CATO-2 Deliverable WP 2.2-D 2.2 01 Screening of the impacts of large scale CCS on the electricity market

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1 Executive Summary

The Netherlands is heavily dependent on the success of both carbon capture and storage (CCS) and renewable electricity for its decarbonisation policy. The same holds for the EU and some of its Northwest European Member States like Germany and the United Kingdom. This report discusses several scenarios for the Netherlands within the context of a liberalised and a more and more connected energy market in Northwest-Europe. These scenarios are based on the recent ECN/PBL reference projections 'Energy and Emissions 2010-2020' published in April 2010. These scenarios have been expanded up to the time horizon of 2030 and have been subject to additional sensitivity analyses on the role of CCS, other fossil fuel price and CO_2 price paths. The research reported here shows that CCS on the new coal fired power plants currently under construction 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 currently still in place mainly in the form of financial support as long as these renewable options are not yet profitable (SDE, Stimulering Duurzame Energie). For CCS, financial support is only granted now for a selection of the first demonstration projects planned in the EU. At the start of this research, it was 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 report shows that from a technical and economic point of view, there is room for deployment and growth of both technology options. In addition, it shows under conditions such a two fold growth will be feasible. These conditions are mainly of a policy and economic nature. As future is inherently uncertain, the most important uncertain driving forces are highlighted and discussed. Recent changes in the political arena may also induce changes in policies. Further analysis of these recent developments will be part of phase B of the CATO-2 WP 2.2 research.

This report highlights the joint role of CCS and wind energy in reducing CO_2 emissions. In addition it has looked into the issues of flexibility and reliability of the energy system. 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. Therefore, also the electricity scenarios for these neighbouring countries have been taken into account in the analysis.

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

- Flexibility or reliability considerations seem to impose no technical constraints on CCS in Dutch power generation.

- 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.

- 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 compared to the wholesale market price: variable cost exceeds the returns. Gas fired production would then be more attractive, but would result in a higher electricity price due to the higher natural gas prices. In that case, deployment of CCS can reduce the variable cost of production and improve the position of these coal power plants in the merit order, compared to gas fired power. However, the higher investments needs of CCS may constitute a barrier. The high investment would need a higher wholesale electricity price or a higher CO_2 price that can deliver such a higher electricity price. Additional and dedicated CCS policies are needed as long as CCS is not cost-effective on its own.

- 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 cost assumptions and scenario calculations, this would require more than 60 €/ton CO_2.

- 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.

- Dedicated specific CCS policies are needed in the period after the first demonstrations, assuming that the CO_2 price will be too low.

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

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Draft A	42	First version for internal and UU review	
2010.11.04	1-56	Includes comments made by UU and from internal ECN review	
2011.01.14	1-56	Public version	

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2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are documents that are the "legal" basis to the work performed)

	Title	Doc nr	Version date
AD-01	Beschikking (Subsidieverlening CATO-2 programma verplichtingnummer 1-6843	ET/ED/9078040	2009.07.09
AD-02	Consortium Agreement	CATO-2-CA	2009.09.07
AD-03	Program Plan	CATO2-WP0.A-D.03	2009.09.29

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	Doc nr	Issue/version	date

2.3 Abbreviations

(this refers to abbreviations used in this document)

3 Introduction

3.1 Background

The electricity markets in Northwest Europe will undergo structural changes in the near future. Besides expected but modest electricity demand growth and increasing fuel and CO_2 prices, new investments in power generation capacity (including wind energy) are foreseen as well as decommissioning of old power plants. The European Union and the Netherlands have formulated ambitious targets to curb down greenhouse gas emissions by 2020, to increase the share of renewable energy, and to speed up the pace of energy saving and efficiency improvement.

For the EU the renewable energy target amounts this 20%; for the Netherlands it equals 14% (of final energy demand, EU target) or the somewhat more stringent national 20% renewable energy target, based on primary energy input (VROM, 2007). Renewable electricity is a major part of the overall renewable energy target. For the Netherlands, 35% share of the electricity demand equivalent to 55 TWh of production in 2020 is an element of planned new policies [1] as part of the Dutch Clean & Efficient Program, initiated in 2007 by the Balkenende IV cabinet. The renewable energy part 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 had the largest share in the total newly built 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.

Within the EU Emission Trading System, CO_2 prices are anticipated to increase on the longer term with more stringent climate policies in place. CO_2 Capture and Storage (CCS) is considered an important technology in the transition portfolio to a long term sustainable energy supply and needed according the Dutch governments (EZ, 2009; VROM, 2007; ECN/PBL, 2007, 2009). CCS is considered to play an important role in the Dutch climate policy (EZ/VROM, 2007; 2009).

CCS is able to reduce emissions in the Netherlands by tens of megatons per year. An amount of 4 to 21 Mt CO_2 avoided per year is assumed as the maximum feasible capture potential in the Netherlands by the year 2020 (ECN/PBL, 2007; 2009; Broek, 2010). In 2030 or 2050 higher captured volumes are possible, up to 80-100 Mt but very dependent on uncertain and future scenario assumptions (Damen, 2007; (Broek, 2010); (Broek et al., 2010). 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. The expected CO_2 price will be too low to make CCS a cost-effective option. Therefore, 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 (Seebregts et al, 2010; Groenenberg et al, 2010). The recent reference projections for the Netherlands (ECN/PBL, 2010) support such conclusions. These projections

[1] Currently uncertain as the cabinet Balkenende IV has been succeeded by another cabinet (as of 14 October 2010). The previous national goal of 20% renewable energy, based on primary energy, is not valid anymore. So, the 35% renewable electricity part may be relaxed as well.

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.

This report will discuss the implications of the above developments for the Dutch electricity market, in terms of potential reductions in CO_2 emissions, amounts of CO_2 captured in Dutch power generation, impacts on wholesale market electricity prices, and imports. The time horizon is 2030. These impacts are based on scenario analyses for the Netherlands embedded in the Northwest European electricity market. That market is already interconnected and is projected to be more strongly interconnected in the near future. The Netherlands has a central geographical position within this market. This central and attractive location does not only apply to electricity with new connections to the UK and Denmark, and an expected increasing role of offshore wind energy, but also to CCS (CO_2 Hub) and gas (Gas Roundabout).

3.2 Research questions

1. What will be plausible large scale rollout scenarios for CCS in the Dutch power generation, within the context of the most recent ECN/PBL Dutch Reference Projections (ECN/PBL, 2010) This Reference Projection takes into account the current economic crisis in the years 2009-2010. From 2011 onwards, a long term average GDP growth of 1.7%/year has been assumed. One policy variant is based on existing policy measures (like those already implemented and part of the Clean & Efficient programme) and another policy variant with additionally proposed policy measures.

2. How flexible and reliable will the electricity production system be in a variant with both large scale deployment of CCS and large shares of intermittent electricity production by wind energy?

3. What do 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 including CCS power plants and new gas-fired power plants in the Netherlands?

The remainder of this report will consider these questions.

3.3 Guidance to the reader

These research questions have been tackled within the context and constraints of the new reference projections for the Netherlands (ECN/PBL, 2010). Chapter 4 will provide an outline of the basic assumptions in these new ECN/PBL Reference Projections Energy and Emissions 2010-2020[2], for the Netherlands (abbreviated as NRP-NL). A long term outlook up to 2030 and 2040 has been constructed in a consistent manner from these projections. Figures up to 2030 are presented in this report. Basically after 2020 a further increase in renewable electricity has been projected. Chapter 5 provides an overview of the energy models and methodology used by which the results have been obtained. These results are summarized in Chapter 6. The issue of flexibility and reliability is covered in Chapter 7. Finally, Chapter 8 gives a summary of main findings from this research and modeling results.

[2] ECN/PBL, 2010

4 NRP-NL: the New Reference Projections for the Netherlands: background and assumptions

ECN and PBL made new reference projections for the Dutch government (ECN/PBL, 2010). The 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 reference projections and other long term energy outlooks made in previous years (e.g. ECN, MNP, 2005; WLO, 2006; ECN/PBL, 2009). The new reference projections will be the basis for policy assessments of current or new policy measures by the Dutch government. It is therefore also used as starting point and basis for the analyses documented in this report to support ongoing CATO research which require up-to-date scenario information.

4.1 Two policy variants: only one is used as basis

The new Dutch reference projections denoted as NRP-NL in the remainder of this chapter consist of two policy variants:

1. SV, based on *existing NL and EU policies* and instruments (‘*NRP-NL-SV*’).
2. SVV, equal to assumptions as in SV but supplemented 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 report, the new reference projection variant SVV is used as the main scenario, as it contains high shares of wind energy[3] . It is denoted as NRP-NL-SVV in the remainder of this report. The additional what-if cases on additional CCS on new coal or even new gas power plants have been analysed in the context of this NRP-NL-SVV projection. For comparison purpose, the original variant SV is shown without any changes to the original results.

To understand the results of the analyses, the scenario assumptions of NRP-NL are relevant and need to be understood well. Therefore these assumptions are summarized here.

4.2 Economic growth and electricity demand

The projected GDP growth in NRP-NL is lower than in the Global Economy and Strong Europe long term scenarios for the Netherlands of the previous reference projections (WLO, 2006), see table 4.1. Also the projected growth in electricity demand in NRP-NL takes into account the effects of the economic crisis. The 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% (CBS, 2009). 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 12 years, since the liberalisation of the EU electricity market. The average net import in the years 2000-2008 was 18 TWh.

[3] . For comparison, the results of the first variant NRP-NL-SV will be summarised more briefly

Table 4.1 GDP and electricity demand, scenarios and projections since 2006

	GDP growth %/year (2011-2030)	Electricity demand [TWh] 2020	2030	2040
Global Economy (High Oil Price variant) (WLO-GEHP)	2.7	156	181	212
Strong Europe (WLO, 2006) (WLO-SE)	2	137	148	161
Green4Sure (CE, 2007; ECN, 2007)	2	127	124	n/a
CE (2009)	unknown	140		
Update reference projections 2009				
UR-GE (fuel prices as in (EC, 2008))	2.7	156	181	n/a
UR-GE (h) (higher fuel prices (IEA WEO 2008)	2.7	156	180	n/a
New Reference Projections 2010				
NRP-NL-SV	1.7	130	136	n/a
NRP-NL-SVV	1.7	128	131	n/a

So far CCS projections for the Netherlands have not been based on the New Reference Projections 2010. The Strong Europe scenario was used by (Van den Broek, 2010) as basis for CCS scenarios up to 2050, analysed with the MARKAL-NL-UU model. A few years earlier, the Green4Sure scenario (CE, 2007) was defined as a normative scenario based on the economic growth figures of the Strong Europe scenario. The results for this Green4Sure scenario were calculated by ECN, based on assumptions provided and determined by CE (ECN, 2007). The Green4Sure scenario exhibits additional policies on energy saving, renewable energy (e.g. wind energy and biomass co-firing) and CCS.

The UR-GE and UR-GE(h) scenarios are updates of the WLO-GEHP scenario. The main differences are:

- somewhat changed fuel price projections
- different CO_2 price path (higher)
- inclusion of policies since 2005
- inclusion of new power plants currently under construction or power plants for which definite investment decisions were made (at the end of 2008). Most of these new power plants have been included in the Green4Sure scenenario as well.

The UR-GE scenario has been the basis for the (Seebregts and Groenenberg, 2008; 2009) study on the impacts of CCS on the Northwest European electricity market. The UR-GE(h) differs mainly from UR-GE in the fuel price assumptions. UR-GE(h) uses the IEA World Energy Outlook 2008 (IEA, 2008) fuel prices as basis.

4.3 CO_2 prices and fuel prices

NRP-NL assumes the following CO_2 price path:

- 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 (ECN/PBL, 2009) used 35 €/ton as a default value.

- Increasing to 50 €/ton CO_2 in 2040.

The natural gas and (imported) hard coal prices have been assumed equal to the prices used in the most recent EU baseline 'Trends to 2030 – update 2007' (EC, 2008), see also Figure 4.1 below. The default fuel price projections of NRP-NL and UR-GE scenario (ECN/PBL, 2009) have been assumed equal to this EU baseline. For hard coal an additional handling cost of about 0.2 €//GJ is used.

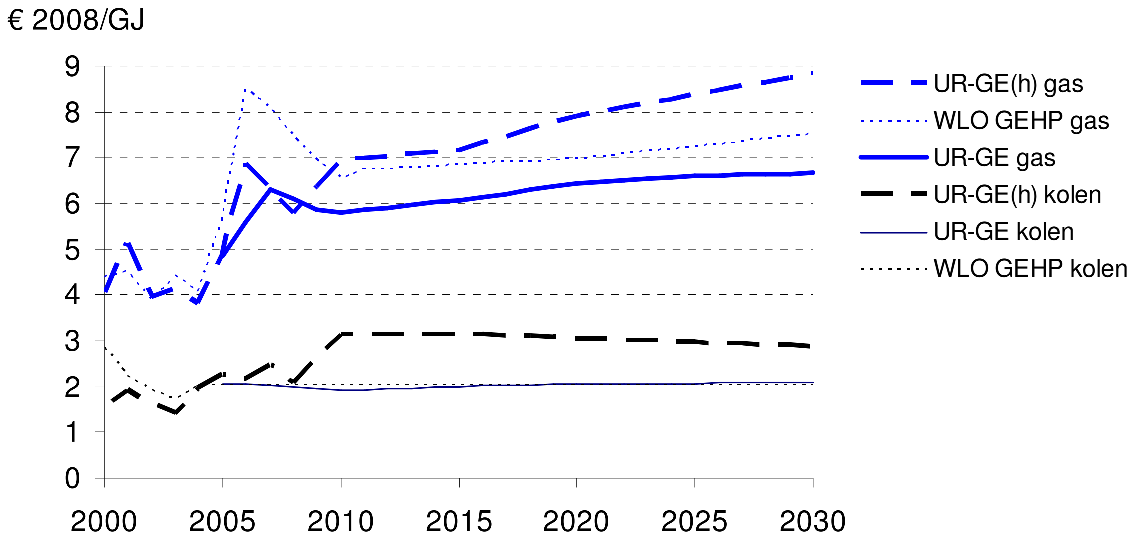


Figure 4.1 *Natural gas and (imported) coal prices assumed for NRP-NL (equal to UR-GE), Source: (ECN/PBL, 2009; Seebregts et al, 2009).UR-GE equal to (EC, 2008) fuel prices. UR-GE(h) equal IEA WEO 2008 prices. WLO-GEHP equals the high oil price variant of the WLO Global Economy scenario (WLO, 2006).*

