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The influence of international climate policies on the deployment of CO_2 capture and storage at the national level

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Abstract

The deployment of large scale CO_2 Capture and Storage (CCS) may depend largely on the emissions price resulting from a greenhouse gas emission trading system. However, it is unknown whether such a trading system leads to a sufficient high CO_2 price and stable investment environment for CCS deployment. To gain more knowledge, we soft-linked WorldScan, an applied general equilibrium model for global policy analysis, with MARKAL-NL-UU, a techno-economic energy bottom-up model of the Dutch power generation sector and CO_2 intensive industry. Results from WorldScan show that CO_2 prices in 2020 could vary between 20 €/tCO_2 in a GRAND COALITION scenario, in which all countries accept greenhouse gas targets from 2020, to 47 €/tCO_2 in an IMPASSE scenario, in which EU-27 continues its one-sided emission trading system without the possibility to use the Clean Development Mechanism. Results from MARKAL-NL-UU 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 CO_2 abatement technologies (including CCS) develop are less crucial for introduction of CCS than the CO_2 price development, and the combination of biomass (co-)firing and CCS seems an important option to realise deep CO_2 emission reductions.

Keywords: climate mitigation policy; applied general equilibrium model; linear optimisation model;

1. Introduction

The Fourth Assessment report of the IPCC published in 2007 [1] underpins the necessity to limit the human induced increase of the mean temperature on earth to maximum 2°C or even stricter. In a recent publication by Meinshausen et al. [2] it is argued that diminishing the annual global CO_2 emissions to 50% of the 2000 level in 2050, is not sufficient to reach the proposed mitigation as discussed in the political arena [3]. Instead they state that the cumulative amount of CO_2 emitted in the period 2009-2050 should not be more than about 700 GtCO_2 to have a

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75% probability of global warming to stay below 2°C. Using this cumulative CO_2 emission approach, they state that also short term action is required, because the probability of exceeding the 2°C increases to 53-87%, if global GHG emissions are more than 25% above 2000 levels in 2020.

It is expected that CO_2 capture and storage (CCS) may play an important role in realising the necessary emission reductions. The European Union (EU) has enabled CCS as a CO_2 reduction technology under the Directive for the Geological Storage of CO_2 [4]. The EU also adapted the Directive that regulates the GHG emission allowance trading scheme (EU-ETS) such that the deployment of CCS on a commercial scale will be driven (ultimately) by a CO_2 price [5]. Specifically, under the EU ETS the stored CO_2 emissions will be considered as not emitted. However, allowances will have to be surrendered for any leakage. Though this EU-ETS instrument is meant to provide a stable environment for investments in GHG mitigation measures, it is uncertain whether the EU-ETS (or a global emission allowance trading scheme) will be sufficient to actually realise CCS at large scale and in time for the following reasons. First, it is uncertain whether an effective international coalition that takes care of a trading scheme with long-term targets will ever be formed. Furthermore, it is questionable whether the CO_2 price resulting from the EU-ETS will be high enough to finance CCS in time. Also, the CO_2 price development within the EU-ETS is quite uncertain in the post-Kyoto period 2013-2020, and especially thereafter. Finally, the ETS still suffers from inefficiencies [5], such as a lack of stable investment environment due to the absence of long-term targets, uncertainty about the future of the Clean Development Mechanism (CDM), and the additional 20% target for the consumption share of renewable energy in the year 2020. These inefficiencies make long-term capital intensive emission reduction options such as CCS less attractive.

In summary, the (uncertain) development of international climate policy may have a major influence on the deployment of a key technology such as CCS. In order to be able to deploy CCS effectively in a national climate mitigation strategy, we need more insight in this influence. Therefore, we address the following research question: what could be the impact of different international climate policy frameworks (e.g. whether there is effective international coordination or not and whether CDM is allowed in future climate policies) on the implementation of CCS in a national energy system like the system of the Netherlands?

To investigate the impact of energy and climate change policies, top-down computable general equilibrium models and/or energy bottom-up models could be used [6]. The first type of models is 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. The second type can investigate the implementation of a specific technology such as CCS in detail, but neglects potentially important interactions of the energy sector with the rest of the economy. A solution is to combine the strengths of both type of models by soft-linking them. In our study, we used WorldScan [7], a general equilibrium 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 CO_2 emission prices on world, regional, and national level. By feeding these into MARKAL-NL-UU [8], a techno-economic bottom-up model of the Dutch power generation sector and CO_2 intensive industry, we were able to explore the prospects of CCS on a national level. The Netherlands is an interesting country for CCS deployment, because it has good CO_2 storage possibilities, and relatively short distances between large point sources and potential sinks for CO_2.

