Available online at www.sciencedirect.com
SciVerse ScienceDirect
Energy Procedia 37 (2013) 7573 – 7581
Energy Procedia

GHGT-11

Prospects for CCS in the EU Energy Roadmap to 2050

Mikael Odenberger[a]*, Jan Kjärstad[a], Filip Johnsson[a]

[a]*Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

Abstract

The aim of this paper is to estimate the prospects of carbon capture and storage (CCS) in the European electricity supply system taking into account possible forthcoming policy based on the recent EU Energy Roadmap communication, which suggests a 93 to 99% reduction in CO_2 emissions relative 1990 levels from the electricity sector by the year 2050. Furthermore, the effect of whether or not onshore storage will be accepted is investigated. The work is based on techno-economic modeling of the European electricity generation sector under different assumptions (scenarios) of the future with respect to electricity demand and fuel prices. The results indicate that the contribution from CCS on a member state level depends on local conditions, e.g., access to local fuels like lignite, and whether or not onshore storage will be allowed. Excluding on-shore storage in aquifers, the modeling results give that CCS is centralized around the North Sea. Natural gas fired conventional power plants is likely to be a serious competitor to coal CCS in the short to medium term providing large emission reduction opportunities by fuel shifting from existing coal power plants to new high efficient gas fired combined cycles. Such development can be a barrier for early deployment of CCS, and hence, result in a delay in commercialization of CCS. The scenarios presented in the Energy Roadmap prescribe power systems almost without net CO_2 emissions by 2050, which implies that CCS technologies by the year 2050 must be of a zero-emission type. The modeling presented here indicates in general a large increase in technologies with low CO_2 emissions, renewables as well as a significant contribution from CCS technologies, where CCS in the investigated scenarios have the potential to contribute as much as 25-35% of total electricity generation at around year 2050.

Selection and/or peer-review under responsibility of GHGT

Keywords: Energy systems; EU; Policy; CCS

1. Introduction

The present work takes departure in recent market and policy development which have implications for CCS within the EU. The European Commission´s (EC) communication “Energy roadmap 2050” [1], which presumably will found the basis for targets and goals for the European energy system to 2050,

---

* Corresponding author. Tel.: +46 31-772 10 00; fax: +46 31 772 35 92.
E-mail address: Mikael.odenberger@chalmers.se

Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.701

depict different ways (scenarios) to fulfil the EU´s objective of reducing the greenhouse gas emissions from the energy system with least 80% by 2050, relative to the 1990 emission levels. Moreover, the Roadmap implies large CO_2 emission cuts within the electricity supply system, i.e., between 93 and 99% relative to the 1990 emissions. This obviously calls for new power plant technology which must have more or less zero CO_2 emissions. Since there will be a continued need for base load over the foreseeable future as well as there exist large resources of fossil fuels both within EU (e.g. lignite) and globally, the choice is to either apply CCS technologies or soon stop exploiting the fossil fuel resources if the above emission reduction targets should be met [2]. Yet, the CCS development has encountered some draw backs lately with for example a negative German legislative response to allow storage onshore as well as a delay in the EU supported CCS demonstration projects, partly due to local opposition to storage. Hence, it seems hardly reasonable to assume that CCS has reached commercial status by 2020, a year which previously has been commonly used as somewhat of a target year for introduction of CCS. In addition, the current market situation with relatively low prices on natural gas, points in the direction of increased interest for gas fuelled power generation technologies, which if used to replace coal power plants can significantly reduce CO_2 emissions and, thus, become a serious competitor to CCS in the mid-term perspective until the cap on CO_2 has been reduced substantially.

Currently, 50% of the electricity in Europe is generated by coal and natural gas with coal being responsible for approximately 70% of the CO_2 emissions from this sector, corresponding to 24% of the CO_2 emissions from all sectors [3]. In line with what is mentioned above and due to obvious restrictions in the turn-over in capital stock of power plants and associated infrastructure, it seems clear that fossil fuels will continue to account for a large share of global and EU energy supply over the coming decades, even with the ongoing and expected continued significant expansion in deployment of renewable electricity generation and efficiency measures, (e.g. World Energy outlook, [4]). There is at the same time an increasing dependency on natural gas in the European power generation sector. Thus, a continued and increased possibility to use coal as a fuel will enhance security of supply (SoS), but under strict CO_2 mitigation commitments this can obviously only take place if combined with CCS which in turn requires that CCS becomes commercially available. If so, CCS may, in addition to help reducing CO_2 emissions, enhance SoS in Europe through allowing continued use of domestic and imported coal and provide necessary lead-time to develop a cost-efficient sustainable energy system.

Although there are extensive research and development of all steps of the CCS chain capture, transport and storage, there are surprisingly few studies [5, 6] in open literature which give a detailed analysis on the ramp-up of CCS where the entire CCS chain is analyzed from a systems perspective, including analysis of a transport and storage infrastructure. Recently, studies have started to emerge (e.g. [7, 8]) but there is a need to continue to develop a methodology which combines energy systems modeling with a detailed description of the existing power plant stock (vintaging of current capacities) combined with an analysis of the development of a CCS infrastructure. In addition, the CCS infrastructure should be included in an appropriate level of detail in order to make it possible to be integrated in the energy systems modeling at a reasonable complex level. The work presented in this paper is one step in developing such methodology and, thus, the work combines techno economic modeling with an analysis of the transport and storage infrastructure required to meet the CO_2 flows obtained from the modeling. The current power plant stock is taken from the Chalmers power plant database [9] and used as input to the modeling. The CCS infrastructure analysis is described in more detail elsewhere [10]. The work further develops previous work by the authors reported elsewhere [11, 12], including presentation at previous GHGT conferences [6, 13, 14, 15]. The aim is not to predict any energy future but to assess the effect of a CO_2 emission cap on the stationary energy system by means of scenario analysis, with focus on the power generation system. Thus, the emission cap imposed in this work gives a cost of emitting CO_2

and can be seen as corresponding to an Emission Trading Scheme (ETS), but restricted to the European power generation sector.

2. Methodology

This scenario analysis is limited to the European electricity supply system from the year 2010 to 2050. The analysis is carried out by means of the techno-economic ELIN model which under different assumptions on the cost for electricity generation estimates the development of the electricity generation system in EU-27 (plus Norway and Switzerland). The ELIN model minimizes the total discounted system cost over the entire time horizon investigated, here from 2010 to 2050 (cf. [12]). The model includes a detailed description of the present stationary European electricity generation system (power plants) and potential CO_2 storage sites as obtained from the Chalmers Energy Infrastructure Databases [9]. Given assumptions on remaining life times for each power plant, projections for development of the specific electricity demand of the member states (MS) with a common European cap on CO_2 (which gives a price on CO_2 emissions), the ELIN model generates a mix of existing technologies and new investments to meet the demand (electricity as well as CHP heat).

The model includes 16 intra-annual time steps (four seasons, weekday/weekend and day/ night) to reflect variations in load, and thus, accounts to some extent for the need of power with different characteristics (peak/base-load). In the modeling, the existing capacity may be used until the end of the assumed life time or be prematurely phased-out due to unprofitability due to CO_2 penalty or the relatively lower efficiency compared to that of new plants. In other words, particular focus is put on analyzing turn-over in capital stock of the existing power plant infrastructure, timing of investments and infrastructural implications of technology mixes on a regional level. In addition, the modeling includes existing limitations in cross-border transmission capacity (limited by current net transfer capacities (NTC)) and the possibility to make investments in new cables between countries when cost efficient in the cost minimization.

Two scenarios are investigated: The first scenario, the “Market” scenario, is market oriented in the sense that policy mechanisms are limited to a CO_2 price and demand side development is similar to current trends, with an assumed public acceptance for nuclear as well as for CCS. The Market scenario is inspired by the “Reference High GDP” and the “Diversified Supply Technologies” scenarios from the Energy Roadmap communication by the European Commission [1], combining relatively high economic growth with a policy almost entirely focusing on carbon markets. The second scenario, the “Policy” scenario, includes several policies and targets including specific targets for renewable electricity generation (RES-E), demand side efficiency measures as well as a cap on CO_2. The Policy scenario is in turn coarsely based on the “High Energy Efficiency” scenario of the EC Energy Roadmap communication. However, we here assume an even more aggressive end-use efficiency strategy implying slowly declining overall electricity demand post 2030. In addition, both scenarios (Market and Policy) are calculated for two cases, i.e., with and without the possibility to use onshore aquifers as storage for captured CO_2. The exclusion of onshore storage obviously reduces the national storage availability for several MS, and thus, can have large implications from the MS specific conditions for CCS (see a parallel paper on the CCS transportation infrastructure [10]). Compared to earlier work by the authors [11, 12, 13, 14, 15], the present work includes MS specific cost-supply of transportation and storage for captured CO_2, updated technology descriptions as well as potentials for RES-E and updated scenario descriptions as described above (based on the EU Energy roadmap 2050). In addition, it is worth mentioning that technology costs has been updated by costs applied in the “World Energy Outlook, 2010” [16] and fossil fuel prices is given by cost-supply curves adapted from “World Energy Outlook, 2011” [4]. Moreover, wind power and solar PV have been implemented taking into account wind and solar irradiation conditions down to the spatial scope of NUTS-2 level (The NUTS classification (Nomenclature of territorial units for statistics) [17]). For more details on the modeling procedure see previous work by the authors (e.g. [12]).

3. Results

Figure 1 presents the modeled development of the European electricity supply for the Policy (Figure 1a) and Market (Figure 1b) scenarios for the case when on-shore aquiferCO2 storage is allowed.

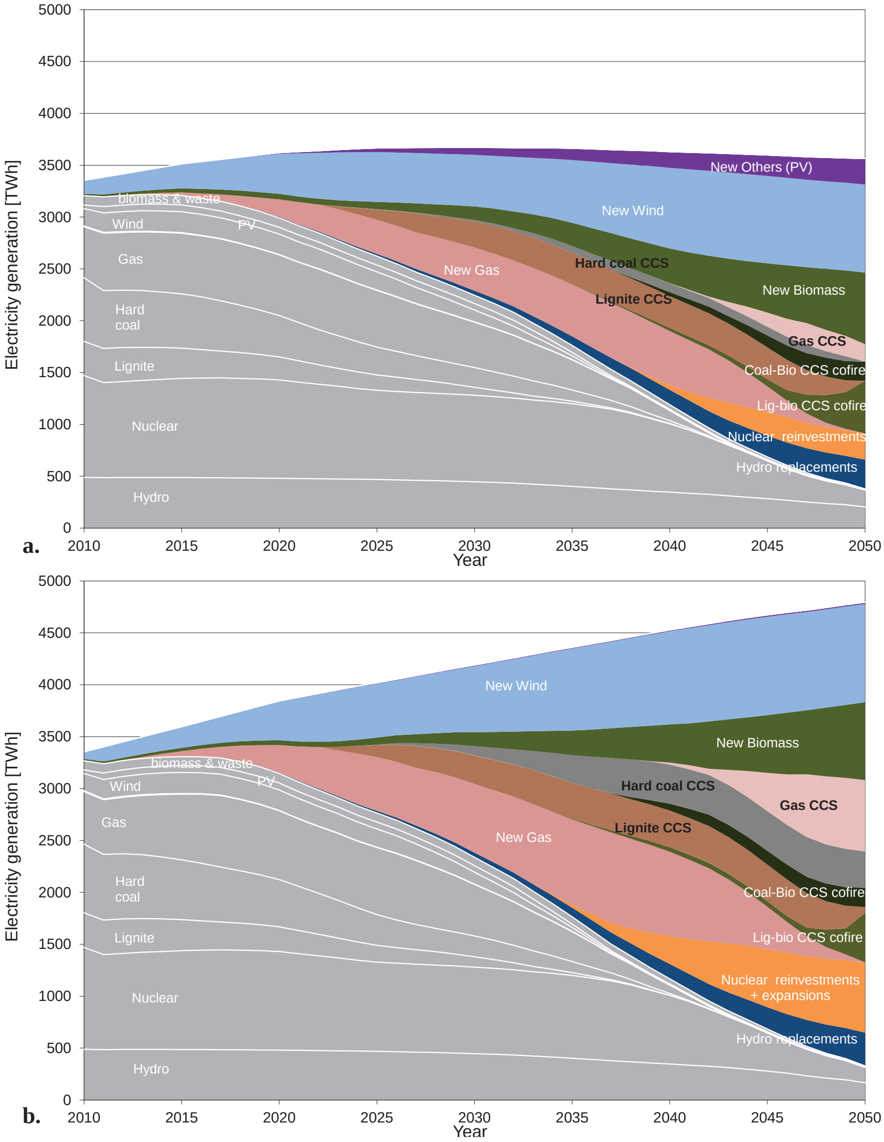

Fig. 1. Electricity generation in EU-27, Norway and Switzerland including storage in onshore aquifers, grey area in the figure indicate generation in the existing power generation system (a) in the Policy Scenario (b) in the Market Scenario

Figure 2 gives the amount of CO_2 captured per MS (Policy scenario Figure 2a and Market scenario Figure 2b) as derived from the scenarios as well as cumulative captured CO_2 intended for storage. The results indicate that CCS technologies can play an important role to reach an electricity supply system almost free of net carbon emissions by 2050 similar to what is required by the EU Energy roadmap 2050. The role of CCS becomes particularly important if society fails in curbing growth in electricity demand (Figure 1b). In the Policy scenario (Figure 1a) the contribution to electricity generation from CCS reaches about 25% around the year 2050, corresponding to roughly 900TWh. For the Market scenario the corresponding figure is around 35%, which corresponds to about 1800TWh. The total European cumulative capture from 2025 to 2050 is 9.5Gt CO_2 in the Policy scenario and 15.4Gt in the Market scenario. However, the prospects of CCS on an EU MS level (Figure 2) vary and depend on differences in local conditions in terms of current energy supply, fuel supply chains and distance to suitable storage locations. From Figure 2 it can be seen that if onshore storage is limited by excluding onshore aquifers as possible storage space (storage in onshore depleted oil and gas field is here assumed to be feasible but this implies that the main storage potential is off-shore). Not allowing on-shore aquifer storage means that the application of capture receives a more profound role close to the North Sea. In addition, since CCS fuelled by lignite yields lower specific CO_2 abatement cost than CCS applied to hard coal and natural gas, the result indicate early implementation of lignite CCS in MSs currently having lignite as a fuel (Figure 1). Yet, when storage onshore is limited, there is less lignite CCS in the south and eastern of Europe (Figures 1 and 2), due to the increased CO_2 transportation distance and cost. However, in such a case CCS in the UK fuelled by hard coal increase its competitiveness, due to closeness to vast offshore storage, compared to the lignite CCS in south/east of Europe with long costly transportation routes. Obviously, restricting on-shore storage requires higher CO_2 prices for CCS to become competitive resulting in a delay in implementation of CCS. This is mostly due to that when not allowing on-shore storage modeling yields that there is less use of lignite as a fuel in east of Europe. Yet, excluding on-shore storage gives little effect on the overall role of CCS in the European electricity generation towards 2050 with only a somewhat lower cumulative capture over the period, i.e., down 1-1.5Gt CO_2 compared to when onshore aquifer storage is allowed (*cf.* Figure 2). Towards the end of the period studied, i.e., near 2050, both scenarios include strict emission caps; 93% in the Market scenario and 99% in the Policy scenario. Thus, all results indicate that for CCS being an option it needs to be of a more or less zero emission type. Figure 1 indicates that by 2050 almost all fossil fired power generation is in the form of CCS with co-combustion of biomass (it is assumed that burning biomass yields no net CO_2 emissions and, thus, that biomass co-firing in a CCS plant can off-set the CO_2 emissions caused by the fact that capture is assumed to be ~90%). Other ways to meet the strict emission cap would be advances in capture technology approaching 100% capture.

Figure 3a-b also indicates that in the mid-term perspective natural gas power generation as well as wind power increase in the total generation mix, this on behalf of existing lignite and hard coal fired power plants. Obviously, natural gas fired power plants without capture cannot be part of a system approaching zero emissions but the relative CO_2 abatement, when shifting fuel from coal to gas, makes natural gas a significant contribution to generation until 2045 when emission reduction exceed 80% (Figure 4b). Figure 3 presents the fuel use (Figure 3a) for natural gas, hard coal and lignite and the fuel price development (Figure 3b) as derived from the modeling (which as input uses cost supply-curves of these fuels). The gas to coal price ratio on an energy equivalent basis is assumed to remain between two to three throughout the period, which is similar to current and historic trends for the last decade [18], and also the expected development if current trends in fuel markets is sustained, i.e., an expected long term abundance of natural gas [19]. Furthermore, the CCS technologies included in the model require a gas to coal price ratio at around 2.5 or less for gas CCS to be competitive compared to hard coal CCS, which

