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Carbon Capture & Storage in power generation and wind energy: flexibility and reliability issues in scenarios for Northwest Europe

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Abstract

The Netherlands is both heavily dependent on the success of carbon capture and storage (CCS) and renewable electricity for its decarbonisation policy. The same holds for the EU and some of its Member States like the United Kingdom. This paper discusses several scenarios for the Netherlands within the context of a liberalised and a more and more connected energy market in Northwest-Europe. The research reported here shows that CCS on new coal fired power plants does not pose a threat to the increase in the electricity production by large quantities of wind energy in the electricity system, and vice versa. For renewable energy, several additional policies are in place mainly in the form of financial support as long as these renewable options are not yet profitable. For CCS, financial support is only granted now for a selection of the first demonstration projects now planned in the EU. It is not yet clear if large scale CCS and high shares of wind energy can be incorporated in a balanced way in the electricity system. This paper shows that from a technical and economic point of view, there is room for both, and under which conditions such a two fold growth will be feasible.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Among the options for deep CO_2 emission reduction in electricity generation, both deployment of large scale CO_2 capture and storage (CCS) and renewable electricity production are among the high potential options. Within the European Union (EU) and in particular its Member States surrounding the North Sea, large scale deployment of offshore wind energy and CCS applied on new coal-fired power plants seem attractive. Member States and the EU formulated renewably energy targets for the year 2020. For the EU this amounts this 20%; for the Netherlands it equals 14% (of final energy demand, EU target) or the more stringent national 20% renewable energy target, based on primary energy input. Renewable electricity is a major part of the overall renewable energy target. For the Netherlands, a 35% share equivalent to 55 TWh in 2020 is an element of planned new policies as part of the Dutch Clean & Efficient Program, initiated in 2007. It includes mainly wind energy and to a lesser extent, co-firing of biomass in coal power plants. In addition, both offshore wind energy and CCS will be stimulated on short term by extra funds as part of the European Economic Recovery Plan (EERP). Within the EU, wind energy contributed the largest share of new generation capacity in 2008 and 2009. Wind energy is an important option, not only to reduce

CO_2 emissions but also to achieve the renewable energy targets in the Netherlands and Europe. However, high shares of electricity produced by intermittent sources as wind energy will require sufficient flexibility of the electricity system.

CO_2 capture and storage technology is anticipated to play an important role in the Dutch climate mitigation portfolio [1, 30, 33]. CCS is able to reduce emissions in the Netherlands by tens of megatons per year. ECN assumes 4 to 10 Mt CO_2 per year as the maximum feasible capture potential in the Netherlands by 2020 [2, 3]. In 2030 or 2050 higher captured volumes, up to 80-100 Mt are possible, but very dependent on uncertain and future scenario assumptions [4]. For the time being, the EU Emission Trading System (ETS) will not result in high enough CO_2 prices to make CCS a cost-effective option. Additional policy measures are needed to deploy CCS. From another study, it follows that effective technology policies are required to advance the timely introduction and diffusion of CCS technologies [5]. The recent scenarios and reference projections for the Netherlands [6] support such conclusions. These projections will be used as main illustration in the rest of this paper, for scenarios including both large deployment of CCS and renewable energy, in particular wind energy.

2. Research questions, scenarios and methodology

Research questions

The research reported here focuses on the following questions:

1. Is there a limit to CCS if the electricity system has to be *flexible enough* to copy with the high shares of intermittent renewable production, in particular wind energy?
2. Are multi-fuel coal/biomass gasification combined cycle power plants more flexible than new and modern pulverised coal-fired power plants in case both designs are equipped with CCS? As an example the planned Vattenfall/Nuon Magnum plant in the North of the Netherlands, currently under construction as a three-unit CCGT.
3. What will high shares of renewable electricity production with low marginal costs of production mean for the *business cases* of the currently being built or planned new coal-fired and new gas-fired power plants in the Netherlands?
4. What *policy messages* result from the analyses?

Scenarios and assumptions

These research questions have been tackled within the context and constraints of the new reference projections for the Netherlands [6]. A summary of underlying assumptions is given in Section 3 of this paper. Techno-economic assumptions on new generating capacity are based on [7], for new fossil power plants, with and without CCS, and on recent estimates made as part of the renewable energy support scheme and CHP subsidy scheme in the Netherlands, [8] and CHP [9], respectively. The relevant parameters have been input to the Dutch cost estimates in the recent OECD Projected Cost Of Generating Electricity study [26].