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 section 3 and 4. Finally, in section 5 conclusions are drawn with respect to the impact of international climate policy on the implementation of CCS.

2. Methodology

The version of the WorldScan model that was used to assess the macroeconomic consequences of climate policy scenarios, has global coverage with 14 regions or countries. These regions can be divided into four categories with respect to climate policies: 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 [9]. Furthermore, WorldScan distinguishes 25 markets for goods and services, and factor markets for labour, capital, land and natural resources in the regions. 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. From a recent WorldScan study [10], we derived four global policy scenarios, namely the BASELINE, IMPASSE, IMPASSE - NO CDM, and GRAND COALITION scenario. The BASELINE is a so-called middle-course scenario without climate policy developed by the Dutch Environmental Assessment Agency [11], in which the worldwide economy grows with around 2.7% per year, and global energy demand doubles current consumption in 2050, and triples it in 2100. The GRAND COALITION scenario describes an 'ideal' development of climate policies. In this scenario, international negotiations succeed in forming a "grand coalition" that includes the Annex I countries and also large, fast-growing developing countries such as China, India and Brazil. Initially up to 2020, Annex I countries commit themselves to absolute targets, more advanced developing countries to relative targets, and emissions of some least-developed countries are not restricted. After 2020 all countries accept relative or absolute targets. In the IMPASSE scenario, 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 the post-2012 period. The EU keeps ETS with a reduction level of 20% below 1990. CDM is used with some restraint and the use of CDM continues to increase slightly after 2020. The IMPASSE-NO CDM scenario is similar as IMPASSE, except that the ETS does not allow for CO_2 reduction measures in developing countries by CDM. In all scenarios except for the BASELINE the renewable energy target (20% of EU energy usage in 2020) is imposed at the EU-level.

The WorldScan runs resulted in time series for the international CO_2 price, energy prices, the development of the electricity and energy demand, and the contribution to the renewable energy target in the Netherlands. These results were used as input in MARKAL-NL-UU, a techno-economic model of the Dutch power generation sector. 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 [12]. MARKAL calculates the technological configuration of an energy system by minimising the net present value of all energy system costs. The CO_2 price was implemented as a tax on CO_2 emissions. Consequently, all mitigation measures with lower cost than this tax were implemented in a model run. Besides the 4 WorldScan scenarios, we investigated a fifth scenario GRAND COALITION - RENEWABLE$^+$ in order to investigate the cost-effectiveness of renewable energy versus CCS. In this scenario, the renewable energy share from WorldScan was implemented into MARKAL-NL-UU for the whole period 2020-2050 (on top of the 20% EU renewable target). Finally, we evaluated the impact of the different CO_2 price paths with respect to the CO_2 emissions from the electricity sector, and the contribution of CCS to this CO_2 emission reduction by running MARKAL-NL-UU. The period 2005-2050 was investigated using a time step of 5 years and costs were discounted with a discount rate of 7%. Prices are given in €$_{2007}$ unless otherwise stated.

The main input data of MARKAL-NL-UU are 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 CO_2 capture units in the industry. A detailed description can be found in [8, 13, 14]. 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 [15, 16]. The large scale power plants (with or without capture) are either natural gas combined cycle power plants (NGCC), pulverised coal-fired power plants, 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 are in base load mode only. 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. Other assumptions include the phasing out of nuclear power in 2033 (however, in the sensitivity analysis, the effect of extra nuclear capacity is presented), and bounds on the deployment of photovoltaic systems (max. 12 GW in 2050), wind turbines (max. 6 GW onshore), and biomass availability (max. 137 and 404 PJ in 2020 and 2050, respectively) for the Dutch electricity sector deduced from global biomass availability evaluations [17]. The sink inventory is based on data compiled by [18-22] and resulted in a selection of 123 CO_2 hydrocarbon fields and aquifers which are considered suitable for CO_2 storage (e.g. deeper than 800 meters, reservoir rocks with porosity exceeding 10%) with a total estimated CO_2 storage capacity of 1.2 $GtCO_2$ onshore and 1.1 $GtCO_2$ offshore. 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 [23] is available for storage of Dutch CO_2. Average CO_2 storage and transport costs in and to onshore sinks, offshore sinks, or the Utsira formation were derived from [13], a study which specifically investigates the development of the CO_2 infrastructure.

Finally, in the sensitivity analysis, we examined two aspects: the impact of uncertainty of CO_2 emission ceilings after 2020 on CCS deployment in the near term, and the sensitivity of CCS deployment versus alternative assumptions of key parameters.

3. Results

We highlight a few results of the WorldScan model runs with respect to the developments of CO_2 emissions and energy prices on a global scale, and the developments of GDP and CO_2 price at the level of EU-27. On a global scale, CO_2 emissions are reduced in 2050 to 14 $GtCO_2$/yr in the GRAND COALITION scenario (compared to 58 $GtCO_2$/yr in the BASELINE). However, their cumulative amount over the period 2009-2050 is 964 $GtCO_2$, which is about 270 $GtCO_2$ higher than the 700 $GtCO_2$ needed to have a high probability of warming to stay below 2°C. In the IMPASSE scenarios with only a European climate policy the global CO_2 emissions increase to 55 $GtCO_2$/yr, similar to the BASELINE. As regards the energy prices, we highlight that the coal price increases with 63% between 2005 and 2050 in the BASELINE, while in the GRAND COALITION scenario it is 38% lower than in the BASELINE due to a lower energy demand.

At the EU-27 level GDP grows least in the GRAND COALITION scenario 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%. It is to be noted that any negative economic effects of climate change are not included in WorldScan. CO_2 price developments vary considerable in the different scenarios. In the IMPASSE with CDM and GRAND COALITION scenarios, the CO_2 prices increase to 23 €/tCO_2 in 2020 while in the IMPASSE- NO CDM scenario it increases to 46 €/tCO_2. In the GRAND COALITION scenario CO_2 prices increase sharply to 500 €/tCO_2 in 2050 while in the other scenarios they stay below 70 €/tCO_2 over the whole period.

Important results of the MARKAL-NL-UU model concern the development of CO_2 emissions, electricity generation capacity, and CO_2 storage in the Netherlands. First, in all scenarios the CO_2 emissions of the power sector and CO_2 intensive industry rise from 80 in 2000 to around 113 $MtCO_2$/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 CO_2 emission pathways. In the BASELINE, they keep increasing to 156 $MtCO_2$/yr, while in GRAND COALITION they fall to negative emissions of 2 $MtCO_2$/yr in 2050. Negative CO_2 emissions are achieved by co-firing biomass in coal-fired power plants with CCS. In the IMPASSE scenario the CO_2 emissions only diminish to 52 $MtCO_2$/yr in 2050 due to the low CO_2 prices. Finally, while in the IMPASSE - NO CDM scenario worldwide emissions hardly decrease, the Dutch emissions diminish to 11 $MtCO_2$/yr.

With respect to the electricity generating capacity, it can be observed that whereas in the BASELINE, coal-fired power plants play a dominant role over the whole analysis period, their role is less important in all CO_2 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 CO_2 price remaining around 30 €/tCO_2, the main strategy is to switch from coal to natural gas. In the GRAND COALITION scenarios there are two alternative strategies to reach low CO_2 emissions. In GRAND COALITION - RENEWABLE$^+$, the strategy is to combine 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 scenario the strategy consists of mainly CCS: 39% output from biomass-coal fired power plants with CCS, 49% from NGCCs with CCS, and 5% from wind turbines in 2040. This latter strategy is a business as usual scenario in the sense that the electricity generation sector remains dependent 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 CO_2 emissions of these units were not taken into account in our analysis.

In most scenarios the amount of CO_2 stored in 2020 is very limited: some CO_2 from the ammonia and hydrogen manufacturing units is stored in the GRAND COALITION scenarios. The only CO_2 capture at power plants in this period is realised in IMPASSE - NO CDM with a CO_2 price of 47 €/tCO_2 in 2020 resulting in 26 $MtCO_2$/yr stored. Next, in this scenario the application of CCS increases fast to 43 $MtCO_2$/yr in 2025, while only 14 and 8 $MtCO_2$/yr is stored in the GRAND COALITION scenarios, and IMPASSE scenario, respectively. Around 2030, the GRAND COALITION scenarios catch up with the IMPASSE - NO CDM scenario. Given that CCS is the main CO_2 mitigation measure in the IMPASSE - NO CDM and GRAND COALITION scenarios, storage continues to grow in these two scenarios to around 90

$MtCO_2$/yr. In the end, 1.8-2.0 $GtCO_2$ is stored of which 0.5-0.6 $GtCO_2$ in the Utsira formation. A prerequisite for such a scenario to continue is that a huge CO_2 storage reservoir remains available. From 2040 in GRAND COALITION - RENEWABLE$^+$, the role of CCS diminishes in favour of wind energy. In IMPASSE CO_2 storage remains lower over the whole period, reflecting the lower targets and CO_2 prices.