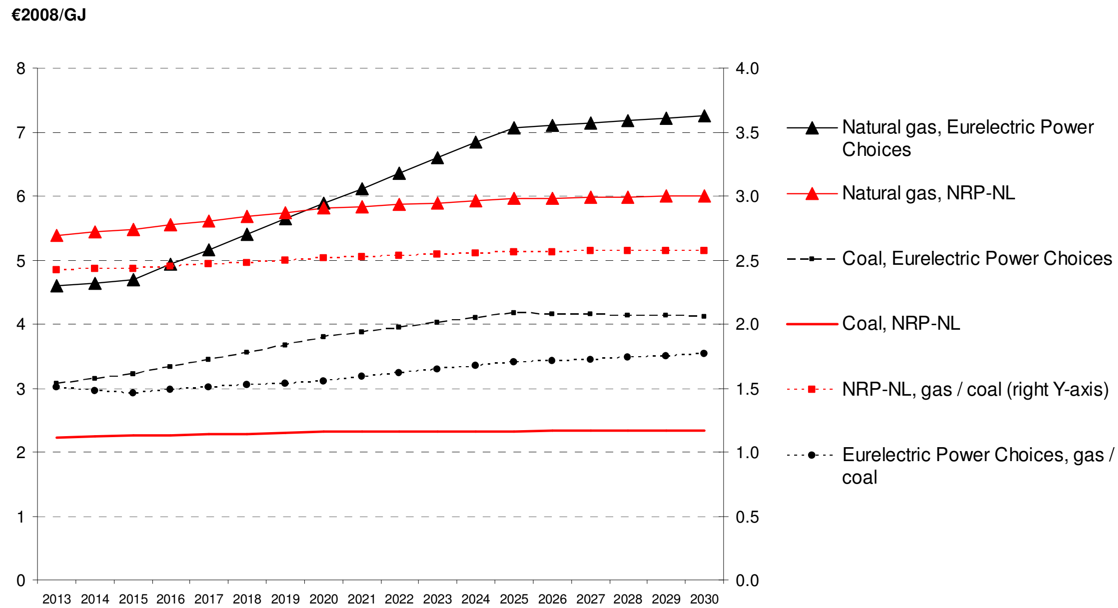


Figure 4.2 *Natural gas and (imported) coal prices from Eurelectric's Power Choices scenario compared to NRP-NL*

4.4 Power generation sector

The assumptions for the power generation sector and the domestic electricity demand for the Netherlands are summarised here. Assuming additional policies aimed at reaching the EU and the Dutch national 2020 targets on renewable energy, energy saving and GHG emission reduction, ECN developed a scenario for the electricity production in the Netherlands. The electricity generation capacity and the production mix are displayed in the next two figures. Interfaces (i.e. cross-border interconnections) and the electricity production system of the neighbouring countries Belgium, France, Germany, Norway and the United Kingdom are also modelled as part of the ECN scenarios. So, the Dutch power generation sector and its electricity market are modelled and analysed as part of the integrated Northwest Europe electricity market.

4.4.1 NRP-NL 10000 MW new fossil-fuel large scale power plants in period 2009-2015

Increase in production capacity
The power generation sector is responsible for a substantial amount of CO_2 emissions. As a consequence, the (new) large power plants have a significant potential for deployment of large scale CCS. The current new build fossil-fired power plants (about 10 GW up to 2015) and electricity generation by wind energy contribute mainly to the overall increase from about 25 GW end of 2008, to a projected generation capacity of almost 42 GW in 2020 (NRP-NL-SVV), see Figure 4.3. In 2010, new gas power plants contribute to the increase in total capacity (Sloecentrale and new Flevocentrale, almost 2 GW). Additional gas CCGT's will come on line in

2011-2013 (about 4 GW). In the period 2012-2015, the new coal fired power plants will be put into operation, about 3.5 GWe in total. The details of these new built plants are given in Table 4.2.

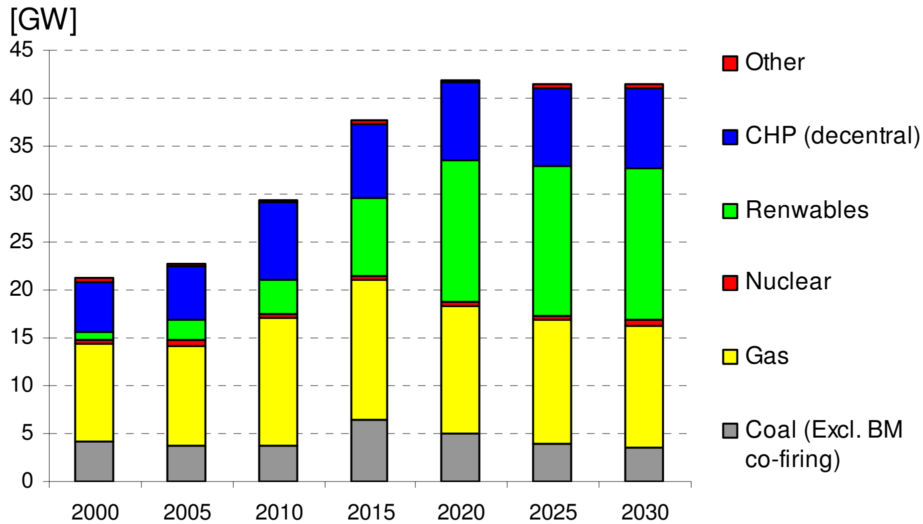


Figure 4.3 *Installed total generating capacity 2000-2030, NRP-NL-SVV, new reference projection*

Increase in electricity production, and change from net importer to net exporter
The domestic electricity production is displayed in Figure 4.4. After 2010, the net electricity import changes to a net electricity export

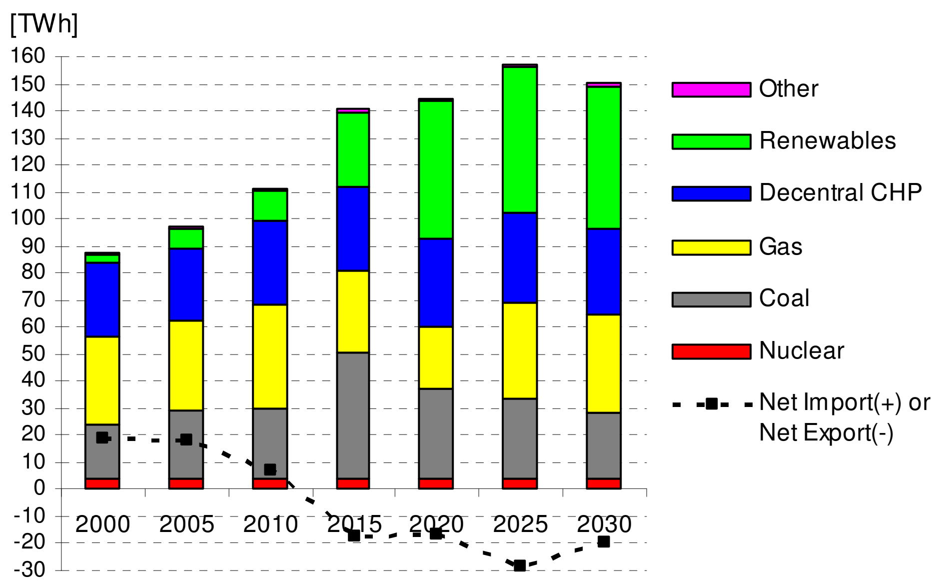


Figure 4.4 *Electricity production and development net import/export, 2000-2030, NRP-NL-SVV, new reference projection*

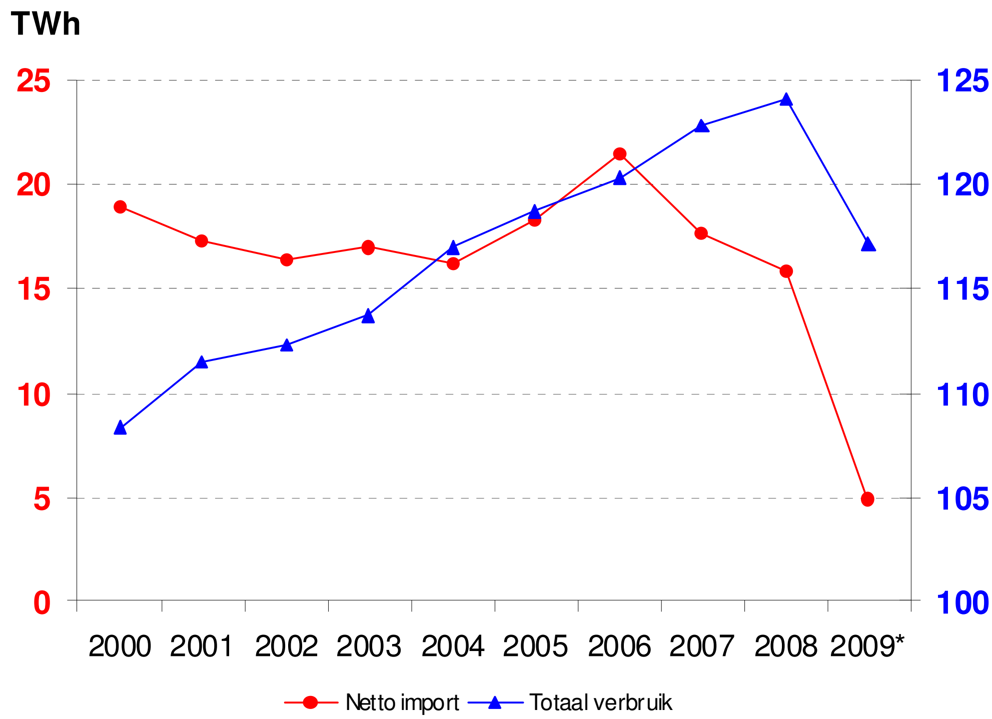


Figure 4.5 *Development of net import of electricity for the Netherlands (realisation in 2009 was 4.9 TWh, close to the value computed in UR-GE(h))*

New built plants and plans in the Netherlands

One of the main drivers of the growth in electricity production is the amount of new build power plants in the Netherlands in the period 2009-2015. The details of these new build plants, either under construction or planned, are given in Table 4.2. The total amount new built large scale fossil fired power plants amounts to almost 10 GW, consisting of almost 3.5 GW new coal-fired and about 6 GW of new natural gas-fired power plants. This excludes new built decentralised CHP and renewable generating capacity (mainly wind energy).

ECN considers the amount of assumed new built power plants in NRP-NL realistic and plausible with the scenario assumptions of NRP-NL. A vast majority of this 10 GW is already under construction or has recently started production (i.e. a few of the natural gas-fired power plants: the Sloe power plant, the new Flevo power plant, and the Intergen plant Maasstroom Energie).

Table 4.2 ***New build large scale power plants in the Netherlands, in the period 2009-2020 (updated from table in Seebregts et al, 2009)***

Company	*Location*	*Capacity [MW_e]*	*In operation (planned)*	*Type*	*Net efficiency*	*Status*
Assumed as part of NRP-NL reference projections						
Gas						
Delta	Sloe area (Sloecentrale)	870	2009	CCGT	58%	In operation since October 2009
Electrabel	Flevocentrale	870	2009/2010	CCGT	59%	In operation?
Enecogen	Rijnmond	870	2011 (Q4)	CCGT	59%	Under construction
Essent/RWE	Moerdijk	400	End 2011	CCGT (CHP)	58% [4)]	License 28-5-2008
Essent/RWE	Maasbracht (Maasbracht-C)	+635	2011	Upgrade Maasbracht-B tot CCGT	58% [5)]	Contracts signed May 2008
Intergen [3)]	Rijnmond	419	2010	CCGT	58%	Under construction
Vattenfall/Nuon [1)]	Eemshaven (Magnum)	1300	2012	CCGT	56%	Under construction
Corus	Ijmuiden	525	2012	Blast furnace gas, CHP	unknown	Start Note (In Dutch: 'Startnotitie') 16-10-2008
Total new large scale gas		**5859**				
Coal						
E.ON	Maasvlakte (MPP-3)	1070	2012	pulverised coal	46% [2)]	Under construction
Electrabel	Maasvlakte	800	2012	pulverised coal	46%	Under construction
RWE	Eemshaven	1600	2013	pulverised coal	46%	Under construction
Total new coal		**3470**				
Other plans but not assumed to proceed in NRP-NL reference projections						
Gas fired						
Advanced Power	Eemshaven	1200	2013	CCGT	58-60%	Start Note 8-7-2008 MER available
Electrabel	Bergum	454	2014	Unknown	Unknown	Via TenneT (2009)
NAM	Schoonebeek	130	2011	gas, CCGT		Via TenneT (2009)

Company	*Location*	*Capacity [MW_e]*	*In operation (planned)*	*Type*	*Net efficiency*	*Status*
Vattenfall/Nuon [11)]	Amsterdam, Hemweg	max. 550	Unknown	CCGT, possibly CHP	min. 57%	Start Note (In Dutch: 'Startnotitie') 11-4-2008
Vattenfall/Nuon [11)]	Diemen	max. 550 MW_e, max. 250 MW_{th}	Unknown	CCGT, CHP	min. 57%, electrical up to 80% total efficiency	Start Note (In Dutch: 'Startnotitie') 11-4-2008
Unknown	Maasvlakte	600	2011	gas	Unknown	Via TenneT (2009)
<u>*Coal fired*</u>						
Essent/RWE	Geertruidenberg	800		pulverised coal	46%	Plan dismissed
Essent/RWE/Shell	Zuid-West Nederland	1000 MW		IGCC	46%	Plan dismissed
C.GEN	Europoort	400-450	2012	IGCC	46%	Start Note (In Dutch: 'Startnotitie') 25-9-2008
C.GEN	Sloe area	400-450	Unknown	IGCC	46%	Press release
<u>*Nuclear*</u>						
Delta	Sloe area	Max. 2500	2018	Nuclear		Start Note (In Dutch: 'Startnotitie') 25-6-2009
ERH	Sloe area	Max. 2500	2019	Nuclear		Start Note (In Dutch: 'Startnotitie') Sep 2010
Unknown	Sloe area	Additional 2500		Nuclear		TenneT (2009)

<u>Notes for Table 4.2:</u>

1) The conversion efficiency is strongly dependent on the fuel mix. The priority alternative (Dutch: voorkeursalternatief) includes a 60% coal/biomass (720 MW, efficiency 45%) and a 40% natural gas (480 MW, efficiency 54%). Using 100% natural gas gives an efficiency of 54% (less than about 58% for other CCGT's; the reason being the gasturbines are designed to cope with syngas instead of natural gas). Vattenfall/Nuon has postponed the decision to build a multi-fuel gasification unit. Building the gas-fired CCGT's (1400 MW, 3 units) has started. A gasification unit may follow later.
2) With 30% biomass as fuel, the efficiency is 1%-point lower (45%).
3) Building has started in January 2008 (Press releases, Intergen en Oxxio, 2007).
4) Environmental Impact Statemen (Dutch: MER). Operating hours 7000 (expectation, as start/stop unit) and 8200 hours (worst case with respect to total emissions, the base load operation unit). The permit (dated 29 May 2008) reports that the CCCT will be used primarily as flexibele peak load unit. It will be switched off often during nighttime.
5) Press release Essent/RWE 29 May 2008; previously in MER: 56% using natural gas, possibly 42% for bio-oil using boiler; in that case an average of about 52% (740 MW gas 160 MW bio-oil). Old unit B was 37% (and 640 MW capacity). PrEssent/RWE, nummer 4, November 2008 reported a value of 58,8%.

6) If unit is built, it will replace the conventional boiler unit Hemweg-7. District heating is being considered. Vattenfall/Nuon is planning to decommision older units within 7-9 years. This involves older units in the region Utrecht and Amsterdam.
7) Intended as additional CHP unit for district heating purposes.
8) Start Note (In Dutch: 'Startnotitie') mentions coal, petcokes (maximum about 25%, natural gas and clean biomass (maximum about 25%). The design will be capture ready such that on the longer term about 85% of the CO_2 produced from coal, petcokes or biomass, can be captured.
9) In the old reference projection RR-GE from 2005 (ECN/MNP, 2005), 2400 MW (4000 MW in WLO-GEHP, WLO, 2006) new build coal was assumed. And no existing coal power plants had been decomissioned. Only the new Sloecentrale was assumed to operate. The remainder of the increase in the gas-fired power d uit decentrale CHP.
10) All net efficiencies are based on a.o. (Seebregts & Daniëls, 2008) based on information from the various Environmental Impact Assessments (In Dutch: Milieueffectrapportage), or press releases later on including more up to date information.
11) Vattenfall/Nuon has decided to really invest in these two gas-fired power plants. The new CCGT at Hemweg will replace the old gas-fired power plant. The new Diemen plant will mainly serve as additional capacity with an expansion of the district heating for the city of Almere.

A licence does not necessarily mean a power plant will be built
At this moment, licences for five new coal-fired plants have been granted, but only three plants are being built It should be noted that granting of licences and permits are no guarantee the power plant will be built.One of the plants (Essent) has already been dismissed. The Vattenfall/Nuon's Magnum plant is waiting for a final investment decision to make it a multi-fuel coal/biomass gasification plant rather than the natural gas CCGT plant currently under construction. In (ECN/PBL, 2010) the construction of this multi-fuel gasification unit has been treated as a sensitivity analysis to the NRP-NL reference projections. It then will exhibit higher production as its position in the merit order is more advantageous as a coal power plant than as a natural gas fired power plant.

4.4.2 New Coal, CCS, biomass co-firing and small scale biomass plants

The 3.5 GWe coal-fired power plants under construction currently under construction are built as 'capture-ready' power plants. The first units will produce electricity in 2012 and 2013. On the longer term, old coal-fired power plants are assumed to be decommissioned, starting shortly after 2015. The existing coal-fired fleet amounts to almost 4.2 GW_e. and consists of 8 units on six locations.
After 2020, no new coal-fired power plants will be built in the Netherlands according the NRP-NL-SVV reference projection. The currently being built 3.5 GW of new coal-fired capacity will be available for CCS in the period 2015-2050, assuming a lifetime of 40 years.
Large scale biomass fired power plants which could also qualify for CCS are not forecasted as plausible within the NRP-NL scenario assumptions. The CO_2 price assumptions are too low to make such plants interesting for investment, also lacking the necessary policy support in the form of a dedicated subsidy scheme. Such a subsidy scheme is restricted to co-firing of biomass in coal-fired power plants and to small biomass power plants. The latter is part of the current SDE subsidy scheme, up to a size of 30 MW_e (Lensink et al, 2009).

The three new 'capture ready' coal-fired power plants are being built in the Rotterdam and Eemshaven areas. First CCS demos may be applied to two of these projects prior to 2020: one at each location. In NRP-NL-SVV only one demo has been assumed, because additional subsidies for a second demo in the Eemshaven area are uncertain. The Electrabel/E.On joint project in Rotterdam, now called the 'ROAD' project (Maasvlakte, Rotterdam) will receive the necessary funds with the EERP and additional national subsidy. Based on a 250 MW_e equivalent, the plan is to capture 1.1 Mton CO_2 by the end of 2015 (Electrabel Newsletter, 2009). This demo has been modelled as part of NRP-NL.

Figure 4.6 *Location of E.On's new coal power plant and routing of CO_2 transport (Source: GdF Suez, 2010)*[4]

4.4.3 Natural Gas and CHP

The share of natural gas fired power plants will remain substantial. Part of those plants will be flexible enough to cope with large shares of intermittent wind energy. Also, decentralised CHP will remain an important option within the NL electricity system, see also the previous Figure 4.3.

[4] GDF SUEZ (20100: *CCS Corporate Program – activities and experiences*, Polish Science for FP7 Seminar, Sustainable Energy and Efficient Use of Energy Resources, Embassy of Poland, Brussels, 25thMarch 2010. Downloadable from http://www.polsca.be/ppt/100325/MDW.pdf (download 4 September 2010).

4.4.4 Nuclear: plans but not modelled

Current Dutch policy is to keep the only nuclear power plant at Borssele open until 2034 if this plant can show it remains safe according the licensing rules. Its safety is re-assessed every ten years. The last safety evaluation was in 2007. The plant then also upgraded its turbines such that the net MW_e increased by about 35 MW_e.
The new Dutch government (since 14 October 2010) aims to give permit(s) for new nuclear power plants if they meet all the licensing conditions and safety regulations. One Dutch electricity producer, Delta, launched a plan in 2009 to have a second nuclear power plant in operation by the year 2018 (Delta, 2009). It is not included in NRP-NL-SVV, because so far a government decision on new nuclear power plants in the Netherlands had not been taken. The outcome is highly uncertain due to the political and societal controversy of new nuclear power in the Netherlands. Recently an additional plan for a new nuclear power plant has been reported by ERH (ERH, 2010). ERH plans to have 2.5 GW_e of new nuclear power to be in operation in 2019. Licences for these new power plants could be granted somewhere between 2013-2015 if all procedures proceed as planned by these two energy companies. The actual electricity market situation in that time window (2013-2015) will be determinant whether companies like Delta and ERH, possibly joined by other European energy companies will make definite investment decisions for these high capital investments. Effects of new nuclear power plants have been investigated in a recent separate ECN study (Seebregts et al, 2010). One of the scenarios developed for that study includes both large scale CCS and high shares of wind energy. The scenarios have a 'what-if' type of character and model a situation without new nuclear and with new nuclear power plants. For its results, the reader is referred to the reference mentioned.

4.4.5 Renewable energy: mainly wind energy and biomass

The prime focus of NRP-NL is on the year 2020 because of the 2020 NL and EU targets and the existing and planned policy measures to achieve these targets. However, the NRP-NL projections have been extrapolated up to the year 2040 for electricity demand and electricity generation assuming no additional policies after 2020. For this study, the reporting time period is restricted to the years 2010-2030 although the.calculations with the electricity market models have been carried out up to 2040.

4.4.6 Decommissioning of power plants

Relatively old and less efficient coal and gas fired power plants are decommissioned in the period 2013-2025, according the scheme outlined below.

Decommissioned power plants	Fuel	Capacity (MW)	Year out of operation
Bergum-10	Gas	332	2016
Bergum-20	Gas	332	2017
Eems-20	Gas	695	2019
Hemweg-7	Gas	599	2014
L.Weide-5	Gas	265	2022
Velsen-24h	Gas (Blast furnace)	459	2016
Donge-1	Gas	121	2015
Maasbracht-A	Gas	638	2013

Decommissioned power plants	Fuel	Capacity (MW)	Year out of operation
Maasbracht-B	Gas	640	2011
Gelderland-13	Coal	602	2017
Maasvlakte-1	Coal	520	2022
Maasvlakte-2	Coal	520	2022
Amer-81	Coal	645	2016
Borssele-12	Coal	406	2022

4.4.7 Other projections for new capacity in the Netherlands

TenneT: more than 30 GW of new fossil and nuclear power plants
The 10 GW of newly built power plants up to 2015 is far less compared to the plans reported by TenneT (TenneT, 2009). The TenneT report projects about 30 GW of fossil and nuclear power generation capacity being built up to 2020. Up to 2017, TenneT reports a value of 25 GW. ECN considers this high value not be realistic. A value of 10 to 11 GW is considered more likely, given current market situations and economic expectations for the next 10 years. About 9 GW of the new power plants has signed a contract with TenneT to be connected to the grid.

CE: only 7 GW new build (including decentralised CHP)
CE (2009) assumes that only 7 GW fossil-fueled generating capacity in the period up to 2020 will be built, including large scale power plants and decentralised CHP. As can be seen from Table 5.2, this 7 GW is too low in view of what is currently already under construction or contracted to being build.

5 Models and methodology used

This chapter summarizes briefly the models and methodology used in the calculation of the electricity market and electricity production system.

5.1 Models to analyse electricity market and electricity production system

5.1.1 NEOMS

For generating results on the total electricity production in the Netherlands, ECN uses a suite of models, which are all integrated in the National Energy Outlook Modelling System (NEOMS, Volkers, 2006).[5] For electricity production, the following three models are relevant.

- POWERS (see section 5.1.2)
- Save-production
- Renewable energy model (‘RES model'). A.o., this model projects the capacity and the electricity production by renewable energy sources.

A graphical display how these three models interface is shown in Figure 5.1. The RES model and Save-production models have been improved as part of the reference projections in 2009-2010 (ECN/PBL, 2009; 2010).

5.1.2 POWERS and Save-Production

The NEOMS graph shows the data flows between POWERS, Save-Production and the other models in the NEOMS. The most important data from the NEOMS database are commodity prices (a.o. wholesale market electricity prices) and other price components of coal, natural gas, biomass and electricity, as well as the steam supply (heat demand) to the industrial and agricultural sectors by refineries and central power generation. The Dutch electricity market model POWERS (Seebregts et al., 2005) provides wholesale electricity market prices for the other models, while the Tariffs Model provides elaborate information on delivery and tax components of prices of natural gas and electricity, allowing the end user and sectoral demand models to determine energy prices for individual sectors and potentials for CHP.
Apart from providing electricity prices to Save-Production, POWERS also uses results from Save-Production, namely on the electricity demand and generation with CHP installations. To achieve equilibrium on the electricity market, these two models have to perform several iterations, until electricity prices are converged sufficiently. Usually, this takes about 4-5 iterations for an entirely new fuel or CO_2 price scenario path. The consistency of the RES model is also checked. The RES model is based on subsidy budgets (MEP or SDE) and electricity market prices to calculate the actual capacity and production of (new) renewable electricity production. In additional, some constraints apply having to do with some practical barriers for large scale deployment of renewable energy sources. The combination of changed wholesale electricity prices (lower of higher) and a limited subsidy budget may lead to different levels of renewable electricity production. E.g. lower electricity wholesale electricity prices may lead to less renewable electricity

[5] See http://www.ecn.nl/units/ps/tools/modelling-systems/

in case of limits in these budgets. Such interactions are taken into account in the integrated NEOMS calculations and iterations.

The extensive data exchange with other models in the NEOMS implies that some data are exogenous to the Save-Production model, the RES model and other sectoral energy demand models, such as electricity prices and steam delivery. With the NEOMS as total perspective, the wholesale electricity prices are endogenous. The same holds for the electricity demand.

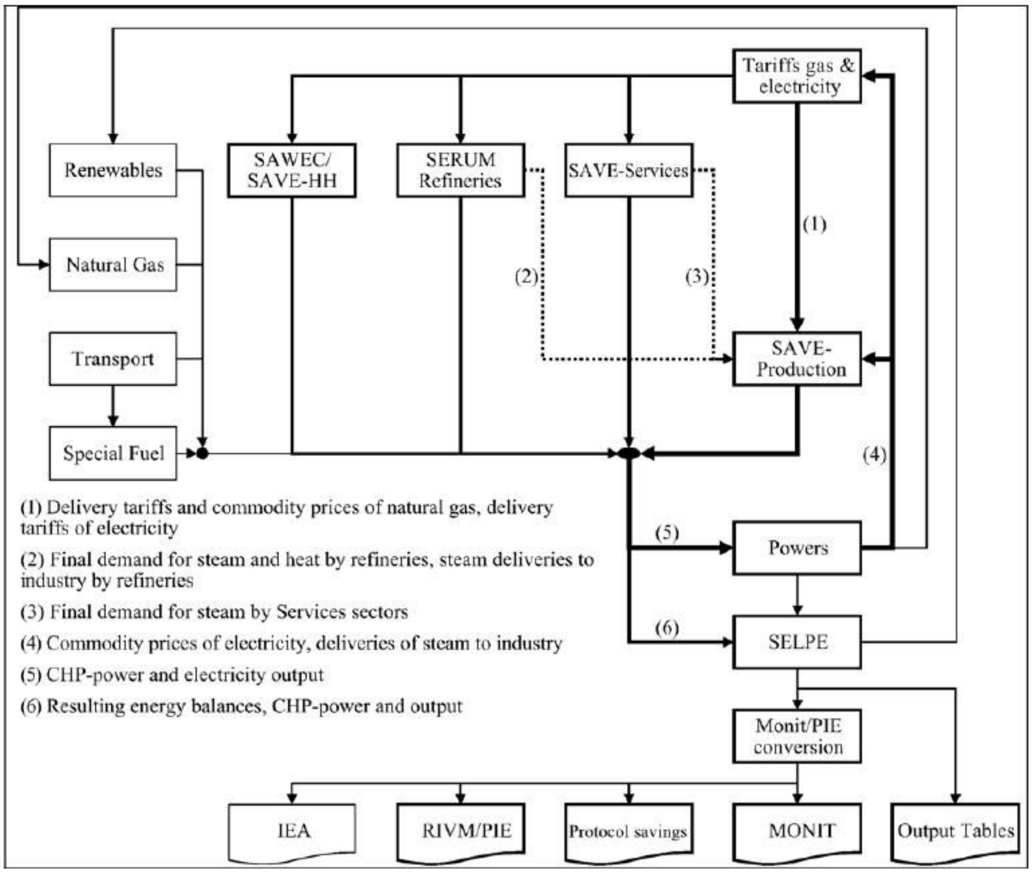


Figure 5.1 *The The Netherlands' Energy Outlook Modelling System (NEOMS, In Dutch: NEV-Rekensysteem): Source: (Daniels & van Dril, 2007)*

For a more detailed description of the POWERS model, see (Seebregts et al., 2005) or (Seebregts & Groenenberg, 2009). As explained before, the POWERS model is usually run in tandem with the Save-Production model (Daniels & Van Dril, 2007) that incorporates in detail the decentralized CHP installations and the end user sectors industry and horticulture. The industry and the CHP installations are potential CO_2 point sources to deploy CCS. A more in-depth analysis on the CCS potential in these sectors will be part of the next phase b in CATO WP 2.2 research (UU/ECN PhD research).

POWERS models the neighboring countries in less detail, but can also compute import and exports of electricity. The countries modelled are: Germany, Belgium, France, the United Kingdom and Norway. The situation in 2020 is presented in the figure below. A future planned interconnection, the CoBra cable with Denmark which is now being considered by TenneT and the Danish TSO is not yet modelled in the POWERS model. Once a definitive decision has been made by these TSOs, ECN will include the interconnection in its electricity market models.

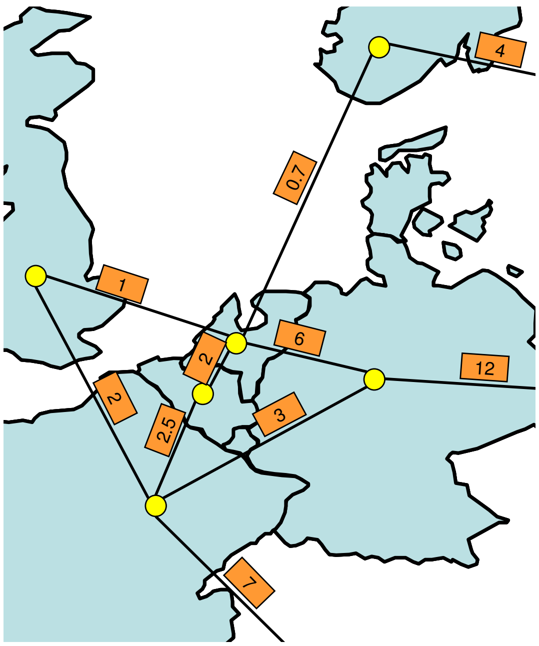


Figure 5.2 *The Netherlands and its interconnections with other countries in NW EU, NRP-NL, year 2020. The numbers indicate the maximum interconnection capacity in GW.*

Powers is able to analyze the full time period 1998-2010, with results aggregated for each year. It differentiates between all 52 weeks per year, at three load (demand) levels: off-peak (23-7 h during working days and weekends), peak (10-16 h; and 19-23h at working days), and 'superpeak' (7-10 h and 16-19 h at working days). The hourly demand load pattern is aggregated into that same level of detail.

Rules of thumb to establish sufficient convergence in the simulation models

For the what-if calculations reported here, the POWERS simulation model for the Dutch electricity production and electricity market has been used in a stand-alone fashion. For this research, the tandem, POWERS with the Save-Prduction model, has only been used as part of what-if CCS deployment analyses, and the sensitivity analyses on the fuel and CO_2 prices.
If either the assumptions of these key scenario drivers change or if POWERS calculates a substantially different wholesale electricity prices compared to a previous model run, re-runs of Save-Production or the RES model are needed to have a completely consistent picture of the electricity production system.

The various model runs with the models in the past five years have shown that a change of more than 2-3 euro/MWh (=0.2-0.3 ct/kWh) is large enough to produce non-negligible changes in the Save-Production results i.e. a noteworthy response in the production of decentral CHP installations. An other rule of thumb is the amount of TWh produced by decentral CHP in two subsequent integrated runs. If this change is less than 2 TWh then we consider sufficient convergence.

Table 5.1 Rules of thumb to decide 'convergence' or to enable stand-alone 'what-if' or other sensitivity analyses.

Criterion	Description, How used in practice?
Wholesale electricity price	The average wholesale electricity price in the years analysed. A change of less than 2-3 euro/MWh in two subsequent model iterations is used a criterion to stop the iteration.
TWh produced by CHP in two consecutive runs	The production by decentral CHP is about 30 to 40 TWh in the scenarios analysed. If two consecutive iterations results in a difference of less than 2 TWh, sufficient convergence ('market equilibrium') is assumed not to warrant additional iteration
CO_2 emissions by installations in POWERS	The ECN reference projections are performed among others, to estimate the national CO_2 emissions and other emissions (NO_x SO_2) in the Netherlands. Given the inherent uncertainty in the key scenario assumptions (economic growth, fuel and CO_2 prices), one (1) Mton of CO_2 is considered as a sensible value to differentiate between two cases. 1 Mton CO_2 is also about 2 TWh as a rule of thumb based on the average CO_2 emission from Dutch power production.

5.2 Cost projection methodologies

For the future cost of electricity generation technology, a variety of sources have been used. Techno-economic assumptions on new generating capacity are mainly based on (Seebregts & Groenenberg, 2009) for new fossil power plants, either with or without CCS. Recent estimates made as part of the renewable energy support scheme and CHP subsidy scheme in the Netherlands (Lensink et al, 2009) and CHP (van der Marel, 2008; Hers et al, 2009; Wetzels et al, 2009) have been used for renewable production and CHP, respectively. The relevant parameters have been input to the Dutch cost estimates in the recent OECD Projected Cost Of Generating Electricity study (OECD, 2010). Appendix B shows more details on these cost estimates. In (Seebregts et al, 2010) more recent cost estimates from other studies are presented, such as recent IEA scenario and EPRI cost studies.

Table 5.2 Sources for cost information and underlying techno-economic parameters

Technology	Country	Sources of information
The Netherlands		
New fossil-fueled power plants, with and without CCS	NL	Seebregts & Groenenberg, 2008, 2009
CHP	NL	Van der Marel, 2008; Hers et al, 2009; Wetzels et al., 2009
Renewable	NL	Lensink et al., 2009

5.3 Additional data on CCS deployment in period 2015-2030

In the next chapter, the results with additional CCS deployment in the NRP-NL-SVV reference projection are given. The following data have been used:

Parameter	Value/assumption
Capture efficiency	90%
Loss in net capacity	20% for first demos, decreasing for next projects
Net efficiency	35% for first demos, increasing to 39% for CCS starting in period 2025-2030

6 Results

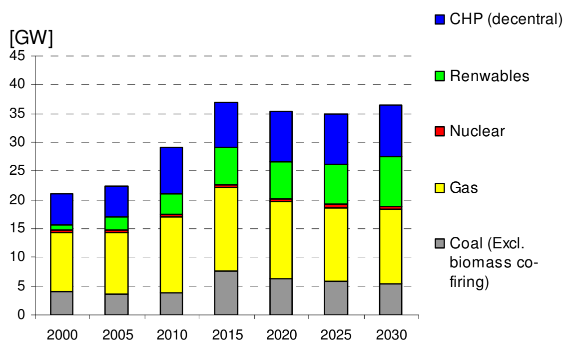
This chapter presents the results obtained in the various model calculations. For comparison purposes, both NRP-NL variants are shown here.

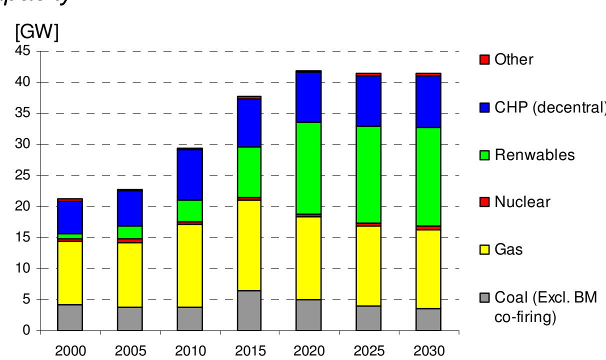
6.1.1 Generating capacity

The electricity generation capacity is given in the figures below. The renewable part of the total electricity generation is given into its separate categories. Wind energy is the main renewable option.

NRP-NL-SV | **NRP-NL-SVV (more RES)**

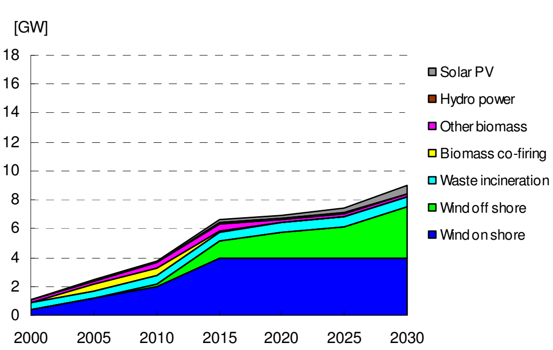
Total capacity





Biomass co-firing is included under 'Biomass co-firing', not under 'Coal')

Renewable generating capacity



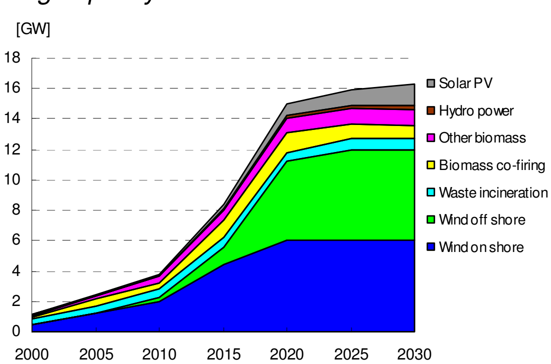


Figure 6.1 Electricity generation capacities, in GW

The generating capacity of the centralized power plants in POWERS are exogenous (assumptions) while the generating capacity from renewables and decentral CHP are mainly the results of the model calculations. In the NRP-NL-SVV variant, the renewable capacity is much higher. In addition, closure of the oldest coal power plants takes place somewhat earlier. The potential for CCS in power generation in NRP-NL-SVV is restricted to the new coal power plants. This amounts to about 3400 MW (gross).

6.1.2 Fuel mix of electricity production

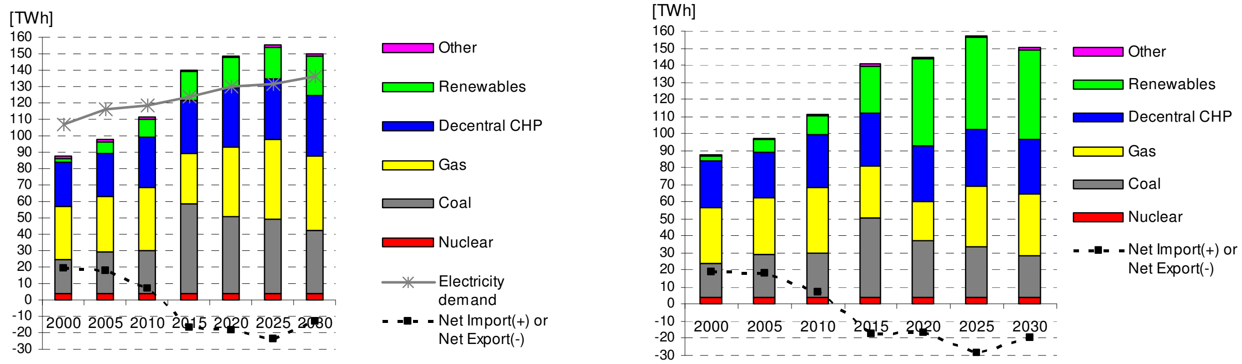
The fuel mix of production is the result of model calculations. The electricity production in terms of TWh is given in the figures below. The renewable part of the total electricity production is given into its separate categories. Wind energy is the main renewable option. The role of production by coal is less in NRP-NL-SVV than in NRP-NL-SV, as co-firing of biomass in the coal power plants leads to a reduction in the use of coal. However, the operating hours of the coal power plants are roughly the same. Biomass co-firing is subsidized reducing the increase in variable cost compared to the original use of 100% coal.in the NRP-NL-SVV variant.

6.1.3 Import or export of electricity

The change from being a net importer to a net exporter of electricity is shown in the previous Figure 6.1. Under the assumptions in the various ECN scenarios and reference projections, this change is quite robust, in particular the changing trend in importing less and exporting more electricity. The trend to net import can be seen in Figure 6.2. After 2010, the Netherlands becomes a net exporter of electricity.

NRP-NL-SV **NRP-NL-SVV (more RES)**

Total electricity production



Renewable electricity production

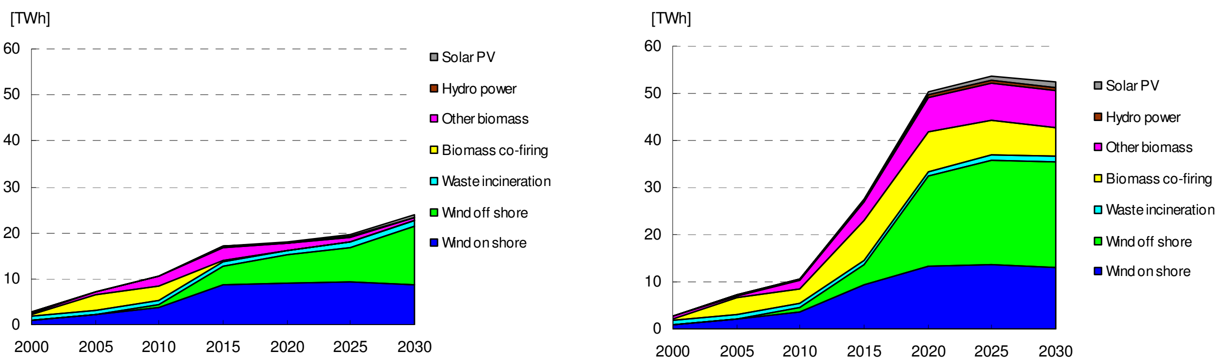


Figure 6.2 Electricity production mix, in TWh

6.1.4 Wholesale market electricity prices

The average wholesale markets prices calculated for NRP-NL show approximately the same values for NRP-NL-SV and NRP-NL-SVV. The latter show somewhat lower prices due to the higher penetration of wind energy, an option with very low marginal costs. E.g. the electricity price in 2020 is 62 €/MWh for NRP-NL-SV, while for NRP-NL-SVV it is 60 €/MWh. With a CO_2 price of 50 €/ton CO_2, the electricity market price will be about 80 €/MWh.
The Figure 5.4 below show an indication of how electricity prices evolve in time, with NRP-NL-SV as basis. For that case, sensitivity analyses have been conducted for lower and higher fuel and CO_2 prices as part of the (ECN/PBL, 2010) reference projections.

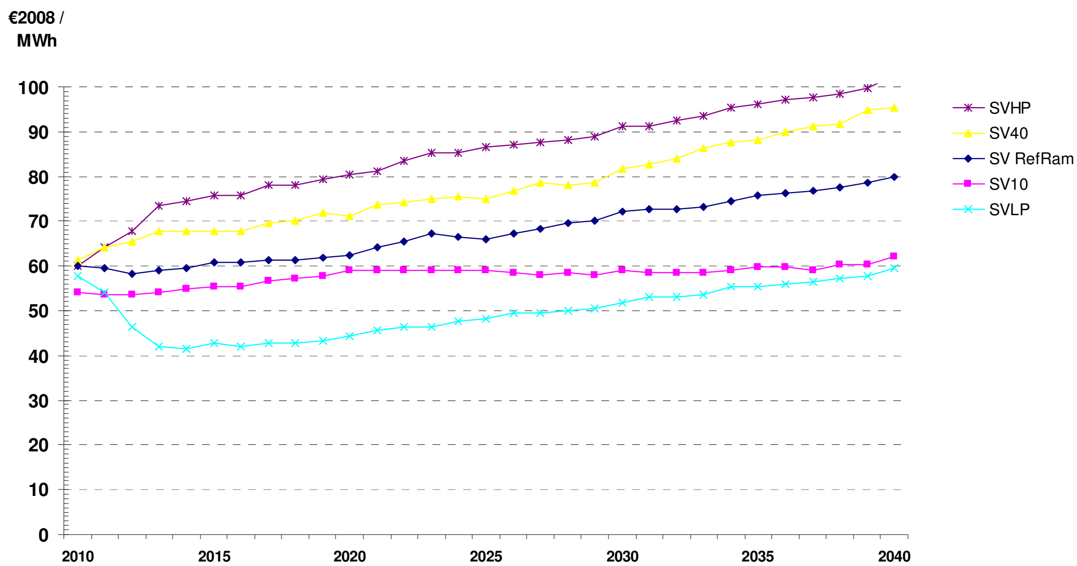


Figure 6.3 *Wholesale market electricity prices project in NRP-NL-SV (=SV RefRam in graph legenda) and four sensitivity analyses for lower/higher fuel prices and lower/higher CO_2 prices. (SVHP = higher fuel prices, +40% for gas, +20% for coal; SVLP = lower fuel prices, -40% for gas, -20% for coal; SV40 = Higher CO_2 price: in 2020 already 40* €/ton; SV10 = lower CO_2 prices, 10 €/ton CO_2 from 2013 onwards).

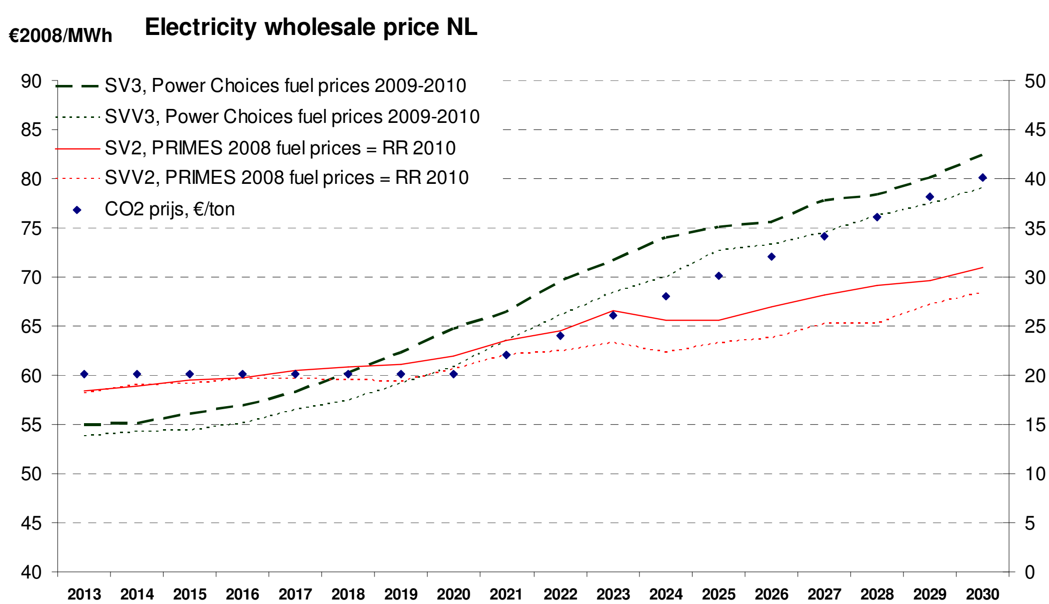


Figure 6.4 *Wholesale market electricity prices project in NRP-NL-SV (SV2 and SVV2) compared to higher fuel price path (SV3 and SVV3 with Eurelectric Power Choices fuel prices)*

6.1.5 CO_2 emissions, production and export

Focusing on the centralized power production, the CO_2 emissions range from 44 Mton in 2010 to 43 Mton in 2030 in the NRP-NL-VV case with high RES. The NRP-NL-V case, with less wind enery and no co-firing of biomass leads to 57 Mton in 2030.

The cases where additional CCS is deployed for new coal power plants lead to a decrease in CO_2 emissions.

The net effect on the CO_2 emissions in 2030 ranges from a 16 Mton reduction in the Slow Coal variant (43.2 – 27.3), up to 22 Mton reduction in the Fast Coal variant (43.2 – 21.4). The total domestic electricity production is almost equal in these cases in 2030. The production is between 87 and 88 TWh.

The effects on the net export in the period 2015 to 2030 also remain limited. This is caused mainly by the financial compensation such that the additional cost of CCS is compensated for. The variable cost of a coal plant with CCS is somewhat smaller than the same plant without CCS, see also Figure 6.9 where the variable cost of production of new and old capacity is compared, for the year 2020 fuel prices, and two values of CO_2 prices (20 and 50 €/ton CO_2).

Table 6.1 CO_2 emissions from central electricity production

	2010	2015	2020	2025	2030
CO2, Mton/year					
NRP-NL-V	44.0	61.3	61.7	62.2	57.2
NRP-NL-VV (high RES)	43.8	54.8	45.0	45.4	43.2
NRP-NL-VV with Slow coal CCS	43.8	54.8	42.1	36.4	27.3
NRP-NL-VV with Fast coal CCS	43.8	53.8	37.7	24.7	21.4
Central production, in TWh					
NRP-NL-V		90.3	95.4	102.4	96.1
NRP-NL-VV (high RES)		89.9	86.2	95.6	87.2
NRP-NL-VV with Slow coal CCS	68.8	89.9	88.9	92.5	86.8
NRP-NL-VV with Fast coal CCS	68.8	90.0	88.2	94.6	87.7
Net export, TWh (negative is net import, positive is net export)					
NRP-NL-VV (high RES)	-6.8	17.5	16.4	28.7	19.6
NRP-NL-VV with Slow coal CCS	-6.8	17.5	20.1	26.4	18.6
NRP-NL-VV with Fast coal CCS	-6.8	17.9	19.4	28.8	18.5

6.1.6 Operating hours of new and old fossil power plants

The operating hours of both old and new power plants have been calculated by ECN's electricity market model POWERS. The NRP-NL-SVV reference projection variant features high shares of renewable electricity production in the period 2020-2030. Despite of this large share of renewable capacity with low and limited marginal costs of production, the operating hours of new coal fired power plants remain at high levels. Existing and older coal power plants will be operating less as is shown from the dispatch results in POWERS. Consequently, these existing plants will be decommissioned beginning with the oldest ones first. This decommissioning takes place in the period 2015-2025. In 2030 only the two pulverised coal power plants Hemweg-8 (Vattenfall/Nuon) and Amer-9 (RWE/Essent) are considered to be still in production.

With respect to the business cases of the three new coal fired power plants assumed to be built, it can be concluded that their business cases are hardly affected negatively by the high share of renewable electricity production. Based on the CO_2 prices assumed up to 2030, these new coal fired power plants will produce between 7200-7500 hours on an annual basis in the period 2015-2030 compared to somewhat higher hours in the case with less renewable energy.
The average operating hours are displayed in Figure 6.6. In Figure 7.2 more details are given differentiating between older and new plants.

During off-peak hours, the very old coal fired plants (built before 1990) and (old) gas-fired will be lower in the dispatch order. Consequently, for these old coal power plants substantially less than 4000 operating hours result, which may also adversely impact start up and shutdown costs, and overall net efficiencies. This frequent start/stop behaviour will further worsen the variable cost of production as it reduces the net efficiency of operation (e.g. see (TU Delft, 2009))[6]. New gas fired plants will operate mainly during peak hours, when the market price is high enough to cover the marginal cost of production.

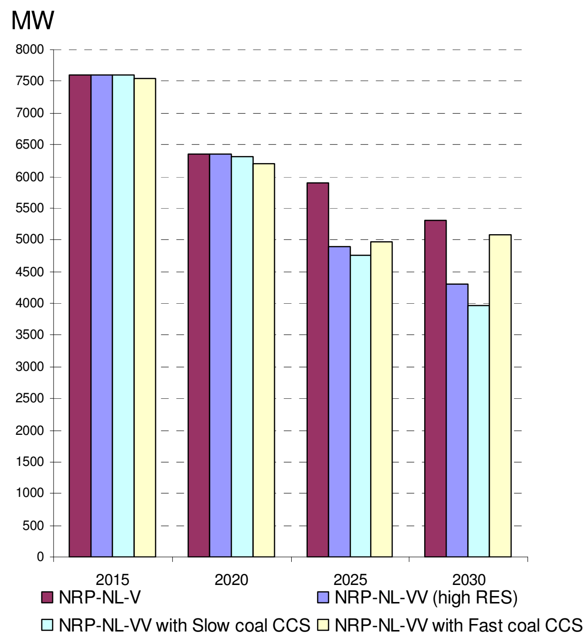
Adding additional CCS to the new coal power plants, the *Slow Coal* and *Fast Coal CCS* variants to NRP-NL-SVV have been defined. In the Fast Coal CCS variant, between 2025 and 2030 additional new coal with CCS is built, in addition to the three coal power plants now under construction. The amount of CCS deployed is given separately in the right side of the Figure 6.5. NRP-NL-VV, after 2020, more existing coal capacity is being decommissioned than in NRP-NL-V leading to less coal capacity in 2025 and 2030.

Assuming additional financial incentives for CCS deployment in the period 2015-2030, thus closing the financial gap for CCS as long as the CO_2 price is not high enough, two variants have been defined with increasing levels of CCS deployment. These financial incentives can be considered to work as a feed-in premium to any CCS MWh produced, similarly as the current SDE scheme for renewable electricity functions. That RES SDE scheme is assumed to be extended and present in the NRP-NL-VV variant up to 2030. It is also valid for biomass co-firing in coal plants.

The effect on the electricity production has been analysed using the POWERS model. The results are given in the Figure 6.6 where the average operating hours of the coal power plants are shown. Figure 6.7 provides more details by showing the differences between new and older coal power plants.

[6] This issue has not yet been included in the POWERS model. It is included in the REPOWERS model that is developed especially to study the extent of these effects. It first trial application was in the ITM project (ITM, 2010).

Installed capacity, in MW_e (net) **Input to model, existing is 4173 MW_e**	**CCS deployment for new coal capacity, in MW_e (net)**



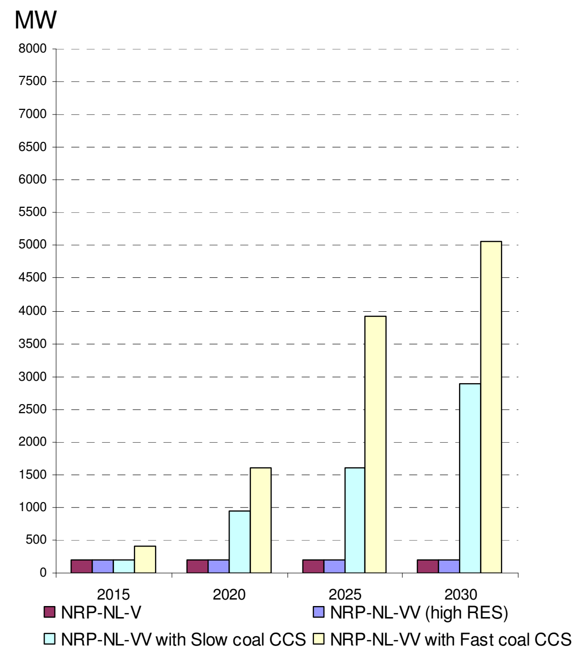


Figure 6.5 Installed capacity for coal power plants (total of new and old, CCS part

Operating hours (full load equivalent) (Model result)

In NRP-NL-V, some existing and old coal fired power plants produce substantially less in 2020 than the other existing and new coal power plants

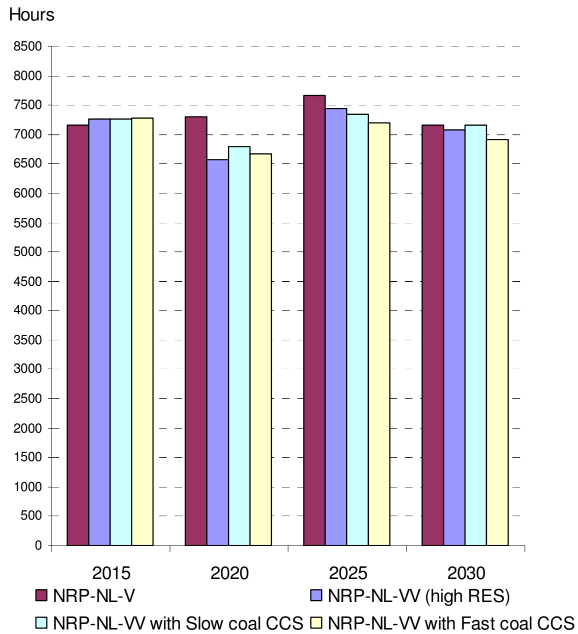


Figure 6.6 Operating hours in several cases for coal power plants (total of new and old, CCS part)

Table 6.2 Captured CO2 (new) coal power plants, and efficiencies of CCS MW capacity

	2015	2020	2025	2030	Remarks
Mton CO_2 captured					
NRP-NL-VV	1.4	1.4	1.4	1.4	One demo, plus 20% co-firing of biomass (additional credit)
Slow Coal	1.4	6.5	10.2	18.5	
Fast Coal	2.8	10.8	24.4	28.4	Two demos in 2015
Fast Coal Gas	2.8	10.8	24.1	29.6	
Average net efficiencies					
Coal with CCS					
NRP-NL-VV	35.0%	35.0%	35.0%	35.0%	Only 1 demo
Slow Coal	35.0%	36.6%	37.3%	38.1%	35% for first demos; increasing efficiencies for new CCS in period 2020-2030
Fast Coal	35.0%	36.9%	38.4%	38.7%	
Coal without CCS					
NRP-NL-VV	42.3%	43.9%	44.8%	45.1%	
Slow Coal	42.2%	43.2%	43.7%	40.3%	
Fast Coal	42.0%	42.6%	40.3%	No coal w/o CCS	

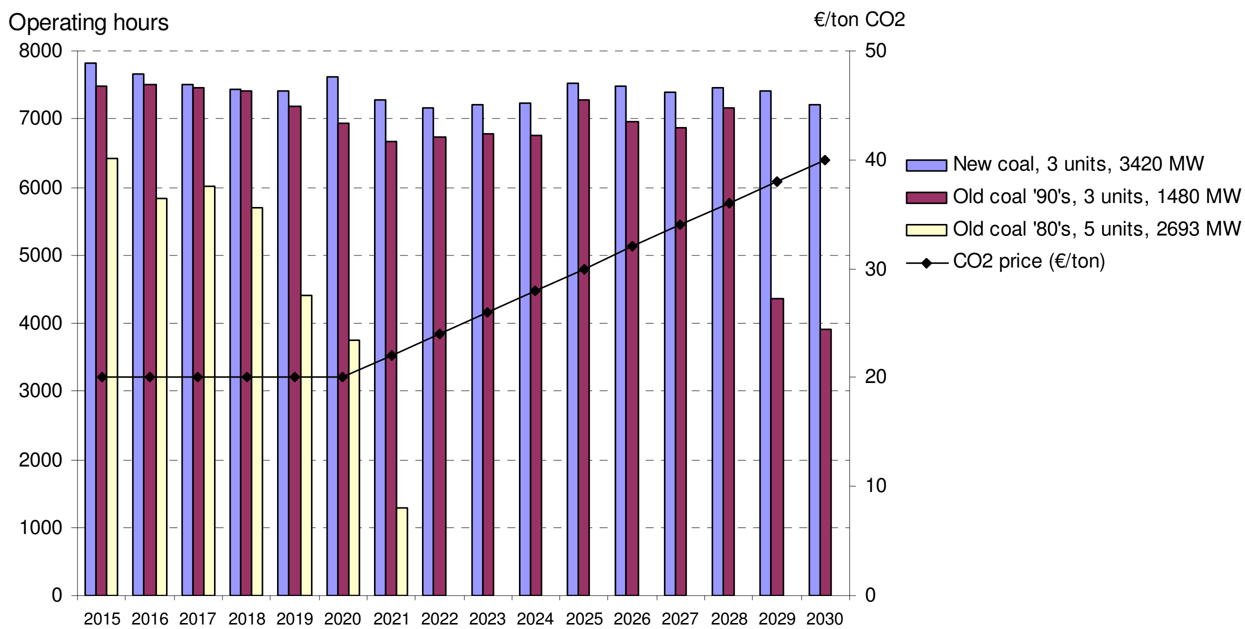


Figure 6.7 *Operating hours (full-load equivalent) coal-fired power, without large scale CCS 2015-2030, the Netherlands, NRP-NL-SVV scenario (only the ROAD CCS demo included).*

The main explaning factors in the operating hours of the various generation options is the merit order. The figure below shows a typical and illustrative marginal cost supply curve.

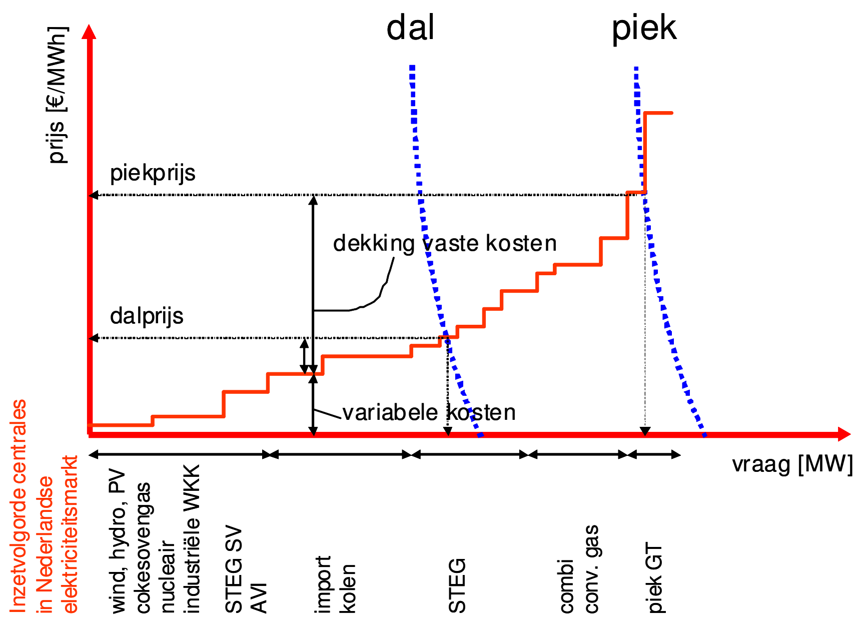


Figure 6.8 The marginal supply curve and market price setting mechanism

The variable cost of production of new and old generation capacity is given in Figure 6.9.

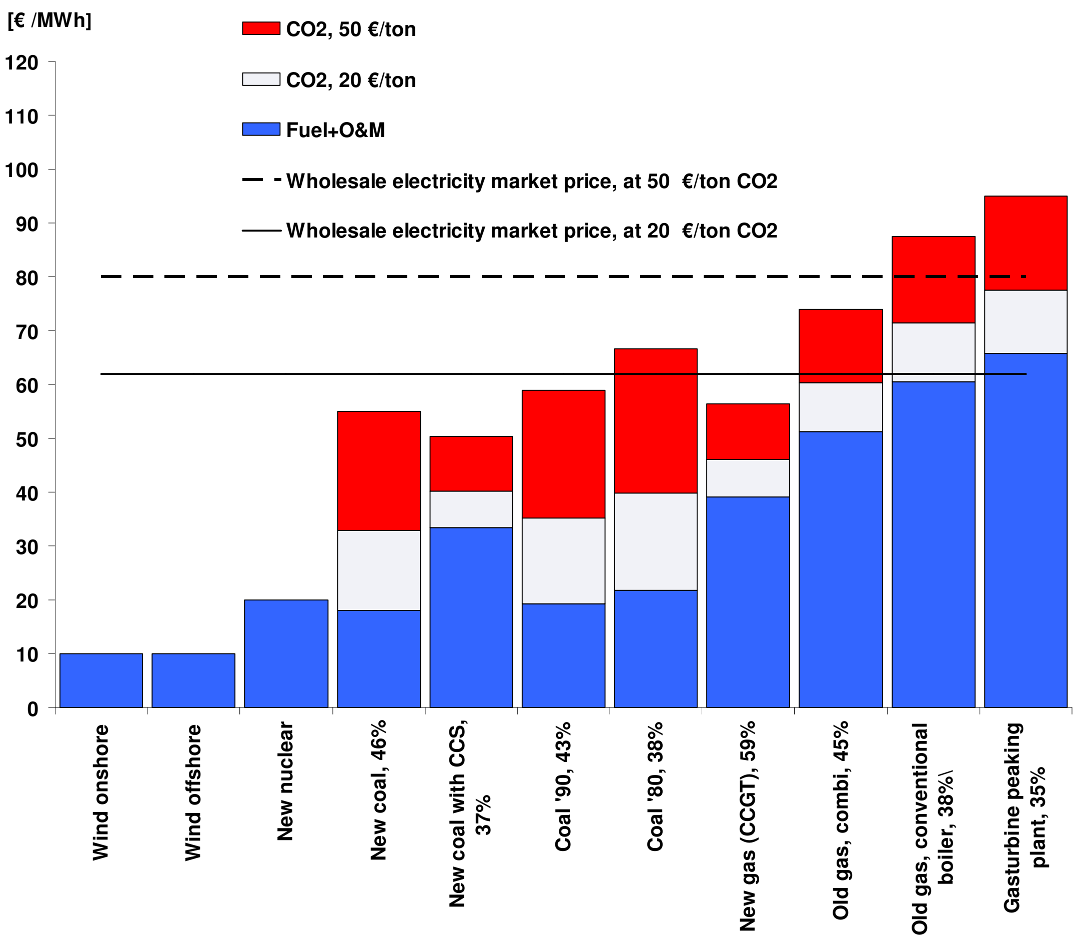


Figure 6.9 *Variable cost of production, for new and existing generating capacity in the Netherlands, year 2020, and NRP-NL-SVV scenario. For nuclear, the total O&M cost is given here. The variable cost (uranium and other O&M) is less, about 5 to 7 €/MWh (Seebregts et al, 2010). For wind is it less than 10 €/MWh and somewhat different for onshore and offshore wind energy.*

6.2 Sensitivity analyses

As part of the original NRP-NL projections, a variety of sensitivity analyses have been conducted. The interested reader can refer to that report (ECN/PBL, 2010) for more details. On the CO_2 price and the Slow and Fast Coal variants reported here, ECN has performed some sensitivity analyses as part of the study for ECF (Seebregts et al, 2010b).
Sensitivity analyses included:

Fuel prices	Higher fuel prices like in IEA World Energy Outlook 2009 (ECN, 2009) or 40% higher (ECN/PBL, 2010) or consistent with Eurelectric Power Choices (this report).
CO_2 prices	Higher CO_2 prices than in NL Reference Projections. Up to 40 €/ton CO_2 in

	2020 (in stead of 20). Up to 90 €/ton CO_2 to calculate indications for the financial gas of CCS, as part of the study for ECF.
Electricity demand	Both higher and lower electricity demands. A higher demand can be caused by higher GDP growth, more luxurious lifestyle, additional electrification of the transport sector (e.g. electric vehicles), or less energy saving. A lower demand can be caused by lower GDP growth, more energy saving (e.g. by more policy measures)
Nuclear	The nuclear power plant planned by Delta is assumed to be constructed. Part of a study assessing impact of the election programmes.

7 Flexibility and reliability

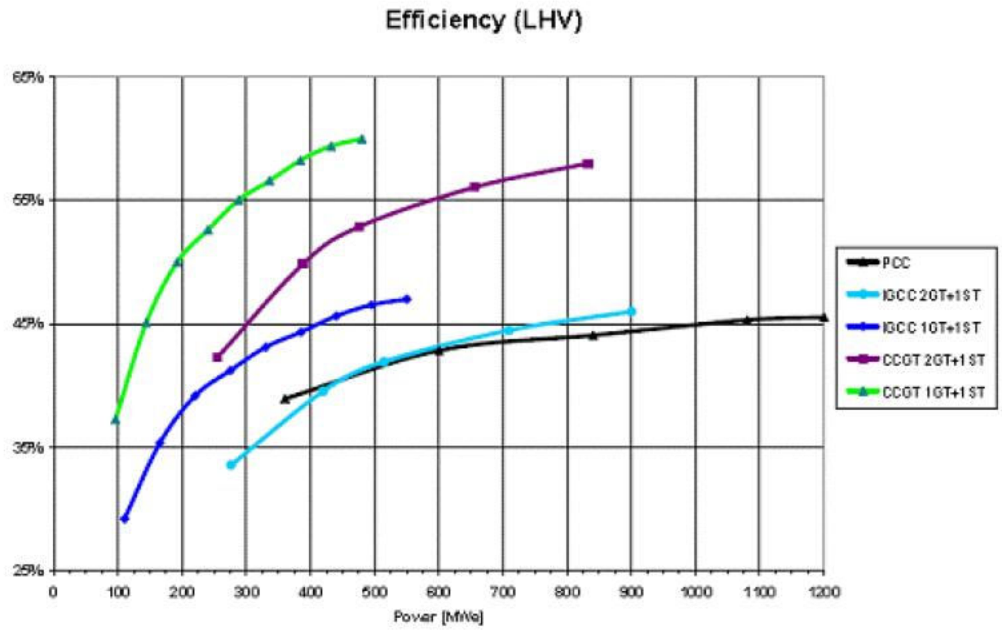
Reliability is traditionally an important aspect for electricity generating capacity and the electricity infrastructure (transmission and distribution networks). High shares of electricity produced by intermittent sources as wind energy will require sufficient flexibility of the electricity system, not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

7.1 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 also 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 TU Delft (TU Delft, 2009), 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 the perspective of net efficiency losses at partial loads, modern pulverised coal (PC) power plants in Europe appear to be as good as IGCC units, see Figure 7.1. The number of gas turbines in an IGCC is determining its efficiency loss at reduced loads.

The current coal fleet under construction in Northwest Europe consists mainly of these PC plants, with net efficiencies of about 46%. They are 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. A sufficient number of full load hours for each of these technologies have to deliver the needed electricity production levels and wholesale market electricity prices, to make the new coal power plant a profitable investment. The calculations by the POWERS model in the NRP-NL-VV context, show that such new coal power plants in the Netherlands will have such high operating hours (see also Section 7.3 and Figure 7.2). 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 operation in a more flexible manner. They can operate down to partial loads of 30 to 20%.



Figuur 9.2 : Rendement van nieuwe centrales

Figure 7.1 Reduction in net efficiency when operating at lower loads (without CCS)
Source: (TU Delft, 2009)

Table 7.1 Existing technology, all without CCS

Technology	Capacity	Start up time	Min Up	Speed in changing load	
	MW	*h*	*h*	*MW/min.*	*%/min.*
Pulverised Coal	500 - 700	6	24	15 - 20	1,5 - 3,0
Conventional gas boiler	630	5	6	10-20	1,5- 3,0
Conventional gas boiler with pre gas turbine ('Combi')	350	5.5	4	10-20	2,8 - 5,5
Nuclear power plant	450	NA	NA	14	
Gas turbine (peaking plant)	10-25	<<1	1	1-2	10-20
IGCC	250	24	24	8	3
CCGT	120 - 350	2	4	4-10	3-5
Industrial CHP unit (steam production)	100 - 450	2	4	3-14	2-4
District Heating (hot water production)	24 - 250	2	4	1-8	2-4
Gas Engine	<1	n.a.	n.a.		
Waste incinerator	24	n.a.	n.a.		
Wind turbine	< 5	<<1	0	100%	

Source: TU Delft, 2009.

Power plants with CCS can be operated down to almost the same minimum load as the equivalent plant without CO_2 capture. However, it is not clear from the TU Delft report how the speed in changing loads will be for new power plants either without or with CCS. For new power plants it can be expected that this speed will be better than for the existing plants, as the future market conditions require this enhanced flexibility. For plants with CCS it is not yet known.
The net capacity and maximal load is lowered by CO_2 capture. This may lead in changes in the merit order i.e. marginal supply curve. The wholesale market electricity price, set by the marginal unit of production can be higher. The TU Delft report does not specify if power plants with CO_2 capture have lesser speeds in changing loads. It can be argued that the reliability of a steady CO_2 supply to the offstream CO_2 transport and storage system will have implications for the flexibility with which a power plant with CO_2 capture is allowed to operate. A multi-output designed gasification power plant like Vattenfall/Nuon's Magnum, may have an advantage with respect to this flexibility. In case the power plant is able to produce or does not want to produce electricity (e.g. at low electricity market prices), it could still produce syngas that can be buffered rather than burnt in a gas turbine. This is a research item not further explored in this report and initial analyses.

Table 7.2 Technology, 2025, also plants with CCS

Technology	Fuel	Maximum load	Minimum load	
		[MW]	[MW]	[%]
Pulverised coal	coal/biomass	1200	360	30
Pulverised coal with CO_2 capture	coal/biomass	875	263	30
IGCC	coal	600	120	20
IGCC with CO_2 capture	coal	525	120	23
IGCC	coal/biomass	1200	368	31
CCGT	gas	1000	306	31
CCGT	gas	500	100	20
CCGT wit CO_2 capture	gas	425	85	20
Nuclear power plants:				
- AWBR	uranium	1465	279	19
- EPR	uranium	1600	305	19
- PBMR	uranium	300	60	20

Source: TU Delft, 2009.