Modeling tools

The basic modelling tool used is the electricity market model (POWERS) covering the Netherlands, Belgium, Denmark, France, Germany, Norway, and the United Kingdom. The POWERS model is coupled and integrated with detailed other sectoral energy demand and supply models, e.g. the Save-Production model that treats the decentralised CHP plants and the industrial energy demand (heat and electricity) [10]. Both are part of the Dutch National Energy Modelling System used to quantify energy scenarios for the Dutch government. The modelling system is able to analyse scenarios up to the time frame of the year 2040, with numerical results on annual basis or an even more detailed time slide resolution. For the power generation sector in POWERS, one year is divided into 156 time periods (weekly demand patterns at peak, shoulder and off-peak loads).

Northwest European context

The Northwest European electricity market will be increasingly coupled as one electricity market which is facilitated by further and enlarged interconnections between these countries, see Section 3.

Uncertainties and sensitivity analyses

As economic growth, electricity demands, and fuel and CO_2 prices are quite uncertain factors, the impact of these uncertain factors have been studied in sensitivity analyses. These sensitivity analyses are not addressed in this paper but can be found in most of the underlying and referenced ECN studies.

3. Scenarios for the Netherlands in a Northwest European context

For the Netherlands within the context of the Northwest European energy system, two recent ECN studies explored the role of CCS in conjunction with the deployment of other power generation options like renewable technology and nuclear power. The first study is the new reference projections (denoted here as 'NRP-NL') for the Dutch government [6]. These projections take into account the impact of the recent and current economic crisis. This has a decreasing effect on the future electricity demand compared to earlier reference projections and other long term energy outlooks made in previous years (e.g. [11, 12, 13]. The new reference projections study is the basis for policy assessments of current or new policy measures by the Dutch government, and therefore also for the CCS analyses reported in this paper. The second study entitled 'Nuclear Energy and Fuel Mix' [14] contains two scenarios up to 2040, with one 'normative' scenario including very rapid deployment of renewable energy and large scale CCS. The two studies differed mainly with regards to economic growth, electricity demand, and time horizon but produced similar results for their 'High Renewable+CCS' variants. In this paper, only the NRP-NL study is used as illustration, up to a time frame of 2030. It features two basic policy variants:

1. SV based on existing NL and EU policies ('NRP-NL-SV').
2. SVV, equal to assumptions as in SV but with additional and planned national policy measures, notably for energy saving and renewable energy. The result is a somewhat lower electricity demand and a substantial higher share of renewable electricity production ('NRP-NL-SVV').

In the remainder of this Section, the new reference projection variant SVV is used as a starting point. It is denoted as NRP-NL-SVV in the remainder of this Chapter. Additional policy packages stimulating CCS are assumed on top of this NRP-NL-SVV projection leading to higher shares of CCS. The contents of such policy packages are further outlined in [5]. To understand the results of the analyses, the scenario assumptions of NRP-NL are relevant and need to be understood well. The main assumptions and driving forces are explained below.

Economic growth and electricity demand, impact of economic crisis

The GDP growth in NRP-NL is less than in the previous Global Economy and Strong Europe long term scenarios for the Netherlands [12]. The Green4Sure scenario [15] is a normative scenario based on the economic growth figures of the Strong Europe scenario. The results for this scenario were calculated by ECN, based on assumptions provided and determined by CE [16]. Green4Sure exhibits additional policies on energy saving, renewable energy and CCS. Van den Broek [17] used the Strong Europe scenario as basis for a modified scenario for the Netherlands up to 2050. However, she used different assumptions on fuel and CO_2 prices.

Effect of economic crisis: impact on electricity demand

The Dutch final electricity demand was 119.2 TWh in 2008, somewhat higher than in 2007 (118.5 TWh). During the second half of 2008, the impact of the financial and economic crisis became apparent and had its impact on the growth in demand. During 2009, the economic decline led to a decrease in the electricity demand with about 4%. A preliminary estimate for the demand in 2009 is about 113 TWh. The net import decreased from 16 TWh in 2008 to 5 TWh in 2009, the lowest figure in the last 10 years. The average net import in the years 2000-2008 was 18 TWh. In the last quarter of 2009, the Netherlands became a net exporter of electricity. This trend from being a net importer to becoming a net exporter has been previously and consistently forecasted in the scenarios developed and analysed by ECN in the last years.

