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The flexibility requirements for power plants with CCS in a future energy system with a large share of intermittent renewable energy sources

A.S.Brouwer[a,b]*, M. van den Broek[a], A.Seebregts[b], A.P.C.Faaij[a]

[a]*Utrecht University,Copernicus Institute of Sustainable Development, Heidelberglaan 2, 3584CS, Utrecht, The Netherlands.*
[b]*Energy Research Centre of the Netherlands (ECN), Unit Policy Studies, Radarweg 60, 1043NT, Amsterdam, The Netherlands.*

Abstract

This paper investigates flexibility issues of future low-carbon power systems. The short-term power system impacts of intermittent renewables are identified and roughly quantified based on a review of wind integration studies. Next, the flexibility parameters of three types of power plants with CO_2 capture are quantified, and used in a power system model of The Netherlands to determine the technical and economic feasibility. We find that coal-fired power plants with CO_2 capture achieve higher load factors and short-term profits than gas-fired plants in future power systems, and that those coal-fired plants are flexible enough to balance high levels of wind power.

Keywords: Carbon Capture and Storage; Power plant; Flexibility; Renewables; Power system modeling

1. Introduction

The power sector in the European Union is facing a structural change towards low-emission power generation in order to reach the emission reduction goal of the European Commission (EC), as the sector may have to reduce its emission by 96-99% by 2050. The EC foresees that the electricity mix will be dominated by three generator types: 1) renewable sources with a share of 59-83% of generated electricity, of which 42%-65% by Intermittent Renewable Energy Sources (IRES), 2) Carbon Capture and Storage (CCS) with a share of 7-32% if commercialized, and 3) nuclear energy with a share of 3-19% [1]. The IEA predicts similar trends for other OECD countries in its 450-scenario [2].

As a result of these structural changes, the flexibility of the electricity system may become an important issue. The intermittent nature of IRES requires the power system not only to adjust to changes

* Corresponding author. Tel.: +31-30-2537736; fax: +31-30-2537601.
E-mail address: a.s.brouwer@uu.nl

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in electricity demand, but also to changes in IRES power production. Moreover, IRES cannot be 100% accurately predicted, which necessitates more (flexible) reserves. Low carbon thermal power generation is relatively inflexible, however. Carbon capture installations will probably reduce the flexibility characteristics of coal and natural gas power plants, and nuclear power is relatively inflexible by itself [3].

In this study, we address the research questions: what kind of flexibility is needed for large shares of IRES, and how can this be delivered by power plants with CCS in an economic and technically feasible way in a future low-carbon electricity system? The focus will be on The Netherlands, which may deploy large scale wind power in the future.

2. Methodology

2.1 Power system impacts of intermittent renewable energy sources

The main questions are answered in three steps. In the first step, the daily impacts of IRES on the power system are determined and quantified to assess which impacts should be accounted for in a power system model. We consider wind power as a typical type of IRES as it has comparable integration characteristics as solar PV and wave power, and as it is the only type of IRES for which large scale integration studies have been performed [3]. The impacts of large scale wind generation on the power system are quantified based on a literature review of 17 wind integration studies. These studies have investigated wind penetration levels of up to 47% of annual power production, with typically levels between 20-30%. Whenever wind penetration levels are mentioned, they refer to the wind power production as a percentage of the annual power production.

2.2 Flexibility of power plants with carbon capture

Secondly, an overview is made of the flexibility parameters (i.e. part-load efficiency, minimum load level, ramp rate, and startup time) of three types of power plants with carbon capture: ultra-supercritical pulverized coal (USC-PC) power plants, combined with post-combustion capture, integrated gasification combined cycle (IGCC) power plants with pre-combustion capture, and natural gas combined cycle (NGCC) power plants with post-combustion capture. The parameters are based on data available in the public domain, as well as expert consultation. Three sets of flexibility parameters are drafted per power plant: a most-likely reference set, a high flexibility set and a low flexibility set.