7.2 Electricity system and CO_2 infrastructure perspectives

The electricity system is a vital energy infrastructure and therefore its reliability is important. Organizations like the national Transmission System Operators (TSO's) and their European wide organization ENTSO-E have the task and responsibility to take care that the electricity system functions reliably (e.g. in System Adequacy reports up to 2025). The effects of integration of large scale intermittently generated electricity are high on ENTSO-E's agenda (ENTSO-E, 2010). Network developments are driven by reasons of Security of Supply (SoS, including reliability), integration of renewable energy sources, and properly functioning of the Internal Energy Market (IEM). Furthermore, a future pan-European CO_2 infrastructure in the time period 2020-2050 is dealt with in the ongoing FP7 CO2Europipe research project (Neele at al, 2010; Mikunda et al, 2010). Such an infrastructure will also have to be flexible and reliable to accommodate CO_2 market needs.

7.3 Operating hours fossil power plants 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 (up to 12000 MW in the cases investigated) wind turbines will seldom or never be disconnected and thus will keep producing electricity and delivering it to the net. In addition, new coal-fired power plants will have high operating hours, e.g. as illustrated in Figure 7.2. The average has been reported earlier in Chapter 6. The production by older coal and gas fired power plants will decrease. Deployment of CCS on these new coal plants results in similarly high operating hours, or even higher, as the variable cost of production by coal plants with CCS gets lower than the original plant without CCS due to the CO_2 price. A similar conclusion on the negligible curtailment of wind energy was drawn in the study (KEMA, 2010), using a similar scenario but only for the 'target' year 2020, and 12000 MW of wind capacity in that year. 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 will anticipate wind supply better in the future
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.

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 anticipated that the combination of much base load capacity, must-run[7] 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 stating that

[7] The must-run capacity consists of waste incinerators (In Dutch: AVI's). part of the decentral CHP plants, about 20% of the total CHP including district heating and some of the industrial CHP plants. Due to its very low marginal cost of production, the only nuclear power plant Borssele is also considered as a must-run installation. Since its upgrade in 1997, the power plant shows very high production figures, equalling about 4 TWh (for a net capacity of 485 MW_e, since a turbine upgrade and extension with about 35 MW_e in 2007).

owners of new coal-fired plants are less willing to invest in large offshore wind parks. However, sufficient parties (and even more so in 2020 or 2030) 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 for the realisation of the Dutch offshore wind energy target.

8 Summary of findings from this screening research

This report is only a first step toward answers to the research questions indicated in Section 3.2. In the next CATOII-B phase further research is planned.

8.1 Main findings

This report highlighted the joint role of CCS and wind energy in reducing CO_2 emissions. In addition it has looked into the issues of flexibility and reliability of the energy system. 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. Therefore, also the electricity scenarios for these neighbouring countries have been taken into account in the analysis.

The findings below should be viewed within certain limitations of the models used. E.g. a detailed analysis of what start-up and ramping down of power plants would have to the overall yearly results, is not included. That will be part of the phase b CATO research. As part of the model calculations, only pulverised coal power plants with CCS were included. Analysis of IGCC plants in the model scenario context, will be a topic of the phase b research.
From the analyses and within the context of the scenario assumptions, it follows that:

1. Flexibility or reliability considerations seem to impose no technical constraints 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. This preliminary finding is based on recent work done by the TU Delft on the flexibility of new power plants, and by reasoning how the electricity market functions. The finding has to be confirmed by deeper and more detailed analysis. Such as:
   a. Effect of ramp up and down of power plants
   b. The design and requirements of a CO_2 market in terms of flexibility and reliability needed from the CO_2 transport and storage part of the chain.

Analyses with electricity market models including more time resolution than POWERS could help in confirmation of this initial finding. ECN has recently developed the REPOWERS model to study such effects. The model was used and tested in the ITM project (ITM, 2010).

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, the current economic outlook and expected (relatively low) CO_2 prices and other barriers will prevent CCS deployment in these installations in the next 10 to 20 years without any additional policy support. 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-NL-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 compared to the wholesale market price: variable cost exceeds the returns. Gas fired production would then be more attractive, but would result in a higher electricity price due to the higher natural gas prices. In that case, deployment of CCS can reduce the variable cost of production and improve the position of these coal power plants in the merit order, compared to gas fired power. However, the higher investments needs of CCS may constitute a barrier. Investments are exogenous hence an input to POWERS. Using the operational results of POWERS, one can conclude a posteriori if the investment is cost-effective, whether it is for a new coal-fired power plant without or with CCS. The operational hours and electricity production as calculated for each power plant by the model should be equal or more than the needed for the defined business case. In addition, the wholesale price should be high enough. The high investment would need a higher wholesale electricity price or a higher CO_2 price that can deliver such a higher electricity price. Additional and dedicated CCS policies are needed as long as CCS is not cost-effective on its own. A separate study by ECN covers such additional policies (Seebregts et al, 2010b).

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 cost assumptions and scenario calculations, CCS 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.

7. As for the other large-scale 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 Germany and the UK, the above findings are to a large extent valid for these other countries as well. However, this has to be confirmed by more detailed analyses using the recent outlooks for these countries, e.g. on the basis of the EU Energy Trends up to 2030 (EC, September 2010).

8.2 Focus of next phase research:

In the next CATO-2b phase of the research, the focus will be on the following elements for which the priorities will be set according the needs and expected impact of the changes.

1. Update the neighbouring countries using the most recent EU Energy Trends 2030 scenarios (published in September 2010, EC, 2010).
2. Implications of recent politically induced policy changes in the Netherlands and Germany.
3. Extension up to the time frame of the year 2040.
4. Based on other CATO-2b research results (from other WP's), the parameters with regard to operational flexibility of power plants with and without CCS could be improved. Furthermore, the flexibility and reliability of the electricity generation park will be modelled into more detail for different scenarios in the Netherlands taking into account recent and new developments in Western Europe.
5. Exploring the feasibility of CCS in gas-fired power plants and large decentralised CHP installations, notably in Dutch industry.
6. Comparison of technology cost data with sources of other CATO-2 partners (UU, KEMA) and information used by Eurelectric in their Power Choices scenario that runs up to the year 2050. That timeframe is also equal to the timeframe used in the scenario and variants analyses with the MARKAL-NL- model (Broek, 2010).

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Appendix A Technology Cost Comparison

A.1 Cost projections and uncertainties

This Appendix presents analysis results of year 2020 cost of electricity projections and associated cost uncertainty. It shows how cost uncertainty on major underlying cost factors propagate into projected cost ranges as quantified and summarised in this chapter. This appendix seeks to clarify the uncertainty that is surrounding the projected cost of nuclear power generation and the generating cost of competing electricity and impact of major underlying factors on cost uncertainty. All comparator generating plants will be assumed to enter into operation early year 2020.

The results show the cost of electricity from the perspective of investors. It concerns cost of electricity projections based on the default assumptions and based on relatively extreme Low Cost and High Cost projections defining our subjective confidence intervals for the cost of electricity for the distinct technologies considered in this study.

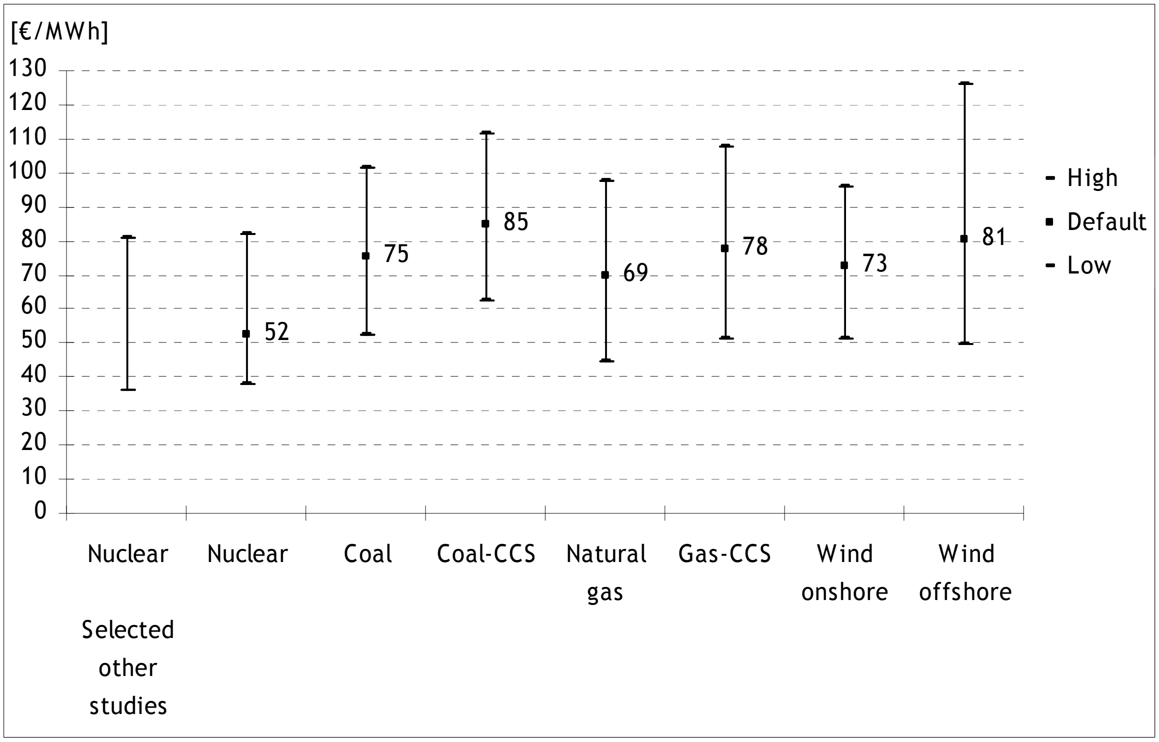
A.2 Projected financial cost of electricity in year 2020

The COE for the electricity generation options has been quantified using financial cash flow analysis. In this approach the annual cost cash flows and annual electricity production over the entire operating plant life to the day before the plant is assumed to enter on-line, i.e. 31 December 2019. The analysis uses the default values for the parameters and the extreme, using three sets of parameter values:

- Two more extreme estimates selecting – for each generation option - the parameter values leading to the lowest cost or the highest cost.
- A default point estimate.

It has been attempted to provide an indication of a subjective 95% confidence interval for the listed parameters based on expert judgment. The default value is the one considered to be a reasonable point estimate at current knowledge, but another value on the confidence interval may well occur instead.

Notes on specific technologies
Nuclear
The assumptions made are deemed to be representative for Generation III reactor designs for future new nuclear build in Europe with plant construction starting not later than in year 2015. The assumptions take as point of departure a n^{th}-of-a-kind EPR reactor but do not prejudge the choice of the reactor design. Typically, larger design PWR and BWR reactors tend to be characterised by higher per kW_e investment cost but lower per kWh fuel and O&M cost as compared to reactors of a design with lower generating capacity. For the reactor designs considered relevant, differences in this regard are accounted for in the assumed bandwidths.
The results are presented in the Figure below. For each generation option the figure presents the default point estimate, and the Low and High cost extremes.



Projected cost of electricity for selected technologies: generation plants entering into service at beginning of year 2020

From the figure it can be gleaned that, with the exception of the lowest values projected in some previous studies, the projected range of the COE for nuclear is about the same order of magnitude as derived from those previous studies as reviewed in (Scheeper et al., 2007). The default value for COE of nuclear is about 52 €/MWh, while the COE of the other options ranges from 69 (Gas) to 85 €/MWh (Coal CCS).

A serious caution is in order. While interpreting the results as displayed in the Figure above, one should be well aware of the impact of the underlying assumptions and the limitations of the analysis. The use of different assumptions could be equally valid and could lead to different but equally valid results. Assumptions on future developments of technology costs (investment and O&M costs) and fuel and CO_2 prices drive the results and are highly uncertain. We have assumed a € 20-50 /tCO_2 interval for the price of carbon with € 35 /tCO_2 as default value. For example, lowering the CO_2 price from 35 to 0 €/ton CO_2 would make the COE of Coal equal to 50 €/MWh. A similar remark holds for the values of the coal and gas prices. They range from 2 to 4 €/GJ (coal) and from 4 to 10 €/GJ (gas).

A.3 Cost sensitivity to major underlying factors

The sensitivity of uncertainty regarding COE for the distinct technologies considered are shown below by means of Tornado diagrams.

Box 1 Uncertainty analysis

The sensitivity of the underlying (but uncertain) parameters for the cost uncertainty has been quantified with the use of standard statistical uncertainty analysis techniques. These techniques are Monte Carlo uncertainty propagation by varying uncertain input parameters at the same time and posterior regression analysis of the simulation results. It uses the @Risk software, an add-on to Excel. Besides the assumptions on Low-Default-High values of the various parameters, the sensitivity analyses also require assumptions on the type of subjective probability distribution of any input that is varied. These additional assumptions have been pragmatic. Either uniform or discrete (subjective) probability distributions for parameters have been used. Uniform distributions are used for 'symmetric' values Low – Default – High; discrete probability distributions have been used in case of asymmetric values or integer values (e.g. plant life and construction period).

A.3.1 Nuclear

Figure 5.2. shows the sensitivity of the COE of nuclear to the underlying cost factors. The higher the sensitivity coefficient (shown in this figure) in absolute terms, the more important is the impact on COE uncertainty exercised by uncertainty about the value of the underlying factor concerned. A positive sensitivity coefficient shows an increasing COE with an increasing value of the underlying factor concerned. A negative coefficient shows a decreasing COE with an increasing value of the underlying factor.