CO_2 prices and fuel prices

The NRP-NL study assumes an CO_2 price path, equal to 20 €/ton in the third ETS period 2013-2020. The impact of the economic crisis is taken into account which will result in relatively low CO_2 price. The previous reference projection UR-GE [13] used 35 €/ton as a default value. For the longer term outlook, the CO_2 price is assumed to increase to 50 €/ton CO2 in 2040.

The natural gas and (imported) hard coal prices have been assumed equal to the prices used in the most recent and publicly available EU baseline 'Trends to 2030 – update 2007' [18]. The NRP-NL fuel prices are equal to the previous UR-GE scenario. For hard coal an additional handling cost of about 0.2 €//GJ is used. Sensitivity analyses on other fuel prices and lower and higher CO_2 prices have been part of sensitivity analyses.

Northwest European energy market context and market models: robust trends

The Dutch electricity system is part of the internal electricity market in Northwest Europe (The Netherlands, Belgium, Germany, France and UK). After a boom in new investments since 2005, with still a lot of power plants under construction, in particular in the Netherlands, the situation now has changed. In addition, new interconnections will become available between the Netherlands and its neighbouring countries. These changes will have a major impact on the price differences and exchanges between Northwest European wholesale electricity markets. To analyze these impacts ECN conducted a study with the electricity market simulation model COMPETES [19] for the year 2020. The COMPETES model is a static model with an EU-20 coverage, and can be run for one year, in contrast with the POWERS model (Seebregts et al, 2005) used for the calculations summarized in this paper. POWERS is a more dynamic model and can analyse a whole scenario time horizon up to 2040, but is geographically limited to six countries [7]. The Netherlands is modelled in quite detail, as it is part of the detailed Dutch National Energy Outlook Modelling System [10].

The analysed developments in the Northwest European markets show that it is very likely that electricity wholesale prices in 2020 of Dutch and neighbouring power markets will converge and the Netherlands will become a net exporting country in most cases. This result is proved to be robust under different scenarios (high and low investment levels, high and low demand growth, moderate and high fuel and CO_2 prices) and also if developments in countries differ, e.g. less demand growth in the Netherlands due to energy saving policy, more restrict environmental policy in the Netherlands regarding new power plants, cancellation of the nuclear phase out policy in Germany and a merger between Dutch and German power producers. The result also confirmed the findings of the previous energy and climate policy related studies conducted for the Dutch ministries of Economic Affairs and of the Environment (VROM). Those studies show that the development of the Netherlands to become a net exporter of electricity is a rather robust result under the assumptions made for the Clean and Efficient Programme [20].

The new NRP-NL analyses with the POWERS model up to 2030 confirm this net exporting development. Because of the economic crisis the expectation is that CO_2 prices will be less (20 compared to 35 earlier in UR-GE). In addition, for Germany and Belgium it has been assumed that nuclear power plants will be phased out later. This combination of lower CO_2 prices and more nuclear power in Germany in the period 2015 to 2030 and consequently less fossil power plants as replacement, results in lower net exports to Germany in the most recent reference projections NRP-NL.

New built coal-fired power plants in the Netherlands: first candidates for CCS

Some plans for new coal power plants in the Netherlands still concern IGCC plants, but these plans have not materialised into definitive investment decisions. In the Netherlands these plans comprise 2-3 units up to 2025 according to the Rotterdam Climate Initiative [21] and the Vattenfall/Nuon Magnum plant in the Eemshaven. The latter is now being constructed as a 3-unit CCGT plant, awaiting a decision for a coal/biomass gasification unit to be added.

CCS policies and CCS deployment

On CCS policies, no specific variant has been defined or analysed as part of the NRP-NL study. Both SV and SVV contain only one large demonstration CCS power plant: the joint Electrabel and E.On demo for their two new coal-fired power plants in the Rotterdam area. Based on a 250 MW_e equivalent, the plan is to capture 1.1 Mton CO_2 by the end of 2015. This demo will receive the required subsidies within the EU EERP and additional subsidies from the Dutch government. In this year, the Dutch government also decided that a demonstration project in the Northern part of the Netherlands would be sponsored. RWE and Vattenfall are considering the NER300 programme to apply for additional funding. RWE is constructing a 2 unit (780 MW_e each) modern pulverized coal plant. Vattenfall/Nuon is constructing a 3-unit combined cycle power plant, which may be converted in a multi-fuel (coal, biomass, natural gas) gasification plant. In the latter case, CCS is an option.