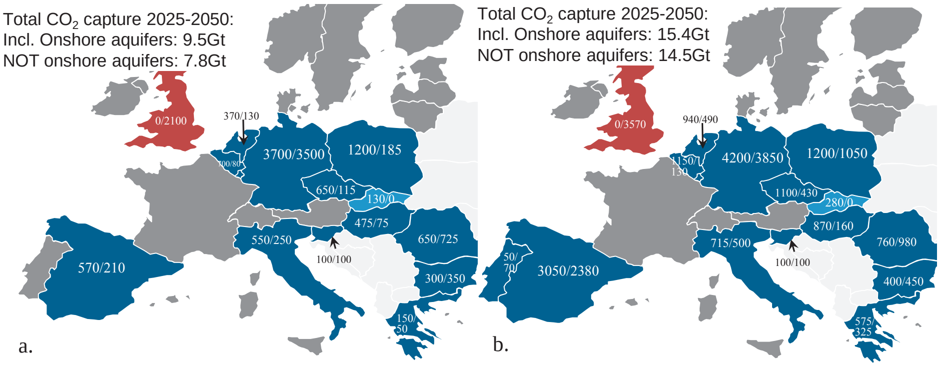

Fig. 2. Captured CO_2 between 2025 to 2050. Numbers gives captured CO_2 in Mt for each MS (first number from calculations including onshore aquifers/second number excluding onshore aquifers). Light blue MS (Slovakia) indicate only application of CCS if onshore aquifers are allowed for as storage, dark blue MSs indicate CCS application whether or not onshore aquifer storage is allowed and red MS (UK) applies CCS only if onshore storage in aquifers is prohibited. (a) Policy scenario (b) Market scenario

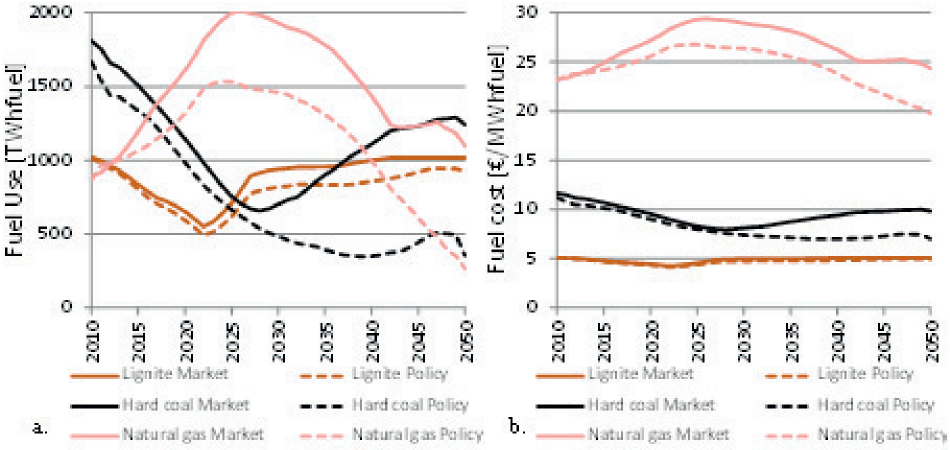

Fig. 3. (a) Fuel use of selected fuels for Market and Policy scenario including onshore aquifer storage (b) Corresponding fuel costs in Market and Policy scenario as calculated from the exogenous cost supply curves given in input data

becomes the case by 2045 (*cf* Figures 1 and Figure 3b). To what extent this will be the case obviously depends on the assumed technology costs.

Figure 4 show the calculated marginal costs for electricity generation and the marginal CO_2 abatement cost (Figure 4a) and the CO_2 emission cap applied (Policy scenario) as well as the amount of CO_2 captured annually (Figure 4b). The overall results in the Policy scenario indicate that CO_2 emissions from electricity generation can be reduced by about 60% (relative 1990) by 2030 by fuel-shifting coal to gas and increased deployment of wind power at a cost of around 50€/ton CO_2, which is in the range (40-50€/ton CO_2) of what is estimated to be required for CCS to be commercially competitive. The Market scenario prescribes 50% emission reduction by 2030 (relative 1990), and, thus, indicates a somewhat lower marginal abatement cost of about 45€/ton CO_2 even though the overall electricity demand is higher compared to the Policy scenario. For the last decade investigated, only renewables and CCS fueled by gas or with co-combustion of biomass is invested in (*cf.* Figure 1a). The marginal cost of abatement exceeds 100€/t CO_2 by 2040 (Figure 4a). However, it should be kept in mind that total emission from electricity generation is by then greatly reduced, by about 80% relative 1990 emissions (Figure 4b), meaning that not much electricity generation would be subjected to an actual CO_2 penalty. The Market scenario indicates similar values (100€/t CO_2) on marginal CO_2 abatement cost even though the cap is somewhat less restrictive (93% *vs* 99% in the Policy scenario). This is due to the higher electricity demand in the Market scenario and that there is no additional policy in force (the Policy scenario includes prescribed RES-E levels simulating certificate scheme) which means that the price on CO_2 emissions bear the full cost of all abatement.