Figure 8.1

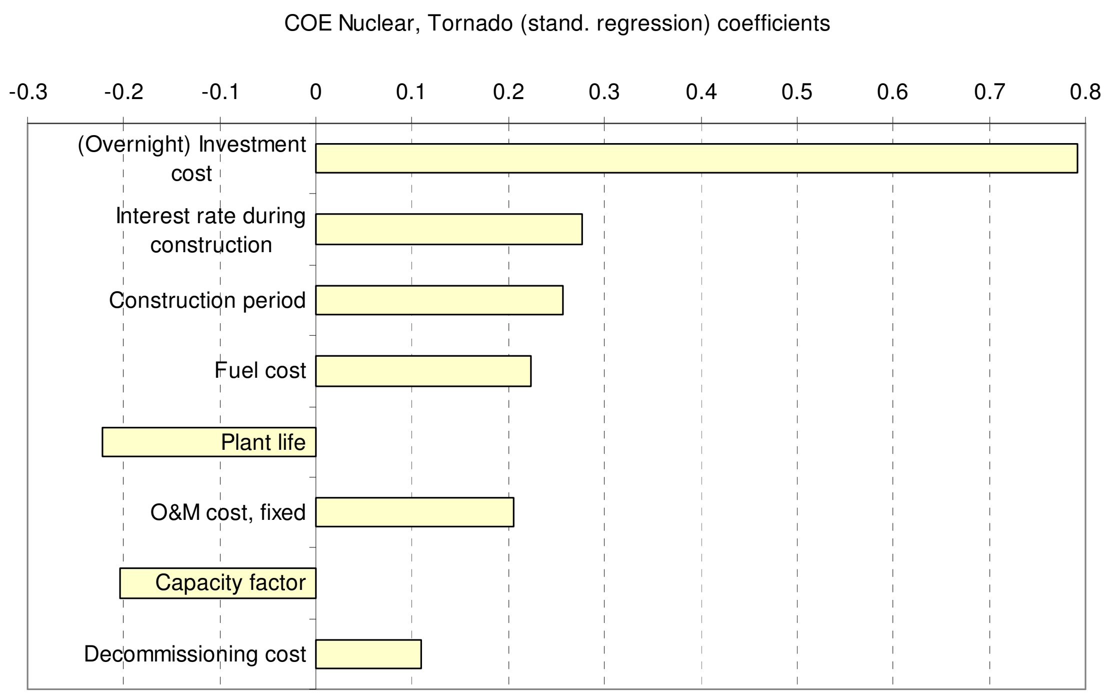


Figure 8.2 ***Sensitivity coefficients of the underlying cost factors for COE Nuclear***

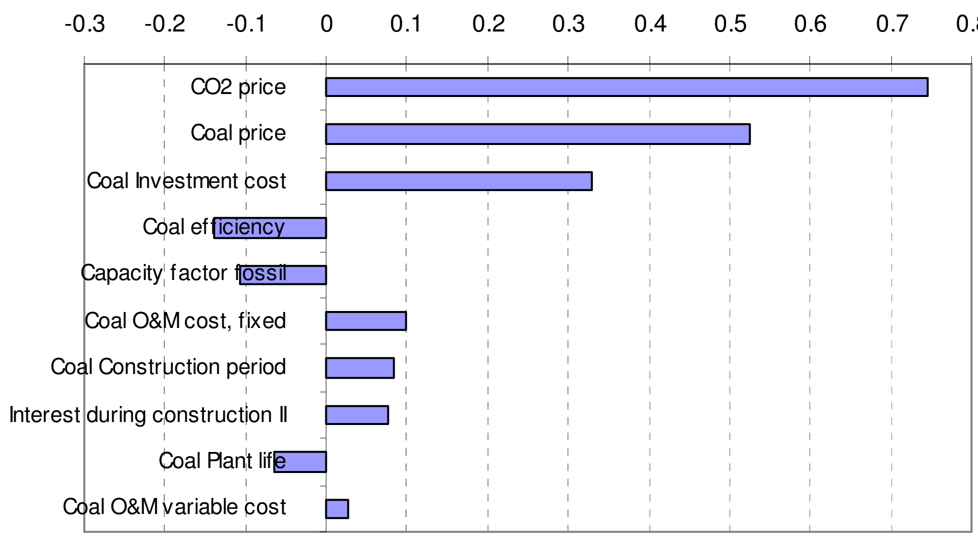
The graph shows the importance of the underlying input parameters for the COE of a NPP. It appears that:

1. The (overnight) investment cost is by far the most important parameter, followed by:
2. Interest rate during construction
3. Construction period
4. Cost of the nuclear fuel
5. Plant life
6. O&M costs
7. Capacity factor
8. Decommissioning costs.

Other financial parameters (real interest rate, debt fraction) are less important. It should be noted that the discount rate during the exploitation phase is a function of a set of underlying factors like real interest rate, debt fraction and technology risk adders. The discount rate thus established has a default value of 9.5%. Its lower and higher values are 9 and 11%, respectively. These underlying factors or its 'product' discount rate are of less importance than the other factors displayed in Figure 8.2.

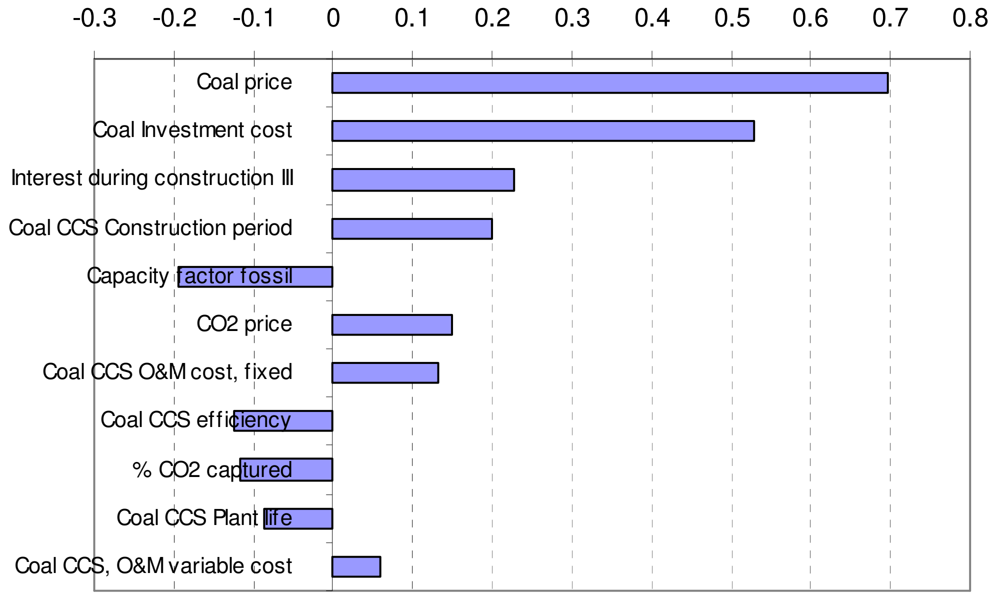
A similar uncertainty propagation analysis has been performed for the other fossil and renewable options. Again, the relative importance of the underlying uncertain factors is presented here in the form of Tornado diagrams. These diagrams show the standardised regression coefficients as an uncertainty importance measure.

A.3.2 Coal



The most important uncertain factors are the CO_2 price, the hard coal price, and the (overnight) investment cost.

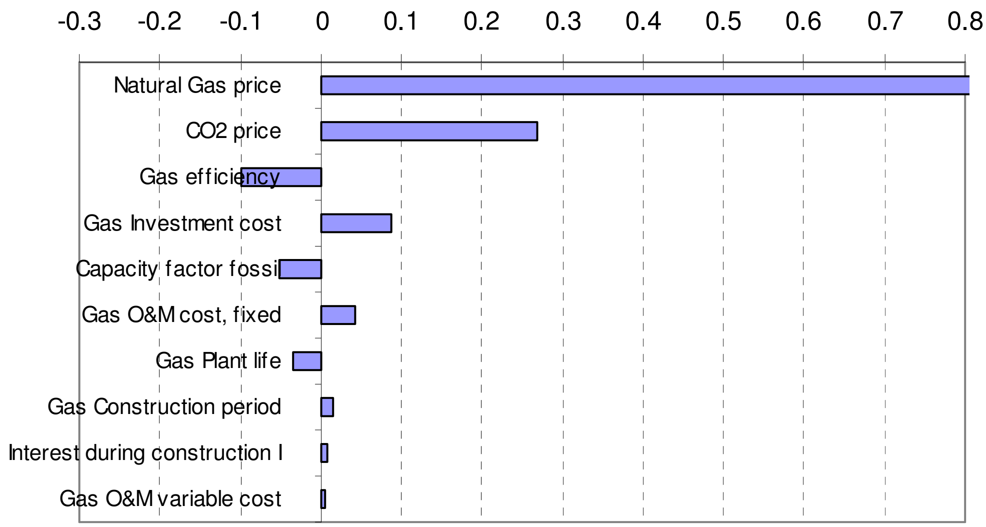
A.3.3 Coal-CCS



The most important uncertain factors are:

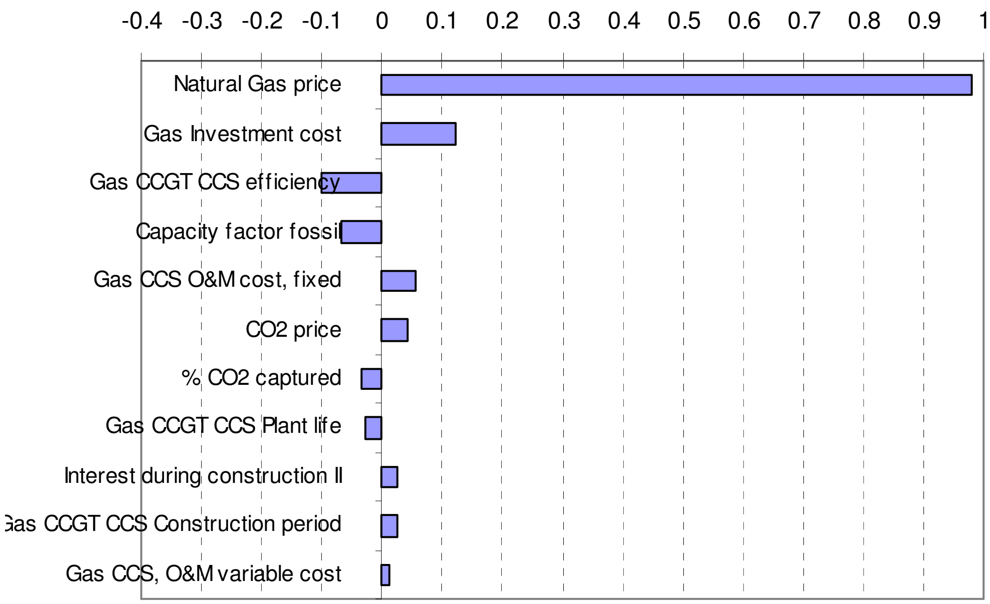
1. the hard coal price (more than coal without CCS because of the energy penalty caused by the net conversion efficiency drop),
2. the investment cost (more than 70% higher than coal without CCS),
3. the interest rate during construction (more important in combination with the high investment), and
4. the construction period.

A.3.4 Gas



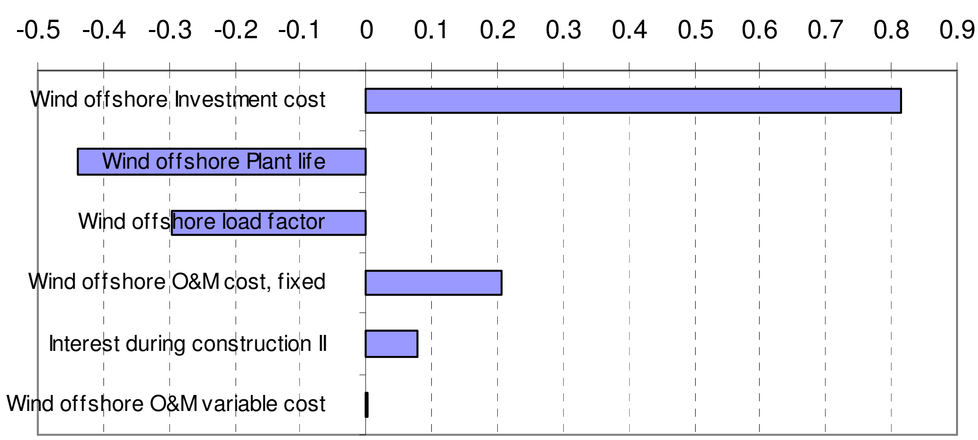
The two most important uncertain factors are the gas and CO_2 prices. The variable cost part of a combined cycle gas turbine plant makes up most of the COE by far.

A.3.5 Gas-CCS



The three most important underlying uncertainty factors are:
1. the gas price (more than gas without CCS because of the energy penalty caused by the net conversion efficiency drop),
2. the investment cost (50% higher than gas without CCS), and
3. the conversion efficiency.

A.3.6 Wind off shore



The most important underlying uncertainty factors are:

1. the investment cost,
2. the life of the wind turbine, and
3. the load factor.

In addition, O&M cost also represent a quite significant uncertainty factor for the COE of offshore wind power.

A.3.7 Impact of CO_2 price on COE of fossil fired options

The bandwidth of the COE of fossil fired options is largely determined by the range of CO_2 prices (20-50 €/ton), most importantly for the options without CCS. A 10 €/ton lower CO_2 price would result in a decrease in COE of about 7€/MWh for coal without CCS or about 3,5 €/MWh for gas without CCS respectively. The COE of CCS options are less sensitive to the price of carbon.

A.4 Bandwidths for projected external cost of electricity

An approximation of the social cost of electricity can be obtained by projecting the net present value of annual private cost and annual (positive or negative) externality values, discounted at an appropriate social discount rate. Such approximation would disregard in value terms those externalities for which not a proper externality value could be obtained. In the Table below we summarise for the generating options considered the financial COE values, and externality values. The reader is reminded that these values cannot be readily aggregated as this would warrant proper discounting. Yet the table provides some insight how quantified externalities would impact the *social* COE of the generation options considered.

Table 8.1 Projected financial cost of electricity in year 2020 and 'best estimates' of aggregate value of externalities, partly based on results of the CASES; euros of year 2007

		Financial COE 1) €/MWh			Best estimate of Aggregate value of externalities 2) €/MWh	
	Low	Default	High	Low	Average	High
Nuclear power plant	38	52	82	2.7	3.8	
Coal (pulverised)	52	75	102	22.2	25.0	51.6
Coal-CCS (pulverised) 1)	58	80	107		n/a	
Gas CCGT	45	69	97	10.4	14.7	21.3
Gas CCGT -CCS	49	75	106	4.6	9.4	16.6
Wind offshore	50	81	126	1.5	1.9	2.7
Wind onshore	51	73	96	1.2	1.7	2.5

Notes:
1) See … for further explanation.
2) See … for further explanation.
3) Aggregate externality value relates to coal-based Integrated Gas Combined Cycle with CCS.

The aggregate externality values shown suggest that the attractiveness of the nuclear power option compared to competing fossil fuel options would be enhanced by adjusting the financial cost of electricity projections for discrepancies between values from the (private) investors' perspective and the ones from the perspective of society as a whole. This conclusion has several major caveats though:

- No account has been made for any inter-subjective difference in valuation regarding the social acceptance of a certain health-related impact from one catastrophic event of a technology as against the same aggregate impact from a great number of visible accident events and/or less visible limbering intoxication by noxious emissions.
- Several major externalities have been disregarded, such as technology biases in public RD&D spending and other forms of indirect subsidisation and, importantly so, externalities related to the supply security of energy services.
- No allowance has been made for damages resulting from human-induced climate change to the extent that these amount to different values than the assumed carbon price.
- Establishment of proper social cost of electricity projections warrant discounting using proper social discount rate(s).