Company	**Location**	**Net Capacity [MW$_e$]**	**Year of first operation (plan)**	**Technology**	**Net Efficiency** (100% coal)	**Status** **UC=** Under construction
E.ON	Rotterdam (MPP-3)	1070	2012	PC	46%	UC 250 MW$_e$ demo CCS (EERP funded) 'ROAD Project'
Electrabel	Rotterdam	800	2012	PC	46%	UC
RWE	Eemshaven	1560	2013	PC	46%	UC
	Total new coal	3430				
Other coal plans not assumed to proceed in NRP-NL reference projections						
Essent/RWE	Geertruidenberg	800		PC	46%	Dismissed
Essent/RWE/Shell	Zuid-West Nederland	1000		IGCC	46%	Dismissed
C.GEN	Rotterdam	400-450	2012	IGCC	46%	Start Note, 25-9-2008
Unknown	Rotterdam	400-450	Unknown	IGCC	46%	RCI, 2009 report
C.GEN	Sloe area	400-450	Unknown	IGCC	46%	Press release

Carbon dioxide captured in power generation: realised and potential for the Netherlands

The amounts of CO2 captured in Dutch power generation differ a lot among the various scenario studies conducted in the last five years. It ranges from a potential of about 4-10 Mton in 2020 according to ECN studies conducted for the Dutch government, up to 33 to 44 Mton for the same year in the MARKAL-UU-NL scenario [17]. Depending on electricity demand growth and the extent of new fossil power generation capacity built in the period 2010-2030, the CCS potential in power generation is about 48 Mton in 2030. This relatively high estimate is based on a high economic and electricity growth scenario (the UR-GE scenario, see [7]. The potential in 2030 for a recent lower economic growth scenario is about 30 Mton [5] based on additional financial support for CCS. In [5] an extreme policy case imposing a (national) Environmental Performance Standard (EPS) on new coal of less than 550 gram CO_2 per kWh produced has been imposed. That case will effectively result in no operation anymore for coal plants in the Netherlands. For neighbouring countries, e.g. for Germany, no EPS has been assumed in this extreme case. The table below provides an overview. The deployment of CCS is very dependent on the main driving forces of the future development of the energy system: (1) economic growth; (2) energy demand; (3) role of fossil (notably coal) in power generation and industry, vs. the role of competing technology like renewable of nuclear power (4) fuel prices, CO_2 price, and wholesale electricity prices; (5) technology development; and (6) energy and climate policies. The deployment of renewable electricity is equally dependent on these aspects. In the two recent 'High renewable' scenarios in particular wind energy grows fast.

Other policies: Clean & Efficient national programme and EU implemented policies

In the NRP-NL variants, the basis for policy assumptions is determined by existing national and EU policies. For the Netherlands, it is basically the 'Clean & Efficient' programme as initiated by the former cabinet in 2007 [1]. The objective of the Clean & Efficient is to achieve the national GHG, energy efficiency and renewable energy targets for the year 2020. These national targets are even more ambitious that the EU targets for the Netherlands.

Two variants apply that differ mainly on the renewable energy policy part. The second variant includes planned but not yet implemented policy instruments. With the fall of the Dutch cabinet last February and the outcome of the June 2010 elections, it is uncertain whether these additional renewable policy instruments will be implemented.

What other scenarios tell about the role of CCS

A variety of recent scenario studies for either the Netherlands or Europe include large deployment of both CCS and high shares of renewable electricity. Scenarios can be subdivided in basically two categories: (1) baseline, ‘business as usual’ (BAU) type of scenarios; or (2) normative scenarios in which medium to long term targets are met, or in which additional policy measures are assumed. In general, the BAU type of scenarios forecast less energy saving, less renewable and less CCS than the more normative scenarios. Among these various scenario studies, most of these forecast an important role for both CCS and wind energy as options to combat climate change. Examples are the ECF Roadmap 2050 [27], the IEA Energy Technologies Perspectives study, Eurelectric’s Power Choices scenario, and the CO2Europipe Policy Scenario [24, 25]. To our knowledge, only the normative 2007 Greenpeace Energy Revolution scenario explicitly rules out CCS as an option.

Scenario, the Netherlands	**GDP growth [%/year] (2011-2030)**	**Electricity demand [TWh]**			**Mton CO_2 captured**			
		2020	**2030**	**2040**	**2020**	**2030**	**2040**	
Global Economy (GE), 2006	2.7	156	181	212	0	0	0	
Strong Europe (SE), 2006	2	137	148	161	0	34		
Green4Sure, 2007	2	127	124	n/a	14-17	26-57	n/a	
UR-GE, 2009	2.7	156	181		4-10	48	Potential	
2010: SB scenario, HIRES and CCS, and additional energy saving	2	120	124	128				
NRP-NL-SV	1.7	130	136		1.4			
NRP-NL-SVV (HIRES)	1.7	128	131		1.4			
NRP-NL-SVV, CCS policy variants, on new coal or new gas in period 2013-2030					**2020**	**2025**	**2030**	
Environmental Performance Standard (EPS) only					0	0	0	
Slow coal, with financial support					7	10	19	
Fast Coal and Gas, with financial support					11	24	30	
Other studies					**2020**	**2030**	**2040**	**2050**
MARKAL-NL-UU (variant based on Strong Europe)					33-44			
CO2Europipe (policy intensive variant of NRP-NL-SVV, including CCS in industry)					8	22		49

4. The need for reliability, flexibility, and sound business cases

Reliability is traditionally an important aspect for electricity generating capacity and the electricity infrastructure (transmission and distribution networks). High shares of electricity produced by intermittent sources as wind energy will require sufficient flexibility of the electricity system, not only on the production side but also on the network (infrastructure) side.

4.1. Production and infrastructures perspectives

Production perspective

In general, open cycle gas turbines can offer flexibility. Modern power plants like natural gas combined cycle gas turbines (CCGTs), new pulverised coal (PC) power plants and even new nuclear power plants (NPP) are designed to operate more flexible and at reduced partial load levels compared to their predecessors. However, it is not clear if this enhanced flexibility is sufficient to cope with large shares of wind energy. In particular the relatively large amount of new coal-fired power plants currently under construction in the Netherlands and neighbouring countries could make the electricity system less flexible. Application of large scale CCS to these coal-fired power plants may make the electricity system even less flexible. Some European power companies therefore plan to invest in integrated gasification combined cycle (IGCC) units (e.g. Vattenfall/Nuon in the Dutch Eemshaven) rather than in modern PC plants. They argue that such IGCCs are more flexible than modern PC plants. However, based on an overview by [22], modern PC plants show improved characteristics with regards to flexibility compared to existing coal-fired plants. They appear even more flexible than IGCC plants in terms of remaining longer at relatively high net efficiencies while reducing the load. IGCC and CCGT units have net efficiencies decreasing faster when going from full, nominal load to partial load. From this perspective, modern PC plants in Europe appear ‘better’ than

IGCC units. The current coal fleet under construction in Northwest Europe consists mainly of these PC plants, with net efficiencies of about 46%, and all designed and constructed as 'capture ready'. Additional advantages are lower investment costs and proven reliability compared to new IGCC plants. So, from a market and investor's perspective, this development is a logical one.

In a liberalized and competitive European electricity market, producers need reliable generating units. This applies not only to the technical reliability but also to the 'economic reliability'. Investments in new capital-intensive generation capacity like coal-fired power plants, wind turbines and nuclear power, require sufficient returns on investment and sound business cases. The assumed full load hours for each of these technologies deliver the needed electricity production levels and wholesale market electricity prices. In addition, flexibility is becoming increasingly important in an electricity market with an increasing number of less predictable intermittent renewable sources. Both new coal-fired plants and new nuclear power plants are therefore designed for operating in a more flexible manner. They can operate down to partial loads of 30 to 20%.

Electricity system and CO2 infrastructure perspectives

The electricity system is a vital energy infrastructure the reliability of which is important. Organizations like the national Transmission System Operators (TSO's) and their European wide organization ENTSO-E have the task and responsibility that the electricity system functions reliably (e.g. in System Adequacy reports up to 2025). The integration of large scale intermittently generated electricity is high on ENTSO-E's agenda [23]. Network developments will be drive by reasons of Security of Supply (SoS, including reliability), integration of RES, and properly function of the Internal Energy Market (IEM). With regards to a future pan-European CO_2 infrastructure in the time period 2020-2050, that topic is dealt with in the ongoing FP7 CO2Europipe research project [24, 25].