Table 1 presents the electricity demand in 2040, the costs for electricity generation and CO_2 emission reduction. The costs of electricity (COE) ranges between 56 and 71 €/MWh in 2020 with highest costs for the IMPASSE - NO CDM scenario due to investments in CO_2 mitigation measures as a consequence of the high emissions permit price. The COE in 2040 varies between 54 and 79 €/tCO_2 with highest costs for GRAND COALITION - RENEWABLE$^+$ due to the combined target for renewable energy and the CO_2 price. CO_2 avoidance costs are also highest in this scenario.

Table 1 Overview of electricity and CO_2 reduction costs for the different scenarios

		BASELINE	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
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).
[b] The costs for CO_2 reduction in each scenario were based on the total undiscounted annualised cost results and CO_2 emissions of MARKAL-NL-UU in relation to the costs and CO_2 emissions of an analogue version of the scenario without a CO_2 price. Only, the GRAND COALITION - RENEWABLE$^+$ scenario was compared to the GRAND COALITION scenario without a CO_2 price.

4. Discussion

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 CO_2 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 CO_2 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 EU27. Similarly, to verify the validity of high CO_2 prices approaching 600 €/tCO_2 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 CO_2 price of 600 €/tCO_2 even deeper CO_2 reductions than in this study would be feasible and/or against lower costs.

Furthermore, it is important to note that none of the scenarios seem to achieve sufficient CO_2 emission reductions to keep temperature increase below 2°C with a high probability according to the latest insights. In the GRAND COALITION scenarios, cumulative CO_2 emissions from energy fuel combustion only were about 964 $GtCO_2$, while total cumulative CO_2 emissions are required to stay below 700 $GtCO_2$ over the period 2009-2050. Investigating scenarios with stricter CO_2 cap developments in WorldScan, would provide additional insights into the consequences of deep reduction strategies. The CO_2 price in such a "grand coalition" scenario may be significantly higher than the 23 €/tCO_2 in our GRAND COALITION scenario in 2020, making CCS commercial at an earlier stage.

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 CO_2 intensive industries.

The WorldScan results show that CO_2 prices in 2020 may vary between 20 €/tCO_2 in the GRAND COALITION scenario to 47 €/tCO_2 in the IMPASSE – NO CDM scenario. In the IMPASSE – NO CDM scenario, 26 MtCO_2 per year are stored in the Netherlands in 2020, thus contributing to 29% of the CO_2 emission reduction in the power generation and CO_2 intensive industry. 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. Furthermore, WorldScan results shows that in this unsuccessful global policy scenario global cumulative CO_2 emissions from fossil fuel firing in the period 2009-2050 amount to 1800 Gt whereas not more than 700 Gt may be emitted to keep the increase of global mean surface air temperature on earth to maximum 2°C with a 75% probability.

In the more successful GRAND COALITION scenario, only 2 and 13 MtCO_2 are stored in the Netherlands in 2020 and 2025 respectively. From 2030, CCS is deployed at large scale (around 50 MtCO_2 per year). Although in this scenario global CO_2 emissions reduce significantly to 13.5 GtCO_2 per year in 2050, the global cumulative emissions of 964 MtCO_2 are still above the safe threshold of 700 MtCO_2. In a pathway with more and quicker reduction of global CO_2 emissions than presented in this study, CO_2 prices may be high enough for early introduction of CCS.

Long-term certainty about the future emission reduction targets is an important factor for investment in reduction options with long life times such as CCS technologies. Without this certainty, it is not possible for firms to formulate expectations about the future price of CO_2. Model runs in which this uncertainty for the years after 2020 is simulated, showed that investment in CCS remains substantially lower compared with a scenario in which there is no uncertainty about future targets. The sensitivity analysis also shows that the rates at which different CO_2 abatement technologies (including CCS) develop, are less crucial for introduction of CCS than the CO_2 price development if the introduction of CCS depends on an emission trading system. Finally, the combination of biomass (co-)firing and CCS seems an important option to realise deep CO_2 emission reductions. In our reduction scenarios for the Netherlands, this option avoids around 30 MtCO_2 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 equilibria in energy and CO_2 markets, give insights into the relation between developments of the energy demand, CO_2 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 CO_2 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.

Further research is needed. First, 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 CO_2 emissions than presented in this study. Furthermore, modelling these deep reduction scenarios poses additional requirements to the models. For example, pathways to even negative CO_2 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 CO_2 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. Finally, 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.

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