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Europe's Coal Supply Security: Obstacles to Carbon Capture, Transport and Storage

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Introduction: Coal's security-of-supply paradox

Europe faces a paradox with respect to coal supply security. On the one hand, coal is a reliable fossil fuel, with ample reserves available from a large number of producers. Globally, coal use has risen at a rate of 4.9% annually in recent years (WCI, 2010). Yet on the other hand, Europe's climate policy objectives will not allow continued use unless this 'dirtiest' of all fossil fuels can be transformed into a 'clean' one, e.g. via new carbon capture, transport and storage (CCTS) technology. CCTS, however, this requires substantial technological advances for application in the medium and long term (MIT, 2007). The Intergovernmental Panel on Climate Change (IPCC, 2005) concludes that CCTS can contribute 15-55% of the cumulative emissions reduction effort through 2100, and assumes a major role in a portfolio of the low carbon technologies needed to mitigate climate change. According to the International Energy Agency (IEA, 2008), CCTS is "the most important single new technology for CO_2 savings" in both power generation and industry. However, the IEA's 2009 'Blue Map' scenario also states that 100 carbon capture plants, a minimum of 10,000 km of pipelines and storage of 1.2 $GtCO_2$ are required for CCTS to become a serious abatement technