by CO₂ emission reduction in developing countries through the clean development mechanism (CDM), can be used in the ETS. This depends on an international agreement. However, the use of CERs is expected to have a major influence on the price of CO₂ and therefore on the choice of abatement technologies.

- *Impact of renewable energy target*

In addition to the CO₂ emission target, the EU has a renewable energy target of 20% in 2020 of total EU energy use (European Union, 2009a). While part of this target will be met through the 10% target for energy from renewable sources in transport in 2020, it is estimated that more than half of the 20% renewable energy target will come from EU ETS sectors (EC, 2008a). This will limit a priori the scope for CCS because part of the fossil fuel based generation will diminish and therefore there is less opportunity to apply CCS. Furthermore, assuming that the total cap for the ETS sectors is not reduced, a renewable target will lower the price of the allowances if it compels power producers to use more renewable energy sources than they would without the renewable target. Lower allowance prices might reduce the profitability of CCS and therefore diminish the use of CCS.

We investigate the impact of climate policy on CCS through a combination of a top-down computable general equilibrium model and a bottom-up energy model. Top-down computable general equilibrium models (CGE models) represent economy-wide interactions, including international trade, energy supply and demand, inter-industry demand and supply for goods and services, factor markets, and consumer demands. They are suitable to assess the influence of energy and environmental policy on the economy, but usually cannot provide technological details which may also be relevant for policy making.

Energy bottom-up models focus on the energy system itself and uses disaggregated data of existing and emerging technologies. They can investigate the implementation of a specific technology such as CCS in detail, but they neglect potentially important interactions of the energy sector with the rest of the economy (Frei et al., 2003; McFarland et al., 2004; Dagoumas et al., 2006; Böhringer and Rutherford, 2008; Van Vuuren et al., 2009).

Using both types of models allows us to enhance their strengths and to reduce their weaknesses. Several solutions exist to achieve that (Hourcade et al., 2006). One solution is to incorporate more technological detail in a CGE model. However, in practice the results with respect to technological detail remain limited: usually not more than a general overview of the resulting energy mix is presented or only some numerical examples (Frei et al., 2003; McFarland et al., 2004; McFarland and Herzog, 2006; Böhringer and Rutherford, 2008). A second solution is to extend an energy bottom-up model with economic interactions, see, for example, the MARKAL-MACRO model (Chen, 2005; Strachan and

² The Blue Map scenario is the most far reaching scenario in terms of emission reductions in the ETP study. In this scenario CO₂ emissions will decrease to 14 GtCO₂ per year in 2050 in order to stabilise CO₂ concentration at 450 ppm.

³ A scheme in which marginal abatement costs are equalised for all major emitting countries and installations, so that all technologies which are cost efficient at a given CO₂ price will be used.

⁴ For example, the 300 million allowances (rights to emit one tonne of CO₂) in the New Entrants' Reserve of the European ETS that are set aside for subsidising installations of innovative renewable energy technology and CCS (EU, 2009).

⁵ Currently, the emission cap for the EU-ETS is depending on the outcome of an international agreement on climate change policy. The EU intends to reduce the GHG emissions with 30% compared to 1990 by 2020 if other developed countries commit themselves to comparable emission reductions, and otherwise with 20% (Council of the European Union, 2007). In the latter case, the cap for GHG emission

(footnote continued)

allowances in EU-ETS is 21% lower compared to the 2005 GHG emissions in 2020 (European Union, 2009b).



Fig. 1. Scheme of the methodology applied in this analysis.

Kannan, 2008). In this approach some aspects of the economy are modelled, like an endogenous energy demand or a GDP which depends on developments in the energy system, but other macro-economic interactions are not included. A third solution is to combine the strengths of both type of models by soft-linking them. For example, in studies by Hoefnagels et al. (2009) and Altamirano et al. (2008), the results from bottom-up models are used in a CGE model to evaluate the macro-economic impacts of a shift in fuel and/or technology mix. Examples of the opposite direction (i.e. to assess the impact of policy on the technology mix) are two MIT studies by Schäfer and Jacoby (2005, 2006) which exports developments of energy demand and energy prices from a CGE model, EPPA, into MARKAL, to assess the impact of climate policy on the transport sector in the United States. In this study, we aimed to do a similar exercise with two models having different geographical scopes in order to assess the impact of global climate policy on the introduction of CCS in a national energy system.

In our study, we used WorldScan (Lejour et al., 2006), a model for international economic policy analysis to determine the consequences of alternative GHG emission mitigation scenarios up till 2050. This generated consistent time profiles of energy demand, energy prices, and CO₂ emission prices on world, regional, and national level. By feeding these into MARKAL-NL-UU (Broek et al., 2008), a techno-economic model of the Dutch power generation sector and CO₂ intensive industry, we were able to explore the prospects of CCS on a national level.

The structure of this paper is as follows. Details about the adopted methodology and input data can be found in Section 2. Results and discussion are presented in Sections 3 and 4. Finally, in the Section 5 conclusions are drawn with respect to the impact of international climate policy on the implementation of CCS.

2. Methodology

2.1. Overview

Fig. 1 depicts a scheme of the methodology applied in this analysis including the soft-link between WorldScan and MARKAL-NL-UU. The WorldScan model was used to investigate four alternative global climate policy scenarios described below (Lejour et al., 2006; Manders and Veenendaal, 2008). The WorldScan runs resulted in time series for the international CO₂ price, energy prices, and the development of the electricity and energy demand in Europe and the Netherlands. These parameters were used as exogenous input in MARKAL-NL-UU, the techno-economic model of the Dutch power generation sector. Next, by running MARKAL-NL-UU, the effect of the CO₂ price on CCS deployment in the Netherlands for the period 2000–2050 was investigated. The driving forces in the MARKAL-NL-UU model were the total Dutch final demand for electricity and the CO₂ price.

2.2. WorldScan

2.2.1. Modelling approach and input data

The macro-economic consequences of climate policy scenarios were assessed using the applied general equilibrium model,

WorldScan. This model has global coverage and in particular detailed regions within Europe; in total 14 regions and countries are specified. Furthermore, it distinguishes between 25 markets for goods and services and factor markets for labour, capital, land and natural resources in the regions (see Appendix A). With respect to climate policies, four categories of regions were distinguished: EU-27 (1), other developed countries (2), fast developing countries (3), and least developing countries (4). The first two groups are referred to as Annex I, and the last two groups as the non-Annex I countries to the Kyoto Protocol (UNFCCC, 1997).

The WorldScan model was calibrated to the base year 2004, for which data were mainly taken from the Global Trade Analysis Project-7 (GTAP-7) database (Narayanan (Editors) and Walmsley, 2008).⁶ This static calibration relied on the following exogenous inputs: elasticities of substitution in production (that are compatible with those in similar models, see Lejour et al. (2006) for details), substitution elasticities in demand for varieties from different geographical origins (taken from Hertel et al. (2007), and income elasticities of consumer demand at sectoral level (taken from the GTAP-database)). Fig. 2 shows the nested structure of constant elasticity of substitution—aggregates that were used to describe production techniques in WorldScan. Each aggregate allowed for a different elasticity of substitution for the underlying inputs.

Furthermore, WorldScan was calibrated to a baseline time path with exogenous projections of population, labour participation, GDP growth rates (that were adopted in the model by adjusting total factor productivities), and energy use in volume terms (see description of BASELINE scenario below). The energy volumes were adopted by adjusting the energy efficiencies indices of the energy carriers at the regional level: a change in the index was compensated by changing the capital requirements (e.g. an increase in the index required an increase in capital inputs such that the energy carrier price was maintained at the level of the previous year).

In WorldScan, seven energy carriers were distinguished: coal, petroleum, natural gas, solid biomass, bio-ethanol, biodiesel, and other renewables without any further subclassifications. Only the first three contributed to the CO₂ emissions simulated in the model. CCS was not included in WorldScan. The following six sectors were assumed to be covered by the EU-ETS: electricity; ferrous metals; chemical, rubber, and plastic products; mineral products; paper products and publishing; and non-ferrous metals.⁷

In WorldScan all agents take prices as given and thus decide on optimal consumption and production and investment quantities. These decisions affect the quantities demanded for imports and production inputs. Changes in demand and supply will affect prices. In equilibrium all prices will have adjusted such that all

⁶ This database contains integrated data on bilateral trade flows and input-output accounts for 57 sectors and 113 countries and regions.

⁷ The coverage of these sectors is somewhat broader than actual coverage by EU-ETS. Most emissions issued by the combustion of fossil fuels in the sectors Electricity and Ferrous metals can be considered to be subject to the EU-ETS emission ceiling, but the remaining sectors comprise also activities that are not covered by EU-ETS (such as publishing as opposed to paper production).

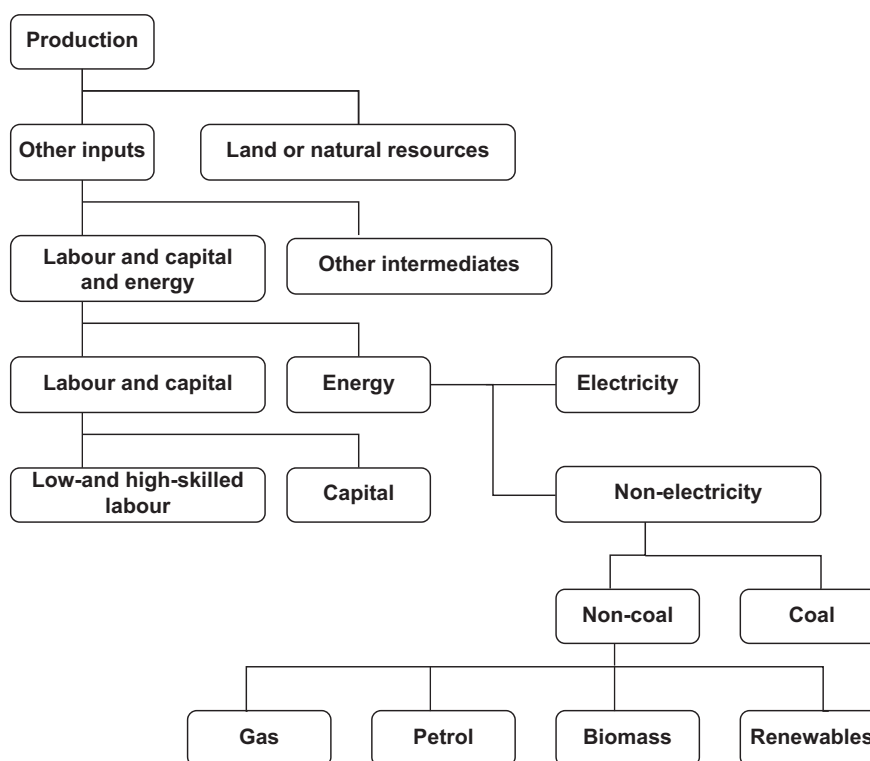


Fig. 2. Constant elasticity of substitution production nest in WorldScan.

markets are clearing and no agents can improve their objective anymore.⁸ In particular, price formation of energy carriers is affected by the production costs, demands for the energy carriers, and the availability of natural resources.⁹

2.2.2. International climate change policy scenarios

The most recent study using WorldScan to investigate climate change policies is (Manders and Veenendaal, 2008). This study built upon scenarios developed by Boeters et al. (2007). From this study, we derived four global policy scenarios, namely the BASELINE, IMPASSE, IMPASSE—NO CDM, and GRAND COALITION scenario. These scenarios do not reflect the recent financial crisis and its impact on economic development. Consequently, the results for 2020 will to some extent overestimate the need for emission reduction (and therefore CO₂ prices), because the actual level of economic activity will be lower, given the lower current level of GDP.

2.2.2.1. BASELINE. Manders and Veenendaal (2008) use as baseline a so-called middle-course scenario without climate policy developed by the Dutch Environmental Assessment Agency (Van Vuuren et al., 2007). This scenario is based on estimates of trends, and is comparable to the reference scenario used by the IEA (2004) and the so-called B2 scenario used by the IPCC (2000). According to this baseline, the global population continues to expand to 9 billion in the middle of this century, and decreases slightly thereafter. Combined with a worldwide economic growth of around 2.7% per year, the global demand for energy will increase significantly: doubling current consumption in 2050, and tripling it in 2100. This expansion takes place primarily in emerging developing countries, thus reducing current

gaps between their energy consumption per capita and that in industrialised countries.

2.2.2.2. GRAND COALITION. The GRAND COALITION scenario results from an “ideal” development of climate policies. In this scenario, international negotiations succeed in forming a “grand coalition” that includes not just the Annex I countries, but also large, fast-growing developing countries such as China, India and Brazil. A new climate mitigation regime follows the so-called “multi-stage approach” (Elzen et al., 2006), and stipulates specific efforts such that the 2 °C target is expected to remain feasible. The present level of development and GHG emissions per capita of the various participating countries determine the extent of the mitigation efforts and the type of commitment (absolute, relative or no commitment at all). Initially, up to 2020, emissions of some least-developed countries are not restricted; whereas more advanced developing countries commit themselves to relative targets. All Annex I countries accept absolute emissions reduction targets. After 2020 all countries accept relative or absolute targets.

The costs of significant emissions reductions remain limited because emission trading is used on a large scale. Not just the countries with absolute targets (Annex I), but also the nations with relative targets (China, India and Brazil) use the Common Trading Scheme (CTS), at least for the energy-intensive sectors. Using opportunities created by the Clean Development Mechanism (CDM) is an option in countries with no restrictions on emissions. But since the greatest potential for relatively inexpensive mitigation options is in the fast-developing countries and can be reached via emissions trading, CDM is negligible.

2.2.2.3. IMPASSE. Despite intensive negotiations, the developed and the larger, fast-developing countries fail to achieve post-2012 climate agreements. In particular, key countries (i.e. USA, Russia, and China) do not consider global warming urgent enough. This leads to an “impasse”, and no follow-up agreements are made for

⁸ Imperfect markets caused by organisations with monopoly power (e.g. OPEC) were not modelled in WorldScan.

⁹ In this WorldScan version, it was assumed that new natural resources are found at same rate at which they are depleted.

the post-2012 period. The USA continues a policy of encouraging technology development, participating in the Asian Pacific Partnership, and promoting platforms such as the Carbon Sequestration Leadership Forum. The EU tries internally to keep its ETS alive—at its stated minimum reduction level of 20% below 1990. Thus, it is hoped that in the long run, when climate policy would rank higher on the international policy agenda, it will be relatively easy to switch over to much more stringent emission restrictions. CDM is used with some restraint and the use of CDM continues to increase slightly after 2020. The other Annex I countries hardly implement climate policies—any policies they put in place are integrated where possible into other policy areas, such as those focusing on security of energy supplies and local pollution. Japan, Australia and Canada fall back on the Asian Pacific Partnership, where the voluntary agreements have little effect. The developing Asian countries also continue to participate in Asian Pacific Partnership. These developing countries take no new initiatives, but are prepared to continue with CDM. In this scenario achieving the 2 °C maximum objective is highly improbable.

2.2.2.4. IMPASSE—NO CDM. This scenario is similar as IMPASSE, except that the ETS does not allow for CO₂ reduction measures in developing countries by CDM.

2.2.2.5. Renewable energy target. In the GRAND COALITION as well as the IMPASSE scenarios the renewable energy target (20% of EU energy usage in 2020) is imposed at the EU-level. The 20% renewable target is maintained as a lower bound in physical terms at the level reached in 2020 in the years thereafter. The burden over member states is shared by trading renewable energy certificates. Consequently, the marginal costs of meeting the renewable energy target are equal in all member states.

Further details on the WorldScan scenarios used in this study are presented in Table 1.

2.3. MARKAL-NL-UU

2.3.1. Modelling approach and input data

MARKAL-NL-UU is based on the MARKAL (an acronym for MARKet ALlocation) methodology that provides a technology-rich basis for estimating energy dynamics over a multi-interval period (Loulou et al., 2004). MARKAL generates economic equilibrium models formulated as linear (or non-linear) mathematical programming problems. It calculates the technological configuration of an energy system by minimising the net present value of all energy system costs. With this model we evaluated the impact of the different CO₂ price paths by looking at the resulting CO₂ emissions from the electricity sector and the CO₂ intensive industry, and the contribution of CCS to this CO₂ emission reduction. In our study the period 2005–2050 was investigated using a time step of 5 years. Prices are given in €₂₀₀₇ unless otherwise stated.

The main input data of MARKAL-NL-UU were the following:

- Development of costs and performance characteristics of electricity generating technologies (including power plants with CCS, nuclear power plants, and renewable electricity generation technologies) and of CO₂ capture units in the industry. The large scale power plants are either natural gas combined cycle power plants (NGCC), pulverised coal-fired power plants with possible co-firing of biomass (PC), integrated coal (and biomass) gasification power plants (IGCC), or gas-fired combined heat and power generation plants (CHP). We assumed that NGCCs can operate in flexible mode, while coal-fired power plants in base load mode only. Key data are shown in Appendix

B, and a detailed description can be found in Broek et al. (2008, 2010b) and Damen et al. (2009).¹⁰ Data for combined heat and power generation (CHP) units were based on two reports in which the profitability of new and old CHP units in the Netherlands is estimated (Hers et al., 2008b, 2008a).

- CO₂ storage potentials, and costs for CO₂ transport and storage. The sink inventory is based on data compiled by Christensen et al. (2004), Kramers et al. (2007), TNO (2007b, 2007a) and Ramírez et al. (2009) and resulted in a selection of 123 CO₂ hydrocarbon fields and aquifers which are considered suitable for CO₂ storage (e.g. deeper than 800 m, reservoir rocks with porosity more than 10%) with a total estimated CO₂ storage capacity of 1.2 GtCO₂ onshore and 1.1 GtCO₂ offshore (see Table 2 for availability of CO₂ storage capacity over time).¹¹ Furthermore, we assumed that the large aquifer in the Utsira formation in the Norwegian part of the North Sea with an estimated capacity of 42 GtCO₂ (Bøe et al., 2002) is available for storage of Dutch CO₂. Based on several sources, we estimated average CO₂ storage costs for onshore and offshore storage in the hydrocarbon fields and aquifers (see Appendix B). We also distinguished between costs for CO₂ storage when facilities of the gas production activities can be re-used, and when this is not the case (i.e. if there is a gap of more than 5 years between gas production and CO₂ storage activities). Average CO₂ transport costs for transport to onshore sinks, offshore sinks, or the Utsira formation were derived from Broek et al. (2010b), a study which specifically investigates the development of the CO₂ infrastructure (see Appendix B).
- Assumptions on import and export of electricity. In the model runs, it is assumed that electricity may be exported from 2010 to 2020, but not in the years thereafter in order to keep the analysis focussed on the Dutch electricity market. In a recent report of TenneT¹² investigating the security of electricity supply in the Netherlands, the Dutch net electricity export grows from 0 GW in 2008 to 4.6–16 GW in 2016 depending on the variant. In the low export variant, the electricity demand in the Netherlands does not decrease due to the economic recession, and not all planned power plants will be built (only around 10 GW). In this variant, the export potential has its maximum in 2013 and then decreases again. In the high export variant, the Dutch electricity growth is less and an additional 18.5 GW power plants will be built between 2009 and 2016, and 2.3 GW wind power. 4.6 GW would mean an export potential of around 30 TWh (assuming an average capacity factor of 75%) (TenneT, 2009). According to TenneT this export potential may either increase or decrease after 2015.
- A limit to the deployment of nuclear power in the Netherlands. Nuclear power phases out in 2033 when the existing 450 MW nuclear power plant in Borssele has to shut down (VROM, 2006). In the sensitivity analysis, the effect of extra nuclear capacity is presented.
- The vintage structure of the electricity generation sector including the large power plants (responsible for 43 MtCO₂ in 2004) and industrial processes (responsible for 26 MtCO₂ in 2004). The vintage was updated with all the plans for new capacity which are in the realisation phase. These include 3.6 GW of PCs (of E.ON and Electrabel in Rotterdam, and RWE in the Eemshaven), and 5.1 GW of NGCCs (see Fig. 3).

¹⁰ All costs were updated to €₂₀₀₇ by using the CEPCI index.

¹¹ The Slochteren field in Groningen with an estimated capacity of about 7 GtCO₂ was not included in the inventory, because it is probably unavailable for CO₂ storage before 2050 (TNO, 2007c).

¹² TenneT is the Dutch transmission system operator who is responsible for administering the national transmission grid and safeguarding the reliability and continuity of the Dutch electricity supply.

Table 1
Implementation of CO₂ emission reduction in WorldScan.

		EU-27	Other Annex 1 countries	Fast developing countries	Least developing countries
All scenarios		World population grows to 9.1 billion people in 2050. The population in the EU-27 and the Netherlands decreases from 489 to 457 and from 16.3 to 15.7 million people between 2004 and 2050, respectively. Average economic growth of 1.7% per year in EU-27, 2.2% in other Annex 1 countries, 4.5% in fast developing countries and 3.9% in least developing countries. Global economic growth amounts to 2.7%. No CO ₂ emission reduction targets			
BASILINE		Overall CO ₂ emission reduction target of 20–30% in 2020 compared to 1990 levels. Emission allocations per country based on per capita emissions.			
GRAND COALITION	2012–2020	No distinction between ETS and non-ETS in the EU after 2012. All sectors become then subject to the single emissions ceiling of the CTS.	Brazil and China reduce CO ₂ emissions by 1% annually compared to the baseline scenario (i.e. they are approximately 5% below baseline after 5 years), and India, Other South-east Asia, and Other Latin America by 0.5% per year. Participation in CTS after 2012	Middle East, North Africa, and Rest of World have no GHG emission reduction commitment and do not contribute via CDM either	
	2020–2050	Target of 20% renewable energy use in 2020. A worldwide target of 13.5 GtCO ₂ in 2050. Emission allocations per country based on per capita emissions. Floor of 20% renewable energy use.			
IMPASSE	2012–2020	Emission target of 20% overall CO ₂ emission reduction compared to 1990 levels in 2020. Distinction between ETS and non-ETS sectors: non-ETS sectors have to meet national reduction targets by national carbon taxation. No trade in emissions allowances outside the EU-ETS. Limited use of CDM-credits: (for ETS-sectors one third of reduction below BASELINE; for non-ETS sectors 3 percent of 2005 emissions). Target of 20% renewable energy use in 2020.	Reduction of CO ₂ emissions by 0.25% per year, compared to the BASELINE scenario.	No reduction commitment at all. Voluntary contribution via CDM in ETS sectors.	No reduction commitment and no contribution via CDM either
	2020–2050	Emission target of 20% overall CO ₂ emission reduction compared to 1990 levels from 2020 to 2050. Limited use of CDM-credits (limits as in period 2012–2020). Floor of 20% renewable energy use. Same as Impasse, except no CDM	Reduction of CO ₂ emissions by 0.25% per year, compared to the BASELINE scenario.	No reduction commitment at all. Voluntary contribution via CDM in ETS-sectors.	No reduction commitment and no contribution via CDM either
IMPASSE—NO CDM					

The industrial processes included were the ones generating small quantities of pure CO₂ (i.e. hydrogen, ammonia, or ethylene oxide production units) or large quantities at a single site (i.e. steel industry, refineries, ethylene production units, and cement).

- Assumptions on the deployment of photovoltaic systems (PV) and wind turbines (see Table 3). This includes the offshore wind energy and PV capacity proposed by the current government (EZ, 2008) as part of its regular energy policy and its additional policy to stimulate the economy (i.e. extra subsidy for a capacity of 500 MW offshore wind energy) (Ministry of General Affairs, 2009).
- Assumptions on biomass availability for the electricity generation sector (i.e. biomass for waste incineration, CHP units and co-firing in coal-fired power plants). Based on a global biomass potential assessment study and a study on the economic impact of biomass use in the Netherlands (Hoeftnagels et al., 2009; Dornburg et al., 2010), a maximum bound was derived for the availability of biomass for electricity generation (see Table 4). Furthermore, it was assumed that 30% biomass can be co-fired in coal-fired power plants built before 2015, and 50%

in newer coal-fired power plants.¹³ If CO₂ emissions originating from biomass firing are captured and stored underground, this leads to negative emissions as we assume that firing biomass is CO₂ neutral.¹⁴

- Costs were discounted with a discount rate of 7%.

2.3.2. Scenarios in MARKAL-NL-UU

2.3.2.1. BASELINE, GRAND COALITION, IMPASSE, and IMPASSE—NO CDM scenarios. The results of the four different WorldScan scenarios were

¹³ Meerman et al. (2009) state that co-firing of 100% biomass in an IGCC with existing technology is possible, but diminishes the thermal input efficiency of an IGCC by 15%. New (advanced) combustion technologies (e.g. circulating fluidized bed) could have higher flexibility. A study which includes details on flexible co-firing in coal-fired power plants, could assess the potential of the biomass co-firing further.

¹⁴ For example, in a coal-fired power plant with an efficiency of 40%, 50% co-firing, and a 90% capture ratio, the CO₂ emissions would be minus 0.40 kg/kWh. Note that we did not include indirect CO₂ emissions due to the production and transport in this analysis. If indirect CO₂ emissions from processing of biomass to make it suitable for co-firing (e.g. wood pellets) and transport were accounted for negative emissions would be minus 0.38 kg/kWh based on Vliet et al. (2011).

Table 2

Availability of CO₂ storage capacity^a over time^b with and without re-use of wells and gas production facilities as modelled in MARKAL-NL-UU.

	2010	2020	2030	2040	2050
With re-use of wells and gas production facilities					
Onshore with re-use (GtCO ₂)	0.3	1.2	1.1	1.0	0.4
Offshore (GtCO ₂)	0.1	0.8	1.0	0.8	0.6
Without re-use					
Onshore (GtCO ₂)	0.0	0.0	0.0	0.2	0.8
Offshore (GtCO ₂)	0.0	0.0	0.1	0.3	0.6
Utsira formation (GtCO ₂)	42	42	42	42	42

^a This is the total CO₂ storage capacity. MARKAL-NL-UU takes into account that if CO₂ is stored, less capacity remains in the following periods.

^b Timing of availability is based on the production plans of the hydrocarbon fields (TNO, 2007c).

translated to four analogue scenarios in MARKAL-NL-UU: BASELINE, GRAND COALITION, IMPASSE, and IMPASSE—NO CDM. As WorldScan generated results for the development of the Dutch electricity demand, the CO₂ price, and the energy prices, these were used as input in MARKAL-NL-UU. The CO₂ price was implemented as a tax on CO₂ emissions originating from electricity generation from fossil fuels in MARKAL-NL-UU.¹⁵ Consequently, all mitigation measures with lower cost than this tax will be implemented in a model run. Also the contribution of the Netherlands to achieve the renewable 20% EU-target in 2020 was taken from WorldScan. This contribution was set as a lower bound in MARKAL-NL-UU for the period 2020–2050.

2.3.3.2. GRAND COALITION-RENEWABLE⁺ scenario. Furthermore, in order to investigate the cost-effectiveness of renewable energy versus CCS, we investigated a fifth scenario GRAND COALITION-RENEWABLE⁺. Given the deep emission cuts and the consequently high CO₂ prices towards 2050, renewable energy use increases substantially in the WorldScan scenario. In the GRAND COALITION-RENEWABLE⁺ scenario, we took over this high share (on top of the 20% EU renewable target) into MARKAL-NL-UU for the whole period 2020–2050.

2.3.3. Sensitivity analysis

In the sensitivity analysis, we examined two aspects: the impact of uncertainty of CO₂ emission ceilings after 2020 on CCS deployment in the near term, and the sensitivity of CCS deployment versus alternative assumptions of key parameters.

2.3.3.1. Uncertainty of CO₂ price. The uncertainty about future CO₂ emission ceilings and associated CO₂ prices was investigated through the inclusion of two *hedging cases*. In the *first case* it was assumed that CO₂ prices up to 2020 are high (IMPASSE—NO CDM), and in the *second case* low (as in GRAND COALITION). After 2020, the CO₂ price could follow three different price paths depending on alternative post-2020 caps. These price paths are based on the three scenarios, BASELINE, GRAND COALITION, and IMPASSE—NO CDM, and were assumed to be equally probable. The purpose of this analysis was to investigate what may happen with CCS deployment up to 2020 if the CO₂ price can go into various directions after 2020. The stochastic modelling method in the MARKAL model was used for this purpose (Loulou et al., 2004).

¹⁵ Currently in the Dutch national allocation plan for the Kyoto-period 2008–2012 at least 16.5 GW is included in the ETS system (EZ and VROM, 2007) of a total of 23.0 GW in 2006 (CBS, 2009). This amount is based on combining the installations in the national allocation plan with the capacities of the database made for Broek et al. (2008) and the Dutch National Allocation Plan (EZ and VROM, 2007). Not included in the ETS system are the nuclear power plant (0.5 GW), wind turbines (1.6 GW), small scale CHP units like gas engines (2.4 GW), small gas turbines, and small steam turbines (e.g. in the waste incineration sector).

2.3.3.2. Alternative assumptions of key parameters. In the sensitivity analysis, we explored the influence of alternative developments of various CO₂ reduction measures (i.e. of PV, CCS, and nuclear), fuel prices, and CO₂ storage potential, as these factors affect the introduction of CCS. Their influence was compared to another scenario, namely the GRAND COALITION scenario. It is interesting to study alternative ways to reduce CO₂ emissions in this particular scenario, because a national strategy to reduce emissions significantly seems more likely in an international policy pursuing a maximum increase in temperature of 2 °C.

3. Results

3.1. WorldScan results

3.1.1. Developments of GDP and energy demand

For each scenario, GDP and energy demand projections as calculated by WorldScan are presented in Table 5.

- In the GRAND COALITION scenario GDP growth in the EU-27 is lowest resulting in a 1.0% lower GDP in 2050 compared to the Baseline. In the IMPASSE—NO CDM scenario, it is 0.4% lower in 2050, while the use of CDM in the IMPASSE scenario limits GDP loss to 0.3%. Note that WorldScan does not include any negative economic effects of climate change itself which occur according to Stern (2006).
- In GRAND COALITION and IMPASSE—NO CDM energy demand in the EU-27 peaks in 2020 and then reduces, and in the IMPASSE scenario it almost stabilizes from 2020. Note that none of the scenarios have a reduced energy demand by 2020 as aimed for by the European Union with their energy package,¹⁶ According to a strategic energy review, this package should lead to a reduction of 5–8% primary energy consumption (EC, 2008b). Also the WorldScan projections for the growth of electricity demand of 2.4% per year are higher than aimed for by the European Union. The strategic review expects an 0.5–0.6% per year electricity demand growth with the energy package and 1.6% per year without (EC, 2008b).

The Dutch electricity demand shown in Fig. 4, grows from 110 TWh in 2005 to 200 and 185 TWh in 2050 for IMPASSE and IMPASSE—NO CDM, respectively. Only in the GRAND COALITION scenario, the electricity demand starts decreasing after 2020. In this scenario, the electricity demand grows to 152 TWh in 2020 and, then, decreases to 120 TWh in 2050.

3.1.2. Development of energy prices

The energy prices resulting from the WorldScan runs are presented in Table 6. The results show that:

- Coal price increases with 63% between 2005 and 2050 in the Baseline scenario. Gas prices increase with 15% between 2005 and 2025 and then decrease slightly. While population grows with 43%, and economy with 240% over the period 2004–2050 in the BASELINE, energy demand grows with not more than 50%. As prices mainly depend on production costs and energy demand developments (scarcity of natural resources is

¹⁶ This energy package encompasses a set of policy measures which must support the achievement of the 20–20–20 targets set by the European Council (Council of the European Union, 2007): 20% reduction of GHG emissions by 2020 compared to 1990, a 20% share of renewable energies in the final overall EU energy consumption, and 20% savings on the EU's energy consumption compared to projections for 2020 as estimated in the Green paper on energy efficiency by the European Commission (EC, 2005).

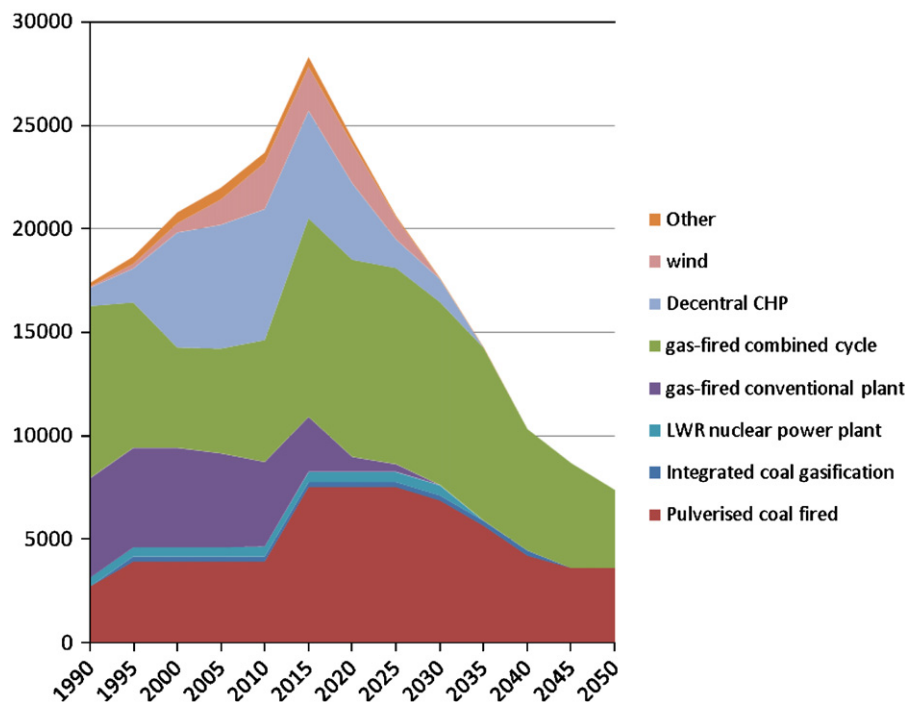


Fig. 3. Development of existing electricity generation capacity in the Netherlands (in MW). It includes planned capacity in the realisation phase.

Table 3

Data for PV, wind capacity, and biomass availability as applied in MARKAL-NL-UU.

Type	To be installed			Upper bound	
	2008	2010	2015	2020	2050
Wind offshore capacity (MW)	228	200 ^a	250 ^a +500 ^b	6000 ^a	
Wind onshore capacity (MW)	222	(1550) ^c	(520) ^c	6000 ^d	6000 ^d
PV capacity (MW)	50	45 ^a	25 ^a		11,600 ^e

^a Source: EZ (2008). The government has made concrete plans to finance the mentioned capacities before 2010 and 2015. These figures were therefore implemented as lower investment bounds in MARKAL-NL-UU. For 2020, the government indicated an ambition of 6000 MW offshore wind energy.

^b Source: Ministry of General Affairs (2009).

^c By 2011 wind capacity on land should have doubled to 4000 MW (VROM; EZ; LNV, 2008). However, the government plans for onshore wind energy were not implemented as lower investment bound, because recent requests for subsidy for wind on land have been very limited EZ (2009).

^d The government also indicates an ambition of 6000 MW onshore wind capacity by 2020 (VROM; EZ; LNV, 2008). However, in an evaluation of the government plans 4000 MW of onshore wind energy is considered to be the maximum under current spatial planning procedures and net capacity (Menkveld (Ed.), 2007). It was assumed that due to spatial limitations this is the maximum amount of wind capacity that can be placed onshore in the Netherlands. In a study that investigates the relation between energy and spatial use Hugo Gordijn (2003), it is recommended to reserve space for wind energy offshore. They estimate that for 20,000 MW wind energy, a surface of 2400 km² would be needed offshore on the Dutch continental shelf. Although this space is available, the locations of wind farms must be carefully planned so that they do not conflict with other sea uses.

^e According to the Dutch energy scenario in the WLO study Janssen et al. (2006), PV may grow from 200 MW in 2020 to 3 GW in 2040. The value of 11.6 GW is obtained with geometric extrapolation.

assumed in WorldScan), it is conceivable that the price of natural gas does not increase very much. On the other hand, the price of coal increases more because of an increased demand for this cheaper fuel.

- In GRAND COALITION coal and natural gas prices are 40% and 20%, respectively, lower than in the BASELINE. Fossil fuel prices are

lower because of worldwide GHG emission reduction in this scenario. However, because CCS is not included in WorldScan, there is also no demand for fossil fuels used in power plants with CCS. Consequently, the prices may have been underestimated.

- The coal price development in WorldScan agrees with values in the World Energy Outlook (WEO) 2009 in which the coal price is 2.5 and 1.5 €/GJ in 2030 in their reference and 450 ppm scenario, respectively (IEA, 2009). However, gas prices in WorldScan are lower than the WEO projections of 8.9 and 7 €/GJ in these WEO scenarios (IEA, 2009).
- The wood pellet price decreases from 7.0 €/GJ in 2005 to around 5.4 €/GJ in 2050. This decline is in line with Uslu et al. (2008) who assess the costs to produce and deliver wood pellets to the Rotterdam harbour in the Netherlands at 4.7 €/GJ.

3.1.3. Development of CO₂ emissions and CO₂ price

Although in the IMPASSE scenarios, a European climate policy is implemented, the global CO₂ emissions almost increase as fast as in the BASELINE (about 55 GtCO₂/yr in IMPASSE versus 59 GtCO₂/yr in the BASELINE in 2050). Only in the scenario GRAND COALITION, global emissions are reduced to 13.5 GtCO₂ per year in 2050, and the cumulative amount of CO₂ emissions over the period 2009–2050 is 964 GtCO₂. This is about 270 GtCO₂ higher than the 700 GtCO₂ needed to have a high probability of warming to stay below 2 °C (see Section 1). Furthermore, note that WorldScan models CO₂ emissions from fossil fuel firing only (being 22 GtCO₂ in 2004). The total amount of CO₂ emissions was already around 27 GtCO₂ in 2000 (Olivier et al., 2005; IPCC, 2007c).¹⁷

The outcomes of WorldScan are coherent with outcomes from other studies. For example, the ETP study by IEA estimates 62 GtCO₂/yr in 2050 in their Baseline scenario (IEA, 2008), and

¹⁷ These emissions exclude post-burn CO₂ emissions from the remainings of biomass after forest fires (around 2.2 GtCO₂ in 2000) (JRC and PBL, 2009).

Table 4
Data biomass availability in MARKAL-NL-UU.

Biomass available	2008	Upper bound			
		2020	2030	2040	2050
1. Worldwide (EJ) ^a	9 (2005)	66	114	181	290
2. For the Netherlands (PJ) ^b	88	448	517 ^c	823	1320
3. For the electricity sector of which (PJ) ^d	49 ^e	137	158 ^f	252	404
Biomass fired in waste incineration installations (PJ) ^g	29	31	32	34	35

^a In the global biomass potential assessment study [Dornburg et al. \(2010\)](#) the biomass potential is estimated to be around 290 EJ in 2050 in a medium development scenario without high levels of learning in agriculture and restraining pressure on natural habitats. In our study, we assumed an average development over time in which the global potential increases from 9 EJ for modern bioenergy use in 2005 (In 2005, also 37 EJ non-commercial biomass (charcoal, wood, and manure for cooking and space heating) was used [Dornburg et al. \(2008\)](#).) to 290 EJ in 2050. The biomass availability for each 5-year time step was based on the average figures for a development with linear growth and one with a growth rate of 8% per year. Note that the choice of growth type has a large consequence for biomass potential estimates over time: e.g. the potential ranges from 29 EJ with 8% growth per year to 103 EJ with linear growth in 2020.

^b The availability of biomass for the Netherlands was derived by applying the egalitarian fairness principle (i.e. equal biomass supply per capita) and the sovereignty principle (the biomass is divided according to the current percentages of national energy use in the global energy use). Until 2025 the sovereignty principle was applied, and from 2025, an average of the two principles.

^c In [Hoefnagels et al. \(2009\)](#), the biomass use in 2030 varies between 150 and 1450 PJ per year.

^d Based on the Dutch biomass study [Hoefnagels et al. \(2009\)](#), in which on average 31% of the primary biomass is used for electricity generation in the different scenarios. The other part of the biomass is used in the transport sector, and chemical industry.

^e The amount of biomass used for electricity generation (excluding organic waste) has fallen from 31 PJ in 2005 to 20 PJ in 2008.

^f The study by [Hoefnagels et al. \(2009\)](#) suggests a biomass use of 120 PJ in the electricity generation sector in 2030 in the high biomass scenario.

^g Part of the biomass is available in the form of organic waste. In the Netherlands 29 PJ organic waste was used in waste incinerations in 2008. We assumed that this will grow at the same rate as the population to 35 PJ in 2050.

Table 5
Development of GDP and the growth of energy and electricity demand in four scenarios as calculated by WorldScan.

Scenario	Unit	GDP		Energy demand growth		Electricity demand growth	
		% Per year		% Per year		% Per year	
		2004–2020	2020–2050	2004–2020	2020–2050	2004–2020	2020–2050
BASELINE	EU-27	2.41	1.37	1.47	0.46	2.50	1.07
	NL	2.31	1.26	2.30	0.36	2.55	1.05
GRAND COALITION	EU-27	2.39	1.35	1.26	−1.59	2.23	−0.11
	NL	2.27	1.10	1.47	−2.18	2.16	−0.77
IMPASSE	EU-27	2.37	1.38	0.86	0.09	2.17	1.03
	NL	2.21	1.26	0.50	0.09	1.97	1.02
IMPASSE—NO CDM	EU-27	2.36	1.38	0.38	−0.02	1.91	0.96
	NL	2.17	1.26	−0.04	0.01	1.60	0.94

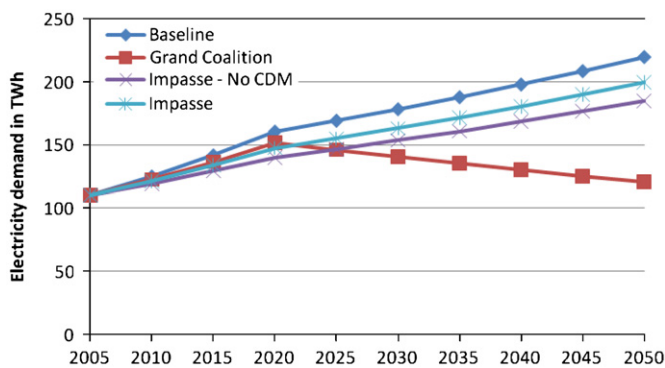


Fig. 4. Development of the Dutch electricity demand for the four scenarios as calculated by WorldScan.

the CO₂ emissions in the SRES scenarios, which are summarised in [IPCC \(2007a\)](#), vary between 35 and 59 GtCO₂ in 2030 ([Fig. 5](#)).

In the IMPASSE and GRAND COALITION scenarios with CDM, the CO₂ prices increase to 23 €/tCO₂ in 2020 while in the IMPASSE—NO CDM scenario it increases to 46 €/tCO₂. The CO₂ price is driven up by the condition that emission reductions should be achieved within the EU itself. These projections are in line with current

forecasts of the CO₂ price for the 3rd ETS phase (2013–2020) presenting prices between €20 and €40 per tCO₂ ([Gorina, 2009](#)) ([Fig. 6](#)).¹⁸

In the GRAND COALITION scenario CO₂ prices increase sharply to 502 €/tCO₂ in 2050 when 45 GtCO₂/yr need to be abated compared to the BASELINE. These figures are very high compared to cost estimates of CO₂ reduction in other studies. For example, in the [IPCC \(2007a\)](#) report it is stated that around 30 GtCO₂/yr may be reduced for less than 124 €/tCO₂¹⁹ in 2030,²⁰ whereas in GRAND COALITION a similar reduction requires an emission price of about 186 €/tCO₂ in 2039. In the ETP study ([IEA, 2008](#)), 35 GtCO₂/yr could be reduced for less than 83 €/tCO₂²¹ in 2050, whereas in WorldScan such a reduction would cost 258 €/tCO₂ in 2043. However, in the ETP study it is also pointed out that marginal

¹⁸ The sources mentioned are Deutsche Bank, Point Carbon, UBS, and Barclays Capital ([Carbon New Finance, 2009](#); [Platts, 2009](#)).

¹⁹ I.e. 100 \$/tCO₂. We assumed that the IPCC data are reported in \$₂₀₀₀.

²⁰ In an evaluation of the energy models used for the IPCC report, it is shown that the results from different models varies between 17 and 30 GtCO₂/yr which could be reduced for less than 124 €/tCO₂ in 2030 ([Van Vuuren et al., 2009](#)). The differences can be explained by differences in baseline, model types, and data input.

²¹ I.e. 100 \$₂₀₀₅/tCO₂.

Table 6
Development of energy prices for the four scenarios as calculated in WorldScan (in €₂₀₀₇/GJ).

		2005	2010	2020	2030	2040	2050
BASELINE	Coal	1.8	1.9	2.1	2.3	2.6	2.9
	Gas	4.7	5.0	5.3	5.4	5.3	5.2
	Wood pellets	7.0	6.8	6.2	5.8	5.6	5.5
GRAND COALITION	Coal	1.8	1.8	1.9	1.8	1.8	1.8
	Gas	4.7	4.8	5.1	4.7	4.4	4.1
	Wood pellets	7.0	6.8	6.0	5.6	5.4	5.3
IMPASSE	Coal	1.8	1.8	2.0	2.2	2.4	2.7
	Gas	4.7	4.8	5.2	5.3	5.3	5.2
	Wood pellets	7.0	6.8	6.0	5.6	5.5	5.3
IMPASSE—NO CDM	Coal	1.8	1.8	1.9	2.1	2.3	2.6
	Gas	4.7	4.8	5.2	5.3	5.3	5.2
	Wood pellets	7.0	6.8	6.0	5.6	5.5	5.4

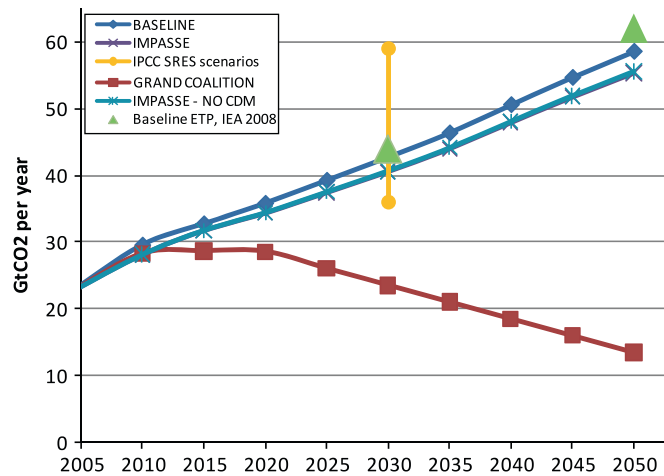


Fig. 5. Worldwide CO₂ emissions from fossil fuel firing for the four scenarios as calculated by WorldScan, the Baseline scenario in ETP 2008 IEA (2008), and the illustrative IPCC SRES scenarios IPCC (2007a).

costs beyond 35 GtCO₂/yr may increase to 200–660 €/tCO₂²² if CO₂ emissions need to be reduced with 50 GtCO₂/yr. One of the reasons for the higher estimates from WorldScan may be that other models incorporate the simulation of cost reductions of abatement technologies through learning-by-doing. These mechanisms are not included in WorldScan.

3.1.4. Renewable energy

In WorldScan it is found that the contribution of the Netherlands to the EU renewable energy target in 2020 leads to a share of 23–27% of renewable energy in the primary energy input (on input basis) of electricity generation in the reduction scenarios. Furthermore, in WorldScan the share of renewable energy in the primary energy input increases to 61% in the GRAND COALITION scenario. We use this value as lower bound in the GRAND COALITION—RENEWABLE⁺ scenario in MARKAL-NL-UU.