2.3 Modelling the performance of power plants with CCS in a future power system

Thirdly, the performance of the three types of power plants in a future power system is analysed using the REPOWERS model for a number of scenarios. The REPOWERS model is a unit-commitment simulation model for the Dutch power sector based on Lagrangian Relaxation. The model optimizes the dispatch of generation units based on their production costs whilst imposing flexibility constraints. It simulates power production at a 1 hour time step and accounts for exchange with Germany, Belgium and the United Kingdom. The model was developed by Energy Research Centre of The Netherlands [4].

The effects of IRES penetration on the role of power plants with CCS in a future power system are determined in 12 scenarios (see table 1). First, two CCS scenarios are evaluated. Both consist of the projected Dutch 2030 energy mix to which 1600 MW of UCS-PC-CCS capacity as well as 1000MW of NGCC-CCS capacity is added for one, and 1600MW of IGCC-CCS capacity and 1000MW NGCC-CCS capacity for the other. For both CCS scenarios, three levels of flexibility are evaluated. For the energy mix with USC-PC-CCS, three wind penetration levels of 20%, 40% and 60% of total electricity generated are considered, in conjunction with carbon prices of €20, €50 and €80 per tonne CO_2 respectively.

Two weeks are simulated: one week with relatively high wind production (200% of average weekly production), and one with low wind production (60% of average weekly production). The technical and economic feasibility of power plants with CCS is assessed by determining the load factors during these weeks, as well as the margin between the generation costs (consisting of fuel, CO_2, and variable O&M costs) and the electricity price ("short-run profit").

Table 1. Overview of scenario runs

		Reference flexibility	High flexibility	Low flexibility
USC-PC & NGCC	20% wind (9GW[a]), €20 $tonne^{-1}$ CO_2	X	X	X
	40% wind (16 GW), €50 $tonne^{-1}$ $_{CO2}$	X	X	X
	60% wind (24 GW), €80 $tonne^{-1}$ CO_2	X	X	X
IGCC & NGCC	40% wind (16 GW), €50 $tonne^{-1}$ $_{CO2}$	X	X	X

a) The installed wind capacity is relatively high due to a high share of onshore wind capacity.

Input data for the REPOWERS model are based on a number of sources. The Dutch electricity generation mix of 2030 is based on projections by the POWERS model [5]. To the generation mix, extra power plants with CCS and extra wind power capacity are added. Fuel prices are taken from [2], Flexible O&M costs from [6], and costs for transport and storage of CO_2 from [7]. Electricity demand patterns and wind speed patterns are based on historic time series of 2009, where the demand is corrected for projected future growth. Power exchange with neighboring countries is modeled at an aggregated level, based on the projected business as usual generator capacity and electricity demand patterns from PRIMES [8]. In short, input parameters consist of a Dutch 2030 national demand of 126 TWh, 28.9 GW installed generation capacity, and 8.8GW interconnection capacity.

3. Impacts of large penetration of wind power

For large scale penetration of wind power we identified four key impacts on powers systems that will require more power system flexibility. First of all, the size of the primary and secondary reserves may need to increase, to balance the increase in variability and reduced predictability of power production by wind. Primary reserves are activated within seconds, and secondary reserves are activated within minutes. Secondly, thermal generation capacity may be displaced by wind generation, as the marginal generation cost of wind power is smaller than that that of thermal power generation capacity. As a result, the amount of CO_2 emissions of the power system as a whole will be reduced. Thirdly, the efficiency of thermal power generators may be affected, because the variability and reduced predictability of wind power production necessitates more variable generation by these generators resulting in more startups, ramping and part-load operation. Lastly, large penetration of wind could result in curtailment of part of the wind generation capacity as a result of overproduction or insufficient transmission capacity [9].

3.1 Quantification of system impacts

Based on the analysis of 17 wind integration studies, it was concluded that the impact that needs most regulation is the increase of reserve sizes. The required size of the primary reserves increases is reported to increase by 0.3-0.5% of the installed wind capacity at 10% penetration, to 0.8-1.0% of installed capacity at 40% penetration. The size of reserves that are required at a timescale from a minute to an hour, among which the secondary reserve, increases more rapidly, from 5-10% of installed capacity at 10% wind penetration to 10-15% of installed capacity at 40% penetration. The increase is caused by the increasing correlation in wind power production between two wind production sites at longer timescales. As a result, fluctuations in power production and forecast errors are not evened out by opposing, uncorrelated fluctuations, but added together. Regarding displaced capacity, it is reported that mostly natural gas fired capacity is displaced, and to a lesser extent coal fired capacity. The exact displacement, and associated to this, emission reductions, also depend on regional characteristics, such as the energy mix. The reduction in generator efficiency has not been quantified by many studies. At wind penetration levels between 10-30%, the actual emission reductions resulting from wind displacing thermal capacity, are 90-95% of the emissions that would have other ways been emitted by the displaced capacity. Lastly, the curtailed wind capacity depends on the presence of sufficient interconnection and transmission capacity. When both are available, curtailment is <0.5% of the potential wind power production, but when either or both are insufficient, curtailment of up to 10% of potential production has been reported.

3.2 Flexibility requirement of system impacts

Of the four impacts, one requires extra flexibility from the power system: the increased reserve size. More reserves will have to be available, while a smaller share of power will be produced by thermal power capacity. The ramp rates of power plants may thus have to increase, and the minimum load (so that plants do not have to shut down), and startup time (to provide slower reserves) may have to decrease.

In addition, the extent of two impacts is determined by the flexibility of the power system: displacement and reduced efficiency. Whilst the makeup of the displaced capacity is largely determined by the merit order, flexibility constraints could also lead to inflexible power plants being displaced, especially at higher levels of IRES penetration. The extent of the efficiency reduction is considerably affected by the part load efficiency, as well as the extra fuel use during startup and ramping.

The REPOWERS model accounts for all four impacts. For each time step, a predefined spinning reserve size is required to be available within 15 minutes, and it is assumed that wind power can deliver downwards reserves through curtailment. Thermal power capacity is displaced by wind power, which has an earlier position in the merit order. Reduction of efficiency is accounted for through part load efficiency curves.. Lastly, the model can curtail wind power when the total production is larger than the demand.

4. Flexibility performance of power plants with CCS

The flexibility of post-combustion power plants is based on modelling and publicly available engineering studies. The full-load efficiency penalty of the capture unit is taken to be 8%point for both USC-PC plants and NGCC plants, based on the penalty reported by ZEP when advanced amines are used [10]. The efficiency penalty is expected to be larger at part-load. In a best case scenario with multiple parallel capture units it could remain stable, as then the operating load of the capture plants can always be kept close to 100% load [11]. In practice, the part load efficiency penalty for a USC-PC plant is expected to be higher, which is mainly caused by throttling losses to keep the steam pressure to the stripper sufficiently high at low loads, and also less efficient operation of compressors. Overall, an USC-PC efficiency penalty increase at 50% load of about 1%point [12] and 2%point [13] are reported. For NGCC plants, the penalty increase is somewhat similar: a couple of percentage points [12] to zero [14].

The minimum load level of a power plant does not seem to be affected by the capture unit. The FEED study of the USC-PC Kingsnorth CCS project states that the minimum load level of the capture unit is 25% of nominal power plant load [15]. A study by Foster-Wheeler reported the minimum load level of a packed absorber column is 30% of the gas design flow rate. The minimum load of a compressor train is 70%, but by using a number of parallel trains that bottleneck can be avoided [12].

The ramp rate does also not seem to be affected by the capture unit. Dynamic modelling shows that absorber can handle large changes in flue gas flow [16], [17]. In the FEED study for the Kingsnorth plant project, preliminary ramp rates of 2-3% of nominal capacity /min were specified between 30-50% and 90-100% load, and a ramp rate of 4-6%/min from 50-90% load [15]. Foster Wheeler Italiana concluded in their study that the ramp rates of a USC-PC plant with CCS are not affected by the capture unit, and that no modifications are needed to improve it. Ramp rates of 5%/min between 50-90% load and 4%/min between 90-100% load can be achieved [12].

Start-up times do not seem to be affected by the capture unit, according to dynamic simulations [17], [18]. However, Foster Wheeler Italiana reports that the stripper will have to heat up to its operating temperature during start-up, which might limit the flexibility of the power plant. This could require 2-4 hours (hot and warm start, respectively), from the moment the steam supply is established. This may especially be a problem for NGCC power plants, because the gas and steam cycles can start quickly, and because the steam is not immediately available to heat up the stripper. The operating flexibility of an USC- PC plant is less affected, as the start-up time of such a plant is also a couple of hours.

Table 2. Flexibility parameters of USC-PC and NGCC power plants with post combustion capture

	USC-PC CCS			NGCC CCS		
	Flexible	Typical	Inflexible	Flexible	Typical	Inflexible
-penalty @ 100% load [%-points]	8	8	8	8	8	8
-penalty @ 50% load [%-points]	8	10	12	8	9	11
Minimum load [% of max load]	25[a]	25[a]	35	40[a]	40[a]	40[a]
Ramp rate [% of max load /minute]	5	4[a]	3	7[a]	7[a]	5
Start-up time [hours]	2[a]	2[a]	4	1[a]	2	4

a) Not affected as compared to power plant without capture unit

IGCC power plants are relatively inflexible as a result of the inertia of the gasifier and the air separation unit, and little has been published on the operational flexibility of this type of power plants with pre-combustion capture. In a study commissioned by IEAGHG, a number of novel operational strategies were explored, which involve storage of O_2, H_2 or syngas - thereby evading the lengthy start-up time of the plant [12]. In our analysis, the flexibility performance of the reference IGCC case with capture is assumed to be the same as that of a IGCC plant without capture, as the capture unit is not expected to affect the flexibility [12]. In addition, a more flexible IGCC unit is considered which could be realized by means of H_2 storage, and a less flexible unit, which could be the result of a retrofit.

Table A3: Flexibility parameters of an IGCC power plant with pre combustion capture

	Flexible	Typical	Inflexible	Sources
-penalty @ 100% load [%-points]	8	8	8	[10], [19]
-penalty @ 50% load [%-points]	8	8	8	[20]
Minimum load [% of max load]	30	50	50	[12], [21]
Ramp rate [% of max load /minute]	5	3	2	[12], [22], [23]
Start-up time [hours]	2	6	8	[12], [22]

5. Model outcomes

Preliminary model results of the load factors are shown in Figure 1. A number of trends can be distinguished. First of all, there is a large difference in load factors between the two weeks considered: during low wind conditions, the coal and natural gas fired power plants run ~95% and 70-80% of the time, respectively. During high wind conditions, load factors are progressively reduced at higher wind penetration levels. Natural gas fired capacity is most affected, and coal to a lesser extent, because the coal:natural gas price ratio is relatively low (1:3). In addition, the coal capacity is sufficiently flexible to deliver the required reserves at higher penetration levels of wind power, also when equipped with a capture unit.