4.2. Operating hours of base-load fossil capacity and wind energy, and impact on business cases

From the scenario analyses based on POWERS and Save-Production model runs, it followed that even with large amounts of wind energy capacity wind turbines will seldom or never be disconnected and thus will not stop production. In addition, new coal-fired power plants will have high operating hours, e.g. as illustrated in Figure 1. The production by older coal plants will decrease, as for the old gas-fired power plants. Deployment of CCS on these new coal plants results in similar high operating hours, or even higher, as the variable cost of production of coal plants with CCS gets lower than the original plant without CCS. A similar conclusion on the negligible curtailment of wind energy was drawn in the study [26], using a similar scenario but only for the 'target' year 2020. That study used another electricity market and dispatching model (PLEXOS). The ECN POWERS market model does not generate surprising results, given the scenario assumptions and the market mechanisms, with respect to dispatching (operational) and to investors' behaviour. These arguments and mechanisms are:

a. Wind energy has very low marginal production costs

First of all, wind energy has no fuel cost by definition, thus keeping the marginal production cost of wind very low (appr. 1 ct/kWh). Based on the marginal production costs and the electricity market price the owners of production units will make the decision whether or not they deploy their production unit. Wind energy has the lowest marginal cost of all technologies and is therefore put high in the merit order of plants.

b. SDE subsidy

Wind turbines will keep on operating as long as the SDE grant plus the (resulting low) electricity price amounts to more than the marginal deployment cost of wind (less than 1 ct/kWh).

c. Wind energy is given priority in case of congestion.

Not disconnecting wind energy is also in line with the intentions of the Dutch bill for Priority to Renewable ('Voorrang voor Duurzaam') that strives for maximal production of the installed renewable production capacity and priority for renewable electricity during congestion.

d. Conventional producers anticipate wind supply

The increase and supply of wind can be predicted increasingly more accurately, thus enabling conventional capacity to take this into account and preventing wind turbines from having to be disconnected.

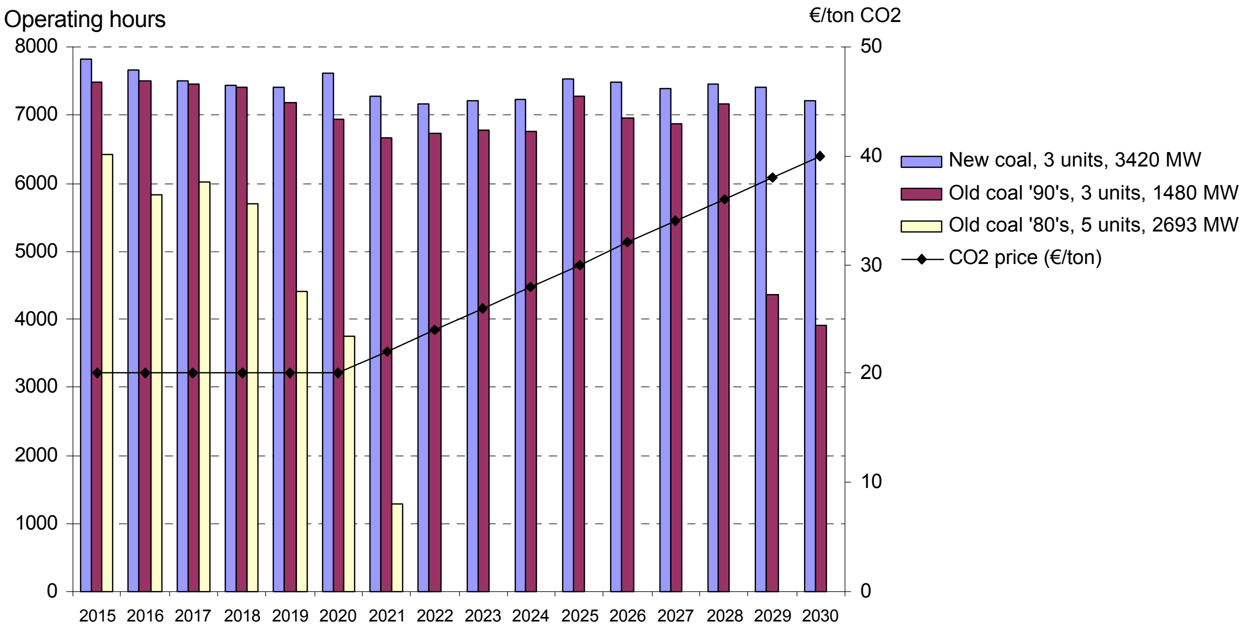

Figure 1 Operating hours (full-load equivalent) coal-fired power, 2015-2030, the Netherlands, NRP-NL-SVV scenario.