Finally, it can be seen from Figures 1a-b that the levels of RES-E generation as obtained from the modeling is similar in the Policy and the Market scenarios even though there is no RES-E policy in force after 2020 in the Market scenario. This means that all RES-E in the Market scenario after 2020 is implemented due to the cost for emitting CO_2. The development in the Policy scenario makes it easier, compared to the Market scenario, to comply with the prescribed emission reduction of 93 to 99% until 2050 from a resource availability perspective due to lower growth in electricity demand. Yet, having several policy measures in parallel is less transparent than a price on CO_2 and it may also be problematic to rely on the success of future energy efficiency measures. In addition, an unbalanced portfolio of policy instruments may lead to redundancy in implemented policies, and thus, a less effective system. Both scenarios give a mix of technology options which should be beneficial from a security of supply perspective. In the Policy scenario this is achieved by combination of policy instruments (ETS and specified targets on RES-E and energy efficiency measures which may be seen as Green and “white” certificates). Yet, the combined policy measures will interfere and result in a low price of green certificates within the simulated scheme compared to the Market scenario for which the CO_2 cap is the only target and which also results in a rather mixed portfolio of fuels. Obviously, the modeling of the two scenarios studied should be seen as examples of a strict climate policy with the aim to illustrate the effect of a market driven (trading) emission reduction compared to a reduction driven by more technology specific targets in addition to emission trading. Both cases seem possible but impose different challenges (success of energy efficiency measures compared to very large yearly investments in CCS).

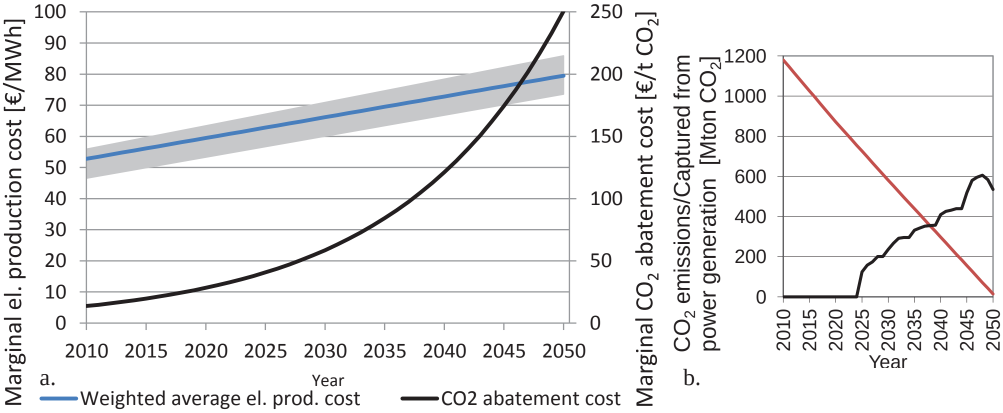

Fig. 4. (a) Marginal electricity production costs and marginal CO_2 abatement costs from the Policy scenario including onshore storage in aquifers. The grey area surrounding the average electricity production costs (blue line) gives the range in which the MSs are within. (b) CO_2 emissions equal to the cap given in the policy scenario (red line) and the captured CO_2 sent for storage (black curve).

4. Conclusions

An assessment of CCS in the power generation sector for EU27, Norway and Switzerland has been made applying the Chalmers Energy Infrastructure database (power plants and CO_2 storage sites) and the techno economic ELIN-model, which is regionalized down to the individual MSs. Two scenarios is investigated; the “Market” scenario and the “Policy” scenario. From the results the following conclusions can be drawn:

- The application of CCS on a MS level is influenced by current fuel infrastructures and whether or not onshore storage will be allowed. If on-shore storage is restricted, CCS is more likely to be centralized around the North Sea.
- Natural gas fired conventional power plants is likely to be a serious competitor to coal CCS in the short to medium term providing large emission reduction by fuel shifting from existing coal power plants to new high efficiency gas fired plants. This can be a barrier for early deployment of CCS without additional support.
- The scenarios described in the Energy Roadmap prescribe a power system almost without net CO_2 emissions by 2050, i.e., a 93-99% emission reduction relative 1990 emissions, which will require advances in CCS technologies in terms of becoming zero-emission power plants. Alternatively, this can be met by co-combustion of biomass in coal fired CCS with the biomass part adjusted to offsetting the remaining fossil emissions to obtain net zero emissions.
- A challenge in the presented scenarios would be the short term balance in electricity generation at around 2050 when most of the energy mix is either intermittent or base load CCS, which should be difficult to handle with respect to load following.
- CCS technologies have the potential to contribute to as much as 25-35% of total electricity generation in the end of the period investigated scenarios.

Acknowledgements

This work is co-funded by the AGS project ―Pathways to Sustainable European Energy Systems‖ and the EU FP7 PLANETS project. Furthermore, some work builds on the collaborative work between Chalmers University and the DG-JRC.

References

[1] European Commission 2011, “Energy Road map 2050”, Commissioning Staff Working Paper, Impact Assessment, SEC(2011) 1565/2.
[2]
[3] European Commission (2006) Commission Communication on Sustainable Power Generation from Fossil Fuels: Aiming for Near-Zero Emissions from Coal After 2020. COM(2006) 1723.
[4] OECD/IEA (2011) World Energy Outlook – 2011. IEA, Paris.
[5] M. Odenberger, J. Kjärstad, F. Johnsson (2008) Ramp-up of CO2 capture and storage within Europe, Int. J. Greenhouse Gas Control, 2, 417-438.
[6] J. Kjärstad, R. Ramdani, P.M. Gomes, J. Rootzén, F. Johnsson (2011) Establishing an integrated CCS transport infrastructure in northern Europe - Challenges and possibilities. Energy Procedia, Volume 4, 2011, Pages 2417-2424.
[7] R. S. Middleton, J. M. Bielicki (2009) A comprehensive carbon capture and storage infrastructure model, Energy Procedia 1, 1611 –1616.
[8] M van den Broek, A. Ramı´rez, H. Groenenberg, F. Neele, P. Viebahn, W. Turkenburg, A. Faaij, Feasibility of storing CO2 in the Utsira formation as part of a long term Dutch CCS strategy (2010), Int. J. Greenhouse Gas Control 4, 351–366.

[9] J. Kjärstad, F. Johnsson (2007) The European Power Plant Infrastructure - Presentation of the Chalmers Energy Infrastructure Database with Applications. Energy Policy. 35, 3643-3664.

[10] J. Kjärstad, J. Morbee, M. Odenberger, F. Johnsson, E. Tzimas (2012) Modelling large-scale CCS development in Europe – linking techno-economic modelling to transport infrastructure. Energy Procedia, proceding from GHGT-11. In press.

[11] M. Odenberger, F. Johnsson (2010) Pathways for the European electricity supply system to 2050—The role of CCS to meet stringent CO2 reduction targets, Int. J. Greenhouse Gas Control 4, 327–340.

[12] M. Odenberger, T. Unger, F. Johnsson (2010) Pathways for the North European electricity supply, Energy Policy 37 (5), 1660-1677.

[13] J. Kjärstad, F. Johnsson (2008) Ramp-up of CO2 capture and storage within the European power sector, Energy Procedia 1, 4201-4208.

[14] M. Odenberger, F. Johnsson (2009) The role of CCS in the European electricity supply system, Energy Procedia 1, 4273-4280.

[15] M. Odenberger, F. Johnsson (2011) CCS in the European electricity supply system - Assessment of national conditions to meet common EU targets, Energy Procedia 4, 5869-5876.

[16] OECD/IEA (2010) World Energy Outlook – 2010. IEA, Paris.

[17] Eurostat – URL:http://epp.eurostat.ec.europa.eu portal/page/portal/nuts_nomenclature/introduction

[18] BAFA - German Federal Office of Economics and Export Control – www.bafa.de.

[19] OECD/IEA (2012) World Energy Outlook – Golden rules for a golden age for gas. IEA, Paris.