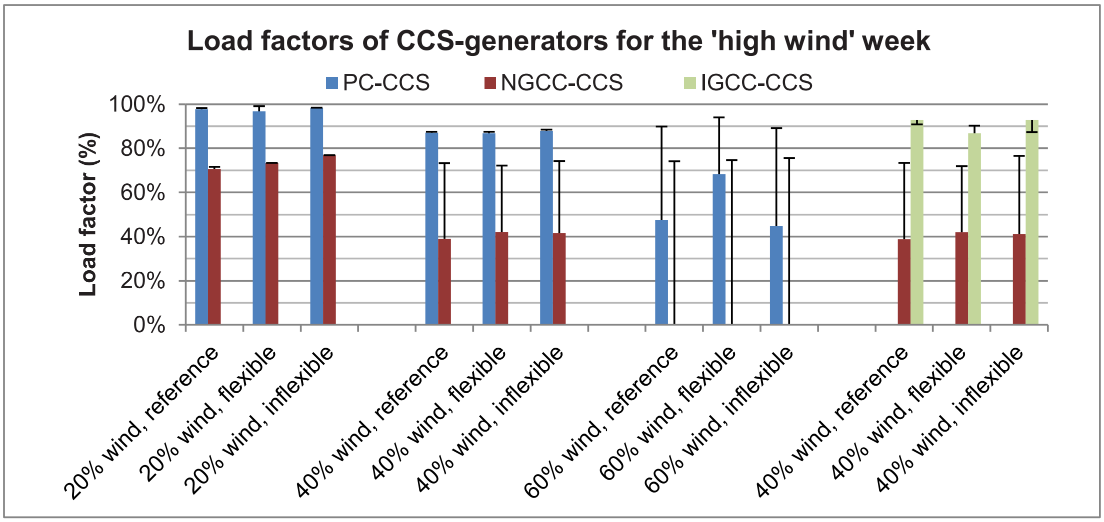

Figure 1: The load factors of power plants with CCS for different scenarios for the week with high wind production. The error bars show the load factors during the week with low wind production, indicating the annual range.

As share of wind power and carbon prices increase, the CO_2 emissions decrease. They are within the ranges of 1.17-0.85, 1.12-0.56, and 0.95-0.22 times the emissions of a typical week in the Netherlands in 1990, for the 20%, 40% and 60% wind penetration scenarios respectively. The larger reductions are achieved during high wind model runs. The flexibility characteristics of the power plants do not significantly affect the load factors up to a wind penetration of 40%: the difference is typically around 1-4%points. The difference in load factor between the PC-CCS and the less flexible IGCC-CCS scenarios at 40% wind penetration are also small.

The weekly short-run profits of power plants with CCS shows that the these are also not much affected by the flexibility characteristics [Figure 2]. Again, a number of trends can be discerned. For all scenarios, the coal fired power plants achieve short-run profits. These increase for higher wind penetration rates in the low wind week, as the electricity price is increased by the higher CO_2 price. The NGCC-CCS plant is less economic: in the high wind week they do not make any profit. In scenarios with 20% and 40% wind penetration, these units are (close to) the marginal generator, which leaves a very small short-run profit margin. During the low wind week, the NGCC-CCS units benefit from the high CO_2 price.

6. Discussion

A sensitivity analysis was performed to assess the robustness of the preliminary model outcomes. It showed that the results are sensitive to changes in the coal:natural gas price ratio, and to the available export capacity. At a price ratio of 1:2, natural gas capacity will displace PC(-CCS) capacity, reducing its load factor and short-run profit. A decreased capacity to export power to neighbouring countries during hours of high wind power production leads to substantial wind curtailment (4% and 22% of total wind power production for 40% and 60% wind penetration respectively), and a further reduction of ~35%point of the load factor of PC-CCS and IGCC-CCS capacity. Instead, power and flexibility will be provided by natural gas fired CHP units.