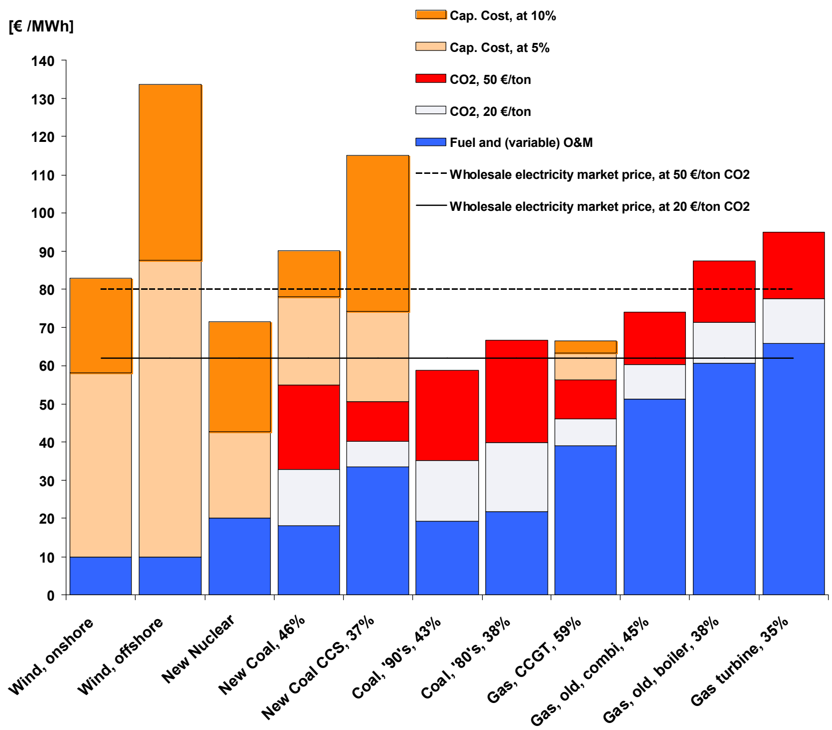

Figure 2 Variable and capital cost of production, for new and existing generating capacity in the Netherlands, year 2020, and NRP-NL-SVV scenario.

e. Is a decrease in investment in new wind energy to be expected due to the investment in much conventional base load capacity?

In our study we initially a priori anticipated that the combination of much base load capacity, must-run capacity plus much wind energy supply could rather lead to downward adjustment or even disconnection of, for example, coal-fired plants. This is an argument sometimes used by environmental organizations when stating that owners of new coal-fired plants are less willing to invest in large offshore wind parks. However, there is a sufficient number of parties (and even more so in 2020) who are interested in the development of offshore wind parks. These need not necessarily be large energy companies such as RWE/Essent, Vattenfall/Nuon or E.On. Companies like Eneco and newcomers such as Airtricity and Bard may be just as relevant to the realisation of the Dutch offshore wind energy target.

5. Policy messages and uncertain future developments

Analyses based on scenarios for highly uncertain future developments should be considered carefully if policy messages are derived from such analysis. Some messages are only valid within the specific scenario context and the underlying assumptions on the main driving forces of future development. Other messages are quite robust under wider ranging assumptions.

One main driving force is the economic growth and economic structure and largely depending on these economic factors, the energy demand. One rather robust development in most of the recently completed international scenario studies is a moderate economic growth in Europe of about 1.8% in GDP/year. Such growth follows after two to three years of economic downturn in the years 2008-2010. Consequently, energy demand projections increase less on the long term than anticipated 3-4 years ago.

6. Summary of findings and conclusions

This paper looked into the issues of flexibility and reliability of the energy system, and the combined role of CCS and wind energy. These issues have been analysed in the context of scenarios with both large-scale penetrations of CCS and high shares of electricity production by wind energy. The analyses and electricity market model runs for the Dutch electricity system have been embedded in an increasingly coupled and interconnected Northwest European market and policy context.

From the analyses and within the context of the scenario assumptions, it follows that:

1. *Flexibility or reliability considerations impose no technical limit on CCS in Dutch power generation. In practice, limits to CCS will be merely determined by economic, market and specific CCS policy conditions and other barriers related to the full CCS chain.*

First, the amount of CCS is limited because CCS is considered to be only viable for newly built coal-fired power plants in the next 15 to 20 years. Theoretically, CCS in new gas-fired power plants or decentralised CHP plants is technically viable. However, both economic and other barriers will prevent CCS deployment in these installations in the next 10 to 20 years. Currently, about 3500 MW of new coal power plants are under construction in the Netherlands. These designs are capable of co-firing biomass as well. In the NRP-VV scenario, the percentage of biomass co-firing is assumed to be 20% (on energy basis).