3.2. MARKAL-NL-UU results

3.2.1. Development of the power sector and CCS in the Netherlands

Fig. 7 summarises the electricity generating capacity for all scenarios. In this section we focus on two points in time in the

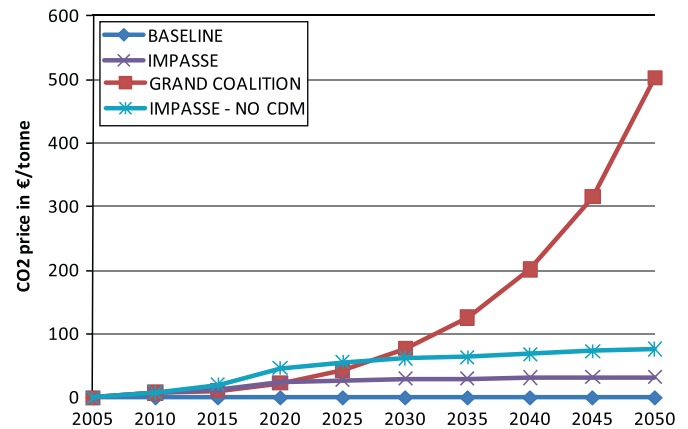


Fig. 6. CO₂ price development for the different scenarios as calculated in WorldScan.

analysis period 2005–2050, namely one in the short term “2020” and one in the long term “2040”.

In general it can be observed that while in the BASELINE, coal-fired power plants play a dominant role over the whole analysis period, this role is less in all CO₂ emission reduction scenarios. The short term strategy is to switch from coal to natural gas and wind energy, the long term strategy is to introduce CCS at large scale in all reduction scenarios except for the IMPASSE scenario. In this latter scenario with a CO₂ price remaining around 30 €/tCO₂, the main strategy is to switch from coal to natural gas.

Specifically about the deployment of CCS, it is found that:

- In the short term, CCS plays a role in the electricity generation sector in the IMPASSE—NO CDM scenario only. In 2020, one power plant of 1.8 GW has been built with CCS, and 2.6 GW of PCs have been retrofitted with CO₂ capture in this scenario. In the GRAND COALITION scenarios, CCS is not used before 2020 because of the availability of low-cost emission reduction options worldwide in this period results in a low CO₂ price.
- From 2030, CCS takes off, leading to an IGCC-CCS capacity between 5.9 and 7.1 GW in 2040. Additionally, in the IMPASSE—NO CDM and GRAND COALITION scenarios 9.5 and 9.0 GW of NGCC-CCS has been constructed in 2040, respectively. In GRAND COALITION—RENEWABLE⁺ only 4.1 GW NGCC-CCS is deployed because of the high share of renewable energy, and in the IMPASSE scenario with a CO₂ price of 30 €/tCO₂ NGCC-CCS is not cost-effective at all. Biomass is co-fired in the CCS coal-fired power plants for 24% in 2020 and between 34% and 48% in 2040 (on the basis of energy input).
- Retrofitting with CO₂ capture units remains limited, considering that 3.6 GW of new PCs will be built around 2015. Besides the 2.6 GW retrofitted in the IMPASSE—NO CDM scenario, retrofitting remains below 0.9 GW in the other scenarios. In the BASELINE without any CO₂ price, the coal-fired power plants keep emitting CO₂, and in the GRAND COALITION scenarios, it is more cost-effective to build IGCCs with CCS compared with retrofitting the older coal-fired power plants.

Fig. 7 also shows two alternative strategies to reach low CO₂ emissions (see Section 3.2.2) in the GRAND COALITION scenarios. In GRAND COALITION—RENEWABLE⁺, it is a strategy combining wind energy, CCS in NGCCs, and CCS in biomass-coal fired power plants, which generate 40%, 15%, and 33% of the electricity in 2040, respectively. In the GRAND COALITION the strategy consists of mainly CCS: 39% output from biomass-coal fired power plants, 49% from NGCCs, and 5% from wind turbines in 2040. This latter strategy is a business as usual scenario in the sense that the

²² The higher end estimate of 660 €/tCO₂ is due to pessimistic assumptions about the costs of CO₂ reduction, especially in the transport sector. The analysis did not include backstop options such as (co-)firing biomass in power plants with CCS (IEA, 2008).

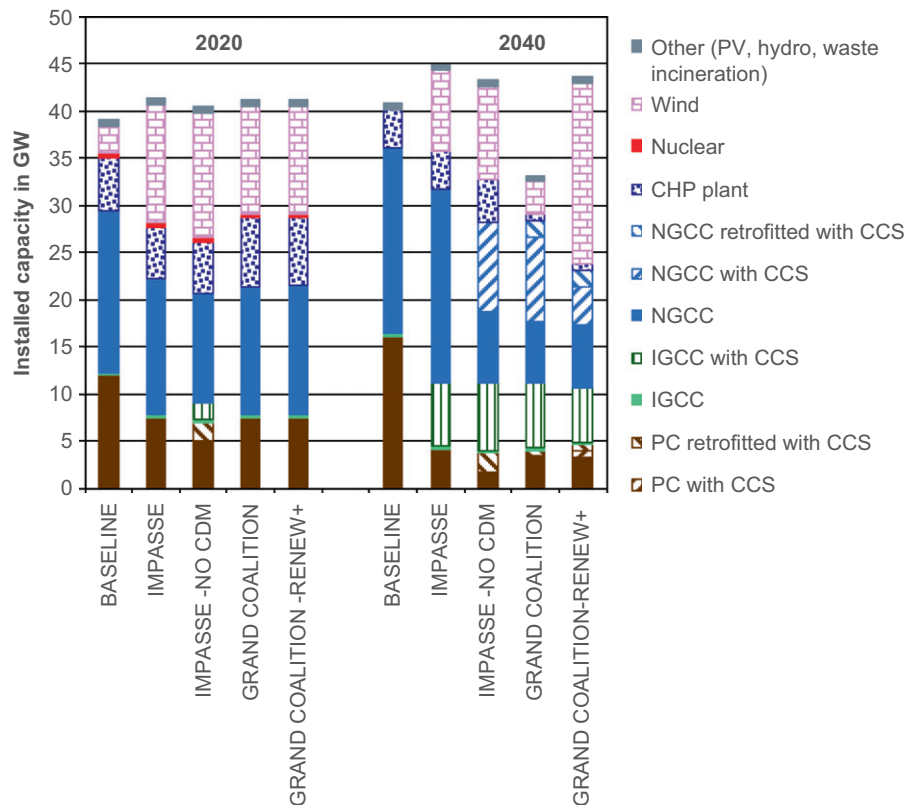


Fig. 7. Total installed electricity generating capacity in the Netherlands in 2020 and 2040 for five scenarios as calculated with MARKAL-NL-UU.

electricity generation sector keeps depending on large scale power plants. Note that in our study, it was assumed that NGCC–CCS can operate in a flexible mode, and that there is additional NGCC capacity which can be used as backup or spinning reserve capacity in both scenarios. However, fuel use requirements and extra CO₂ emissions of these units were not taken into account in our analysis.

In Fig. 8, the primary energy use in the power sector for the years 2020 and 2040 is summarised. This figure supports the observation that coal is the dominant energy source for power generation in the BASELINE, while for all reduction scenarios it is natural gas. The figure also shows the biomass use of which most is co-fired in coal-fired power plants with CCS. In all reduction scenarios, the total amount of available biomass (i.e. 106 PJ) is used in 2020 to reach the EU renewable target. After 2020, the restricted availability of biomass remains the limiting factor for further biomass use in all periods in the GRAND COALITION–RENEWABLE⁺ scenario, and in the other reduction scenarios it is the limiting factor in half of the periods.

3.2.2. Development of CO₂ emissions

Fig. 9 shows the development of the CO₂ emissions from the power sector and the CO₂ intensive industry in the Netherlands for the different scenarios. At first the CO₂ emissions rise from 80 to around 113 MtCO₂/yr in 2015 because the Netherlands is switching from being an electricity importing country to an exporting one with an export of 5–14 TWh in 2015. Next, the scenarios follow different CO₂ emission pathways. In the BASELINE, they keep increasing to 156 MtCO₂/yr, while in GRAND COALITION they fall to negative emissions of 2 MtCO₂/yr in 2050. Negative CO₂ emissions are achieved by co-firing biomass in coal-fired power plants with CCS. The two GRAND COALITION scenarios follow

largely the same emission reduction path, because the extra renewable target in GRAND COALITION–RENEWABLE⁺ is reached by co-firing biomass in the CCS power plants. However, the paths diverge at the end: in 2050 the CO₂ emissions are only reduced to 10 MtCO₂/yr in GRAND COALITION–RENEWABLE⁺. Although in this scenario negative emissions should be achievable as well given the CO₂ price of 500 €/tCO₂, the biomass–CCS combination is limited: the high renewable target of 61% in GRAND COALITION–RENEWABLE⁺ restricts the option of biomass co-firing which is bounded to 50% of the input in this study. In the IMPASSE scenario the CO₂ emissions only reduce to 52 MtCO₂/yr in 2050 due to the low CO₂ prices. Finally, while in the IMPASSE–NO CDM scenario worldwide emissions hardly decrease, the Dutch emissions diminish to 11 MtCO₂/yr.

3.2.3. Contribution of CCS to CO₂ reduction

Fig. 10 presents the amount of CO₂ stored over time per scenario. In most scenarios the amount of CO₂ stored in 2020 is very limited: some CO₂ from the ammonia and hydrogen manufacturing units is stored in the GRAND COALITION scenarios. The only CO₂ capture at power plants in this period is realised in IMPASSE–NO CDM with a CO₂ price of 47 €/tCO₂ in 2020 and 26 MtCO₂/yr stored at this point in time. Next, in this scenario the application of CCS increases fast to 43 MtCO₂/yr in 2025, while only 14 and 8 MtCO₂/yr is stored in the GRAND COALITION scenarios, and IMPASSE scenario, respectively. Around 2030, the use of CCS in the GRAND COALITION scenarios catch up with the IMPASSE–NO CDM scenario. The amount of CO₂ storage in the normal GRAND COALITION becomes even higher. However, from 2045 again most CO₂ is stored in IMPASSE–NO CDM. In this scenario plants retrofitted with CCS are still operating for which relatively a lot CO₂ needs to be stored, while in GRAND COALITION it is cost-effective to invest in new

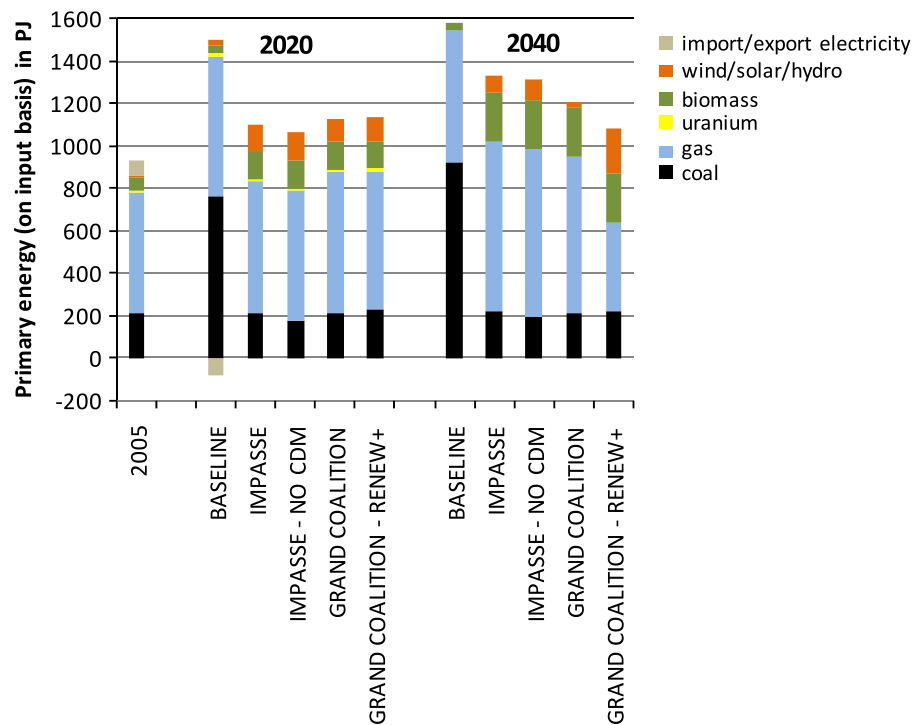


Fig. 8. Primary energy use in the power sector of the Netherlands in 2020 and 2040 per scenario as calculated with MARKAL-NL-UU. Note that it was assumed that for wind/solar/hydro 1 PJe = 1 PJ primary energy.

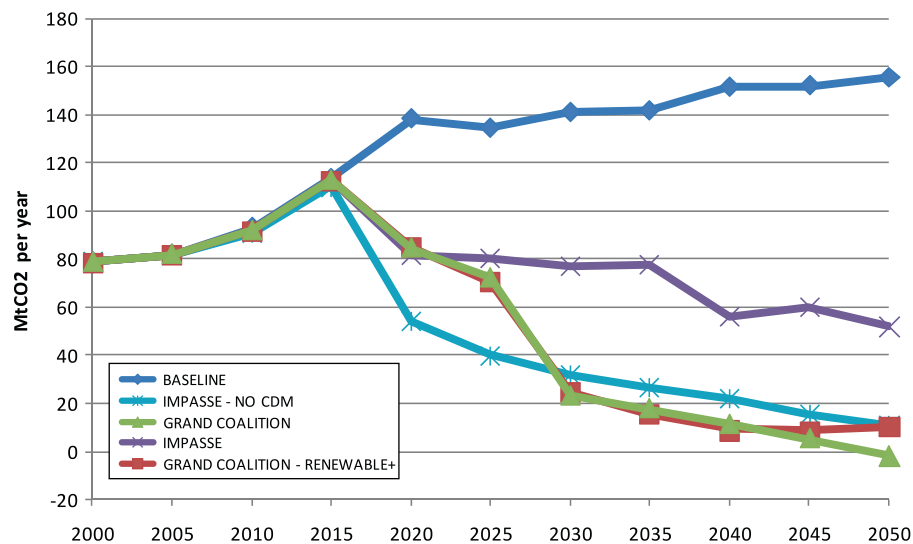


Fig. 9. CO₂ emissions from the power sector and CO₂ intensive industry in the Netherlands per scenario as calculated with MARKAL-NL-UU.

(more efficient) power plants for which less CO₂ needs to be stored. Given that CCS is the main CO₂ mitigation measure in both scenarios, storage continues to grow to around 90 MtCO₂/yr in 2050. In the end, 1.8–2.0 GtCO₂ is stored of which 0.5–0.6 GtCO₂ in the Utsira formation. A prerequisite for such a scenario to continue is that a huge CO₂ storage reservoir remains available. From 2040 in GRAND COALITION-RENEWABLE⁺ the role of CCS diminishes in favour of wind energy. In IMPASSE CO₂ storage remains lower over the whole period, reflecting the lower targets and CO₂ prices.

Fig. 11 summarises the cumulative amount of CO₂ emissions in the Dutch power sector and the CO₂ intensive industry over the period 2009–2050 in the different scenarios. Also the contributions of the different abatement measures to the CO₂ reduction are depicted. In this period, the cumulative CO₂ emissions for the

electricity sector and the CO₂ intensive industry is 5.7 GtCO₂ in the BASELINE, 3.2 GtCO₂ in the IMPASSE, and around 2 GtCO₂ in the other scenarios.²³ In the reduction scenarios between 2.5 and

²³ A translation of the worldwide cumulative CO₂ limit of about 700 GtCO₂ to keep temperature increase below 2 °C (see Section 1) over the period 2009–2050 of (Meinshausen et al., 2009) would translate into a Dutch emission space of 1.5–4.0 GtCO₂ in total. 4.0 GtCO₂ was calculated by using the ratio of Dutch to global CO₂ emissions in 2006, and 1.5 GtCO₂ by using the ratio of Dutch to global population (in the WorldScan scenarios of this study). In the first case, the sovereignty fairness principle was applied (i.e. the percentage reduction of current emissions is equal for all countries) and in the second case, the egalitarian fairness principle (i.e. equal emissions per capita are allowed) (Ringius et al., 2002). Note that in a global trading system, national emission spaces can be enlarged by reducing emissions elsewhere.

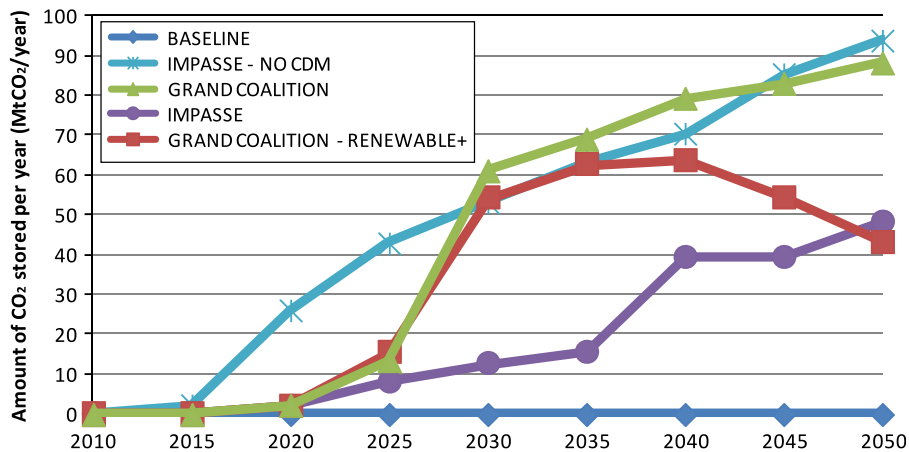


Fig. 10. Annual amount of CO₂ stored in the period 2010–2050 per scenario as calculated in MARKAL-NL-UU.

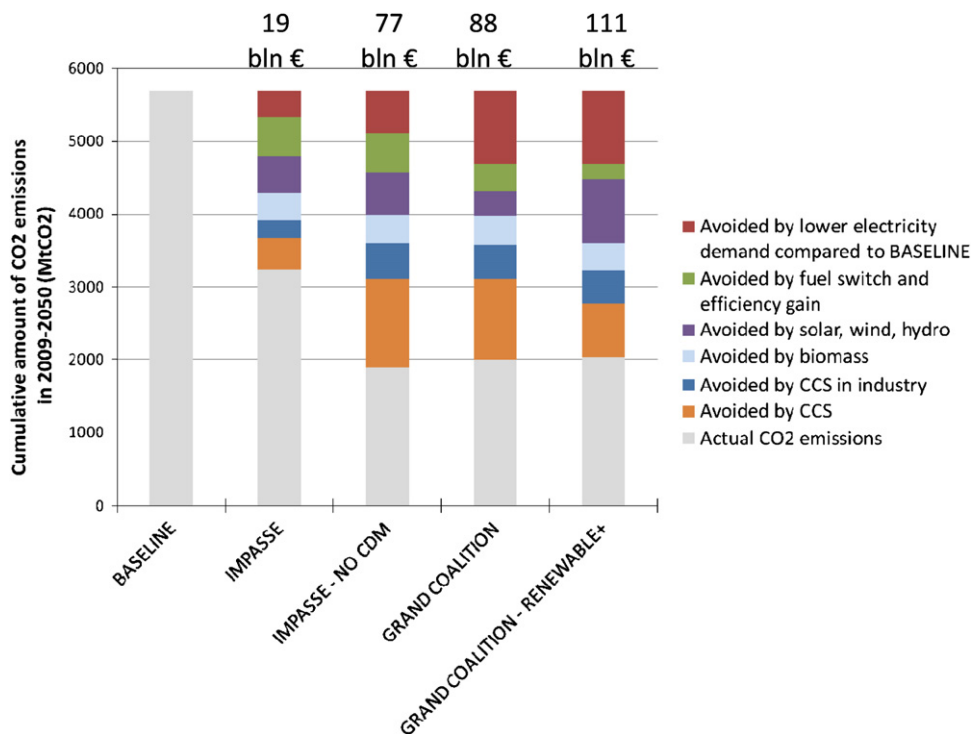


Fig. 11. Contribution of CCS and other abatement measures to CO₂ emission reduction in the Dutch electricity and heat generation sector over the period 2009–2050 for the different scenarios. Total CO₂ reduction costs, in billion €, are also presented.

3.8 GtCO₂ is avoided to which CCS contributes the most with 27–47%.²⁴ The use of biomass contributes with 10–15% to the CO₂ avoidance, and this mostly takes place in power plants with CCS. Only in the GRAND COALITION-RENEWABLE⁺ scenario, part of the CO₂ avoidance by biomass is realised in CHP units.

In Fig. 11 the total undiscounted additional energy system costs due to the CO₂ reduction (as calculated in MARKAL-NL-UU) over the period 2009–2050 are presented. However, these figures do not include other GDP losses as determined in WorldScan (see Section 3.1.1). The CO₂ reduction costs of the IMPASSE scenario with only modest CO₂ reduction are evidently lowest. Although the cumulative CO₂ emissions are slightly lower in IMPASSE—NO CDM than in the GRAND COALITION scenarios, the total undiscounted costs for the CO₂

reduction costs are less (77 instead of 88 or 111 billion € over the period 2009–2050). The reason is that in GRAND COALITION, in order to avoid the very high CO₂ taxes at the end of the period, far reaching and expensive CO₂ measures are taken resulting in negative CO₂ emissions. Furthermore, in GRAND COALITION-RENEWABLE⁺ the high share of renewable energy is responsible for the higher costs.

3.2.4. Electricity prices and abatement costs

Table 7 presents the costs for electricity generation and for CO₂ reduction for each scenario. Electricity costs range between 56 and 71 €/MWh in 2020 with highest costs for the IMPASSE—NO CDM scenario due to its high emissions permit price.

3.2.5. Sensitivity analysis

Fig. 12 presents the amount of CO₂ stored for the GRAND COALITION and IMPASSE—NO CDM scenario with uncertainty about the development of the CO₂ price after 2020. From this year, the CO₂

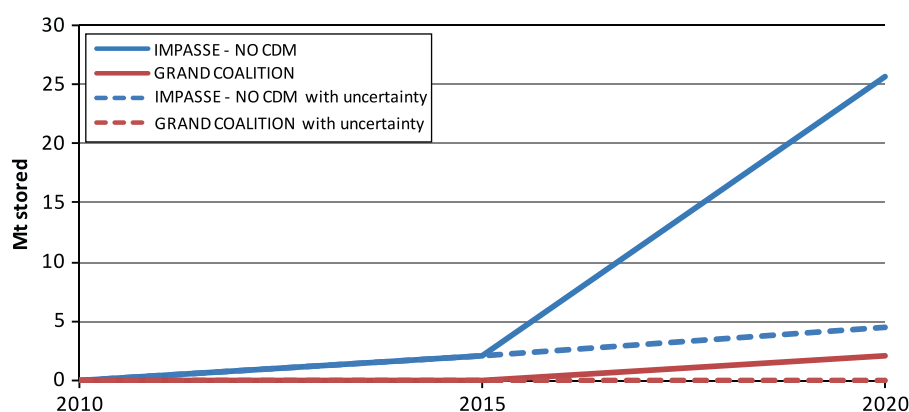
²⁴ The amount of CO₂ avoided by CCS was calculated by comparing the emissions of the power plant with CCS with those of the same type of power plant without CCS.

Table 7Overview of electricity and CO₂ reduction costs for the different scenarios.

		BASILINE	IMPASSE	IMPASSE—NO CDM	GRAND COALITION	GRAND COALITION—RENEWABLE ⁺
Average electricity demand (TWh)		177	163	153	134	134
Electricity expenses (€/MWh) ^a	2020	56	67	71	65	65
	2030	55	64	72	73	74
	2040	54	64	71	69	79
Cumulative amount of CO ₂ stored (GtCO ₂)		0.0	0.7	2.0	1.8	1.4
CO ₂ average emission reduction expenses (€/tCO ₂) ^b	2020	0	16	38	29	28
	2030	0	21	39	45	48
	2040	0	25	38	42	60

^a We used the total undiscounted annualised cost results of MARKAL-NL-UU for the calculation of the cost of electricity (COE). We distributed the costs to the electricity and heat output on exergy basis (i.e. using a factor of 1 for electricity, 0.15 for district heat, and 0.35 for industrial heat) based on typical figures described in Blok (2009).

^b The costs for CO₂ reduction in each scenario were based on the total undiscounted annualised cost results and CO₂ emissions of MARKAL-NL-UU in relation to the costs and CO₂ emissions of an analogue version of the scenario without a CO₂ price. Only, the GRAND COALITION—RENEWABLE⁺ scenario was compared to the GRAND COALITION scenario without a CO₂ price.

**Fig. 12.** CO₂ stored under uncertainty about the development of the CO₂ price from 2020.**Table 8**

Overview of the MARKAL-NL-UU sensitivity variants.

Variant of GRAND COALITION	Implementation
1. High fossil prices	Coal and gas price are around 35%, 65%, and 100% higher in 2010, 2015, and 2020 onwards, respectively, compared to those in Grand Coalition. This results in a coal price of 3.5 instead of 1.8 €/GJ, and a gas price of 8.2 instead of 4.1 €/GJ in 2050.
2. High biomass price	Wood pellet price is around 30%, 65%, and 100% higher in 2010, 2015, and 2020 onwards, respectively, compared to the one in GRAND COALITION. This results in a price of 10.6 instead of 5.3 €/GJ in 2050.
3. Slow CCS	CCS development is delayed with 10 years. I.e. the CCS power plants of 2010 with its specific costs and performance are available from 2020 (see Appendix B), the 2020 plants from 2030, etc.
4. Limited availability CO₂ storage reservoirs	Utsira is not available for Dutch CO ₂ and onshore storage is restricted to 600 MtCO ₂ instead of 1200 MtCO ₂
5. Optimistic development PV	Costs of PV decrease faster (1550, 875, and 675 €/kW in 2020, 2030, and 2040, respectively)
6. No CCS	No CCS is allowed.
7. No bound on nuclear	Expansion of nuclear power is not restricted.
8. Nuclear—no CCS	Nuclear power is not restricted and no CCS is allowed.
9. Less biomass	Biomass availability for the Dutch electricity sector is halved (i.e. 69, 79, 126, 202 PJ in 2020, 2030, 2040, and 2050, respectively).
10. NGCC—CCS base load	NGCC—CCS cannot be operated in a flexible mode

price will either follow the BASELINE, GRAND COALITION, or IMPASSE—NO CDM price path. The analysis shows that in 2020 under uncertainty 21 MtCO₂ less is stored compared to the “certain” IMPASSE—NO CDM scenario, and no CO₂ at all in the GRAND COALITION scenario. Instead extra CO₂ emission allowances are bought. For example, in the uncertainty variant of IMPASSE—NO CDM, the 21 MtCO₂ are emitted in 2020 resulting in 1 billion € extra costs for CO₂ emission allowances, but in the same year 0.8 billion € less is spent on abatement costs. More generally, with uncertainty about the future price of carbon, investments in abatement options with

long life spans will be postponed. For introduction of CCS on the short term, complementary measures besides the EU ETS or CTS are needed as confirmed by Groenenberg and de Coninck. They state that the limited time horizon and short-trading periods of EU ETS probably do not lead to substantial CCS diffusion (Groenenberg and de Coninck, 2008).

In the sensitivity analysis, also a number of MARKAL-NL-UU runs were undertaken as listed in Table 8. Fig. 13 illustrates the variation in these runs resulting from changes in key parameters regarding the development of energy prices, competing technologies, or the

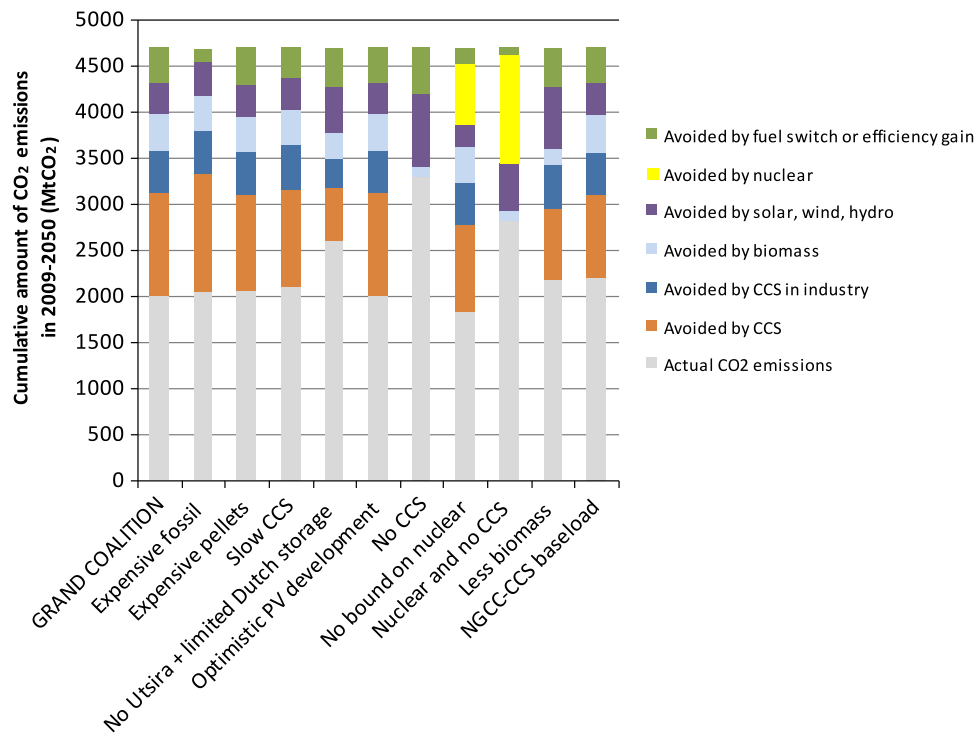


Fig. 13. Contribution of CCS and other abatement measures to the CO₂ reduction in the Dutch electricity and heat generation sector over the period 2009–2050 for different variants of the Grand Coalition scenario.

availability of CO₂ storage. In the variants without any CCS the cumulative CO₂ emissions in the period 2009–2050 are substantially higher (0.8–1.3 GtCO₂ higher). In almost all other variants CCS plays an important role avoiding between 0.9 and 1.6 GtCO₂ in the period investigated. The contribution of CCS is the least in the variant with limited CO₂ storage (0.9 GtCO₂ avoided), and limited biomass availability (1.3 GtCO₂ avoided). Note, that in the limited CO₂ storage variant this is partly due to the CO₂ emissions in the CO₂ intensive industries for which no alternative CO₂ mitigation measures are defined in MARKAL-NL-UU. In the limited biomass variant, CCS becomes less attractive, because less biomass is available for co-firing in the CCS power plants. Finally, in the variant with NGCC–CCS operating as base load and the one with unrestricted nuclear power, 1.4 GtCO₂ is avoided by CCS compared to 1.6 GtCO₂ in GRAND COALITION. In most variants, it holds that there are more cumulative CO₂ emissions with less CCS except for the nuclear variant (more CO₂ with less CCS) and the variant with expensive fossil fuels (more CO₂ with more CCS due to a larger share of coal-fired power plants). The variant Slow CCS shows that under a relatively low CO₂ price of 23 €/t in 2020, the rate at which CCS develops does not reduce the amount of CO₂ avoided by CCS. However, if the CO₂ price follows the IMPASSE—NO CDM path with high CO₂ prices in 2020, 0.4 GtCO₂ less would be avoided over the period 2009–2050 in a Slow CCS variant. In this case the slow CCS technology advancement reduces the amount of CO₂ avoided by CCS, but the CO₂ price remains the most important factor for the introduction of CCS as confirmed by Jakobsen et al. (2008).

4. Discussion

In this paper, we combined the applied general equilibrium model WorldScan with the techno-economic energy model

MARKAL-NL-UU in order to evaluate the impact of international climate policies on the deployment of CCS on a national level. One of the results shows that the CO₂ price in most scenarios is too low in the short term for large scale introduction of CCS. In GRAND COALITION, for example, options for CO₂ emission reduction abroad are less costly, and the need for large scale introduction of CCS only takes off at large scale from 2030 when the CO₂ price increase above 70 €. However, it is important to note that none of the scenarios seem to achieve sufficient CO₂ emission reductions to keep temperature increase below 2 °C with a high probability according to the latest insights. In the GRAND COALITION scenarios, cumulative CO₂ emissions for energy fuel combustion only were about 964 GtCO₂, while total cumulative CO₂ emissions are required to stay below 700 GtCO₂ over the period 2009–2050. Investigating scenarios with stricter CO₂ cap developments in WorldScan, would provide additional insights into the consequences of deep reduction strategies. The CO₂ price in such a “grand coalition” scenario may be significantly higher than the 23 €/tCO₂ in our GRAND COALITION scenario in 2020, making CCS commercial at an earlier stage.

The cumulative emission reductions in IMPASSE—NO CDM is only slightly higher (100 Mt) than in GRAND COALITION. However, the emission reduction in IMPASSE—NO CDM starts earlier, mainly by deploying CCS in the Netherlands from 2020 due to the CO₂ price of €47/tCO₂. In this scenario the CO₂ price is driven up by the condition that emission reductions should be achieved within the EU itself. In the GRAND COALITION scenarios emission reduction starts later, but is more far-reaching in 2050 by implementing expensive mitigation options next to CCS. As a consequence, cumulative undiscounted costs are lower in the first scenario.²⁵

²⁵ Discounted costs are lower in the Grand Coalition scenario where emission reductions are postponed.

This first endeavour to soft-link the global WorldScan model with the national MARKAL-NL-UU model provides a consistent method to investigate the consequences of international climate policy on the cost-effectiveness of a technology at a national level. However, there is still potential for improvement. So far, the energy and CO₂ prices fed from WorldScan into MARKAL-NL-UU determine the cost-effectiveness of the energy technologies in a national context. In principle WorldScan should also receive the power generation package generated by a bottom-up model as well as the use that is made of CO₂ reduction technologies like CCS. Next, Worldscan can calculate the implications of this package for the electricity demand, prices of primary energy carriers and the emissions price and send these back to a bottom-up model like MARKAL-NL-UU. It should be noted that for the IMPASSE scenario, WorldScan should get the power generation package from a bottom-up model including an extended technology database with learning rates that covers the whole of EU-27. Similarly, to verify the validity of high CO₂ prices approaching 600 €/tCO₂ in the GRAND COALITION scenario, a bottom-up model with global coverage could provide the right input for WorldScan. Such a joint analysis of top-down and bottom-up models at the global level would probably show that at a CO₂ price of 600 €/tCO₂ even deeper CO₂ reductions than in this study would be feasible and/or against lower costs.

In MARKAL-NL-UU, insights into the following aspects could improve the results:

- CO₂ reduction measures to replace cogeneration technologies. More CO₂ reduction measures need to be included to assess the CO₂ reduction potential accurately for high CO₂ prices. For example, geothermal heat generation technologies could replace existing district heating systems. Furthermore, a study by Kuramochi et al. (2010) showed that post-combustion CO₂ capture from 50 to 400 MWe may be feasible at costs of 35–60 €/tCO₂ in the midterm (2020–2025). Including this option into MARKAL-NL-UU would require amongst others an in-depth analysis of the scale and heat power ratio's of the cogeneration facilities in the Netherlands.
- Co-firing of biomass in power plants. In this paper co-firing of biomass in coal-fired power plants was limited to 50% of the input. Because the combination of CCS and biomass co-firing shows up as a cost-effective CO₂ emission reduction measure, a further study could provide insights into the cost-effectiveness of power plants that are fully flexible to switch from coal to biomass or vice versa.
- Contribution of CCS in the transport sector. The inclusion of the transport sector into the model would give more insights into the total CO₂ capture potential as CCS can be applied at production units of final energy carriers for vehicles (i.e. at synfuel, hydrogen production units or power plants).
- Flexibility of an energy system with both a high percentage of renewable energy and large scale deployment of CCS power. For example, the GRAND COALITION-RENEWABLE⁺ is characterised by a high share of wind energy in combination with power plants equipped with CCS. Further study should point out whether the electricity system is flexible enough to handle these high shares.

5. Conclusions

In this study we combined the applied general equilibrium model WorldScan used for international economic policy analysis with the techno-economic energy model MARKAL-NL-UU in order to evaluate the impact of international climate policies on the

deployment of CCS at a national level. To demonstrate this, we focussed on the Dutch electricity generation sector and CO₂ intensive industries.

Main results from our modelling are:

- In 2020 CO₂ prices in the EU-27 may vary between 23 €/tCO₂ in a GRAND COALITION scenario, in which all countries accept relative or absolute greenhouse gas targets from 2020, to 47 €/tCO₂ in an IMPASSE—NO CDM scenario, in which EU-27 countries continue their one-sided European emission trading system without having the possibility to use the Clean Development Mechanism.
- Due to the high CO₂ price in the IMPASSE—NO CDM scenario development of CCS on a national level, in the Netherlands, is earlier than in all other scenario's: 26 and 43 MtCO₂ per year are stored in the Netherlands in 2020, and 2025, respectively. However, this is not efficient since in this scenario high costs of abatement within the EU are applied while low cost abatement options are left unused outside the EU.
- In the more successful GRAND COALITION scenarios, CCS is not deployed at large scale in an early stage: 2 and 14 MtCO₂ per year are stored in 2020 and 2025, respectively. Thereafter CCS is scaled up fast to more than 50 MtCO₂ in 2030.
- If the CO₂ price is 47 €/tCO₂ in 2020, uncertainty about the development of the CO₂ price after 2020, reduces the CO₂ storage from 26 to 4 MtCO₂ per year.
- Over the whole period (2009–2050), total cumulative CO₂ emissions of the Dutch power sector and CO₂ intensive industry decrease from 5.7 GtCO₂ in a business as usual scenario to around 1.9 GtCO₂ in IMPASSE—NO CDM, and 2 GtCO₂ in the GRAND COALITION scenarios (one with low and one with a high share of renewables). In these scenarios CCS contributes between 34% (GRAND COALITION-RENEWABLE⁺) and 47% (IMPASSE—NO CDM) of the total CO₂ avoided. CO₂ emissions reduce to around 10 MtCO₂/yr and even negative emissions of 2 MtCO₂/yr in GRAND COALITION in 2050. The sensitivity analysis showed that in the successful GRAND COALITION scenario, restricted availability of biomass and CO₂ storage potential may be limiting factors for the deployment of CCS.

Based on this case study and modelling results we can conclude that:

- International climate policy in combination with uncertainty does not advance the application of CCS in an early stage. For an earlier start of CCS complementary policy making is indispensable.
- A strategy to reduce CO₂ emissions already considerably in 2020 (among others by the deployment of CCS) may lead to lowest cumulative CO₂ emissions in the period 2009–2050 against lowest total undiscounted costs. Another strategy with far reaching emission reductions in later years, may (almost) lead to similar cumulative CO₂ emission reduction; however, cumulative undiscounted costs will be higher. In this strategy it is probably more difficult to adapt to a stringent cumulative CO₂ emission target later on, if the 50% emission reduction goal in 2050 does not appear tight enough to reach the 2 °C target.
- The rates at which different CO₂ abatement technologies (including CCS) develop, are less crucial for introduction of CCS than the CO₂ price development if the introduction of CCS depends on an emission trading system.
- The combination of biomass (co-)firing and CCS seems an important option to realise deep CO₂ emission reductions. In our reduction scenarios for the Netherlands, this option avoids around 30 MtCO₂ in 2040.

With respect to the applied methodology we conclude that a global economic policy analysis tool as WorldScan can be used to obtain an appropriate context to assess the impact of international climate policies on a national level. Its global scope and its approach which seeks equilibriums in energy and CO₂ markets, give insights into the relation between developments of the energy demand, CO₂ prices, and fuel prices. On the other hand, the use of an energy bottom-up model can generate more detailed insights into the effectiveness of different CO₂ reduction strategies. This type of analysis is important, because national governments depend to a large extent on global climate policies for the success of their domestic reductions and vice versa.

Finally, it is concluded that further research is needed with respect to the following issues:

- The consequences of the recent economic financial crisis should be incorporated in the scenarios.
- In order to stay below the 2 °C degrees warming, it is important to study pathways of the energy system with more and quicker reduction of global CO₂ emissions than presented in this study.
- Modelling these deep reduction scenarios poses additional requirements to the models. For example, pathways to even negative CO₂ emissions in some sectors must be modelled properly. This requires that more mitigation options are included in the models in order not to underestimate the potential to reduce CO₂ emissions or overestimate the reduction costs. Also, more detailed modelling is necessary to

investigate the conditions under which new configurations of the energy system can function, such as an energy system with a high deployment of renewable energy in combination with power plants equipped with CCS.

- The linkage between a top-down model like WorldScan and a bottom-up model can be improved by an iterative approach. WorldScan should receive different energy technology configurations generated by bottom-up models, and next, calculate the implications of these configurations for the electricity demand, prices of energy carriers, and the emissions price. These results can be fed into a bottom-up model like MARKAL-NL-UU.

Acknowledgement

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Appendix A. WorldScan classification

See Table A1.

Table A1

Overview of regions, sectors and production inputs in WorldScan.

Regions ^a	Sectors ^b	Inputs ^b
1. Netherlands	Cereals	<i>Factors</i>
EU-15 (old member states) minus the Netherlands	Oilseeds	Low-skilled labour
EU-12 (new member states)	Sugar crops	High-skilled labour
2. Other Europe	Other agriculture	Capital
Former Soviet Union	Minerals	Land
United States	Oil	Natural resources
Other OECD (ex Mexico)	Coal	
3. Brazil	Petroleum and coal products	<i>Primary energy carriers</i>
Mexico, Central and other Latin America	Natural gas	Coal
Middle East and North Africa	Electricity	Petroleum, coal products
China and Hong Kong	Ferrous metals	Natural gas
India	Chemical, rubber, plastic products	Modern biomass
4. Other South and South-East Asia	Mineral products	Renewables
Rest of World	Paper products, publishing	
	Non-ferrous metals	Other intermediates
	Vegetable oils and fats	Cereals
	Other consumer goods	Oilseeds
	Capital goods and durables	Sugar crops
	Road and rail transport	Other agriculture
	Other transport	Minerals
	Other services	Oil
	Biodiesel	Electricity
	Ethanol	Ferrous metals
	Modern biomass	Chemical, rubber, plastic products
	Renewables	Mineral products
		Paper products, publishing
		Non-ferrous metals
		Vegetable oils and fats
		Other consumer goods
		Capital goods and durables
		Road and rail transport
		Other transport
		Other services
		Biodiesel
		Ethanol

^a The numbers refer to the different groups of countries as mentioned in Table 1. Non-Annex I regions are denoted in italics.

^b ETS-sectors and inputs are denoted in bold.

Appendix B. Input data MARKAL

See Tables B1–B3.

Table B1

Technical and economic parameters of electricity generating technologies modelled in MARKAL-NL-UU ^a.

	Technology	2010	2020	2030	2040
Investment costs (in €/kW)	NGCC	676	608	608	608
	PC	1598	1487	1448	1352
	IGCC	2005	1798	1691	1521
	NGCC–CCS	1146	1014	938	838
	PC–CCS	2546	2328	2110	1892
	IGCC–CCS	2769	2374	2130	1956
	Wind onshore	1227	1075	965	866
	Wind offshore	2433	2028	1919	1892
	Nuclear	2652	2652	2652	2652
	PV	4325	2703	1352	946
Fixed O&M costs (in €/kW)	NGCC	19	17	16	16
	PC	77	72	66	61
	IGCC	71	66	60	53
	NGCC–CCS	33	24	22	19
	PC–CCS	95	81	75	68
	IGCC–CCS	92	76	70	63
	Wind onshore	32	25	23	20
	Wind offshore	96	91	86	81
	Nuclear	66	66	66	66
	PV	40	25	13	9
Variable O&M costs (in €/GJ)	NGCC	0.02	0.02	0.02	0.02
	PC	0.36	0.35	0.33	0.33
	IGCC	0.29	0.25	0.20	0.19
	NGCC–CCS	0.41	0.40	0.36	0.35
	PC–CCS	1.29	1.25	1.08	0.95
	IGCC–CCS	0.51	0.41	0.27	0.27
	Wind onshore	0.00	0.00	0.00	0.00
	Wind offshore	0.00	0.00	0.00	0.00
	Nuclear	0.69	0.69	0.69	0.69
	PV	0.00	0.00	0.00	0.00
Efficiency (in %)	NGCC	58	60	63	64
	PC	46	49	52	54
	IGCC	46	50	53	56
	NGCC–CCS	49	52	56	58
	PC–CCS	36	40	44	47
	IGCC–CCS	38	44	48	52

^a Source of performance and cost data: IEA GHG (2003), Hendriks et al. (2004), IEA GHG (2004), Menkveld (2004), University of Chicago (2004), IPCC (2005), Junginger et al. (2005), Verrips et al. (2005), Damen et al. (2006), IEA (2006), Damen (2007), EU PV Technology Platform (2007), Peeters et al. (2007), Graus and Worrell (2009), NETL (2009), Prins et al. (2009).

Table B2

CO₂ transport and storage costs assumed in this study.

		Investment (M€/ (Mt/yr))	Fixed O&M (M€/ (Mt/yr))	Lifetime (years)	CO ₂ storage capacity (Gt)
Transport ^a	To fields offshore	31	0.9	40	
	To fields onshore	20	0.6	40	
	To the Norwegian Utsira field	42	1.5	40	
Storage ^b	Aquifers offshore	196	9.6	21	0.0
	Aquifers onshore	83	3.8	28	0.0
	Depleted gas fields offshore	32	1.4	19	1.0
	Depleted gas fields offshore without re-use	111	5.3	19	
	Depleted gas fields onshore	11	0.4	22	1.2
	Depleted gas fields onshore without re-use	23	1.0	22	
	Norway, Utsira field, off-shore	18	0.9	25	42

^a In the CO₂ infrastructure study by Broek et al. (2010b), each pipeline is modelled separately, CO₂ transport costs are assumed to be proportional to metre length and per metre diameter of the pipeline as suggested by Hendriks et al. (2003, 2007) and varies between 1300 and 4300 €/m² for a specific location depending on the land-use type, and whether there is an existing hydrocarbon pipeline corridor or not. In this paper, we did not model each pipeline, but pipelines with average CO₂ transport costs were derived from the CO₂ infrastructure study Broek et al. (2010b).

^b Unit costs of setting up and maintaining CO₂ storage facilities (e.g. costs for site exploration and development, an offshore platform, drilling costs per metre) were based on several sources (BERR, 2007; Serbutoviez et al., 2007; Torp, 2008; Wildenborg et al., 2008). Based on these unit costs and the characteristics of the individual sinks (e.g. depth, location), we estimated average costs for the different CO₂ storage categories.

Table B3Technical and economic parameters of CHP technologies modelled in MARKAL-NL-UU (excluding units for district heating)^a.

	Efficiency		Investment (€/kW)	O&M costs (€/kWh)	Capacity factor (%)	Capacity GW (in 2005) ^b	Scale (MW)
	Electric (%)	Thermal (%)					
NGCC-CHP existing	32	48	721	0.65	66	2.8	< 250
NGCC-CHP new	43	31	1040	0.78	67		< 250
Steam turbine small	10	74	471	0.56	38	0.3	~15
Gas turbine-CHP existing	32	46	979	0.66	64	0.6	~25
Gas turbine-CHP new large	28 ^c	61	971	0.53	75		~45
Gas turbine-CHP small	25 ^c	64	1470	1.10	75	0.3	~8
Gas engine-CHP existing	41	49	550	0.74	46	1.8	< 2
Gas engine-CHP new	41	49	578	0.68	46		< 2

^a Source of performance and cost data: Hers et al. (2008b, 2008a), and for steam turbines Energy Nexus Group (2002).^b Source: CBS (2009).^c The electrical efficiency of the new gas turbines is lower than of the existing gas turbines, because the new ones include the possibility of supplemental firing of the heat recovery unit Hers et al. (2008b). Thus, the gas turbine can be sized to meet the base load demand while the load swings upward can be met by supplemental firing of the heat recovery unit Boyce (2005).

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