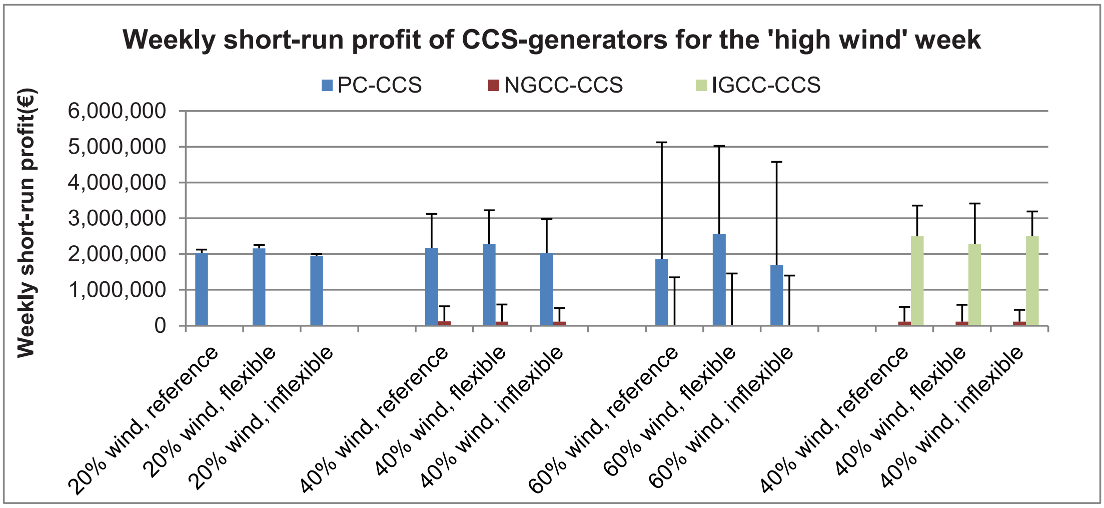

Figure 2: The weekly short-run profits of individual power plants with CCS (800MW coal fired plants and 500MW natural gas fired plants), for different scenarios for the week with high wind production. The error bars show the load factors during the week with low wind production, indicating the annual range.

Although the REPOWERS model already accounts for many power system dynamics, a number of enhancements could improve the results further. Stochastic modelling of IRES power production would allow the model to calculate the reliability and reserve deployment. In combination with a smaller time step, this would allow for in-depth analysis of reserve requirements. A more detailed simulation of neighbouring countries could improve the robustness of the results, as available interconnection capacity was shown to be an important factor when modelling future power systems.

A number of generating technologies were not included in this analysis. Oxyfuel capture was not included because its flexibility performance will probably not be substantially different from that of pre- and post-combustion capture, the results of which show large similarities. Electricity storage was not included because it falls outside the scope of the project, but it will be included in the future. Extra facilities to boost flexibility, such as CO_2 venting or amine storage were investigated with the flexible scenarios as a proxy. An in-depth analysis of these facilities, including their ability to shift production/load is forthcoming.

7. Conclusion

Our preliminary review of wind integration studies shows that wind power, and relatedly other types of IRES, may have four impacts on the daily operation of power systems: increased demand for reserves, displacement of thermal power generation, efficiency reduction of thermal power generation and wind curtailment. These impacts require varying levels of extra flexibility from thermal power plants. The increased demand for reserves may require most flexibility from thermal power generators: faster ramp rates as well as lower minimum load levels and start-up times will enable power plants to provide more reserves. The effects of displacement and efficiency reduction impacts are partly determined by the flexibility characteristics of power plants. Finally, wind curtailment has not been reported to be affected by the flexibility of power plants.

The load factor and short-term profit of power plants with carbon capture in a 2030 power system with varying levels of wind power generation were investigated with the REPOWERS model. Our preliminary results show that coal fired generation with carbon capture has both higher load factors and short-term profits than gas powered generation with carbon capture, considering the currently projected coal:natural gas price ratio of 1:3 and moderate CO2 emission reduction targets. Coal fired generation with carbon capture also maintains high load factors at 60% penetration of wind power, and is able to provide sufficient reserves**.** Improved flexibility of power plants with carbon capture only affects the load factor and short-term profit at higher IRES penetration levels. These findings are dependent on fuel prices, and the availability of interconnection capacity. Further research will be performed to investigate the economic attractiveness of power plants with carbon capture for different energy mix scenarios.

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