2. *Operational behaviour and merit order remain main drivers for power generation.* The most important explanation for the quantitative analysis results is that electricity generating units are dispatched according to the merit order, i.e. the supply/demand curve with increasing marginal cost of production. Marginal costs comprise the cost of fuel, the CO_2 price and other O&M costs (such as start-up). Moreover, the actual construction of new coal-fired power plants should be considered as a fact from the market investor’s perspective. Once fully licensed and built, these plants will produce electricity as long as their marginal cost of production is below the wholesale market electricity prices. In addition, older and less efficient coal or more costly natural gas power plants will produce less or, eventually, be decommissioned.

3. *The expected construction of new coal-fired capacity, either with or without CCS, does not hamper high penetration of wind energy and vice versa in the Netherlands up to 2030.* At very high shares of wind energy the operating hours of new coal-fired power plants without CCS will remain high enough for a sound business case as long as the CO_2 price is not too high. At CO_2 prices of 50 €/ton or higher, the variable cost of production for new coal-fired power plants will become too high. In that case, deployment of CCS can reduce the variable cost of production and improve the position of these power plants in the merit order. However, the higher investments of CCS may constitute a barrier. Additional and dedicated CCS policies are needed as long as CCS is not cost-effective on its own.

4. *For new coal-fired plants now being constructed in the Netherlands in the period 2009-2013, either without CCS, or eventually with CCS, the business cases remain sound* in the context of the (macro-economic) scenarios outlined, *even with high shares of renewable electricity production from wind energy. For CCS, this will only be the case when the CO_2 emission price is high enough. Based on the scenario assumptions, this would require more than 60 €/ton CO_2.*

5. *Therefore, a successful demonstration programme in the next 10 years and further scaling up of CCS in the period 2020 to 2030 are essential for further penetration of CCS in power generation in Northwest Europe in the period 2030 tot 2050.*

6. *Dedicated specific CCS policies are needed in the period after the first demonstrations, assuming that the CO_2 price will be too low.* In addition, CCS is facing social acceptance issues in some EU Member States (e.g. storage of CO_2 in Barendrecht in the Netherlands and the political stand-still in Germany).

7. As for other large-scale but already existent options**:** *new nuclear power or efficient gas power plants and CHP are competitors for future new coal-fired power plants with or without CCS, from a market and investor's perspective and assuming stringent climate policies.* Nuclear power has the advantage that its electricity production cost is not affected by increasing fossil and CO_2 prices, while the returns will increase. The profits will be higher with higher wholesale market prices per MWh under increasing fossil and CO_2 prices. This competitiveness is also confirmed by the postponement or even cancellation of new coal power plants in Germany, now that the nuclear phase out will be postponed. This change in Germany is also taken into account in the recent NRP-NL scenarios. As sensitivity for NRP-NL, Delta's plan for a new nuclear power plant in the Netherlands will reduce the future potential and viability of CCS (after 2020). From another and more Northwest European perspective, any new power plant with low marginal cost will obtain a good position in the overall Northwest European merit order. Because of its geographical location, the Netherlands will remain an interesting location for new power plants, also in the period after 2020.

8. *Similar to CCS, new nuclear power is still a politically and socially controversial option in some EU Member States.* For nuclear, the controversy is mainly related to safety and waste considerations. However, in several countries nuclear energy gets increasing support. EU Member States such as Poland have recently decided to build their first nuclear power plant as an alternative to their largely coal and lignite based fleet. The UK and Sweden have decided to build new nuclear power plants, partly as replacement for older ones (UK) but eventually also as a net expansion of nuclear generation capacity. In Belgium and Germany, the current government coalitions decided to postpone the nuclear phase-out. For Germany, this will provide a 'negative' incentive to embarking on new coal power plants with CCS in the short to medium term (up to 2020-2025). Since technologies such as CCS, wind energy, coal, and nuclear have high capital costs, the investments and plans in the short term are quite uncertain as long as the economic and financial situation is weak. Assuming economic recovery after 2011, this situation may change.

9. *Given the nature of similarity of electricity market mechanisms in other Northwest European Member States such as the UK and Germany, the above conclusions are to a large extent valid for these other countries as well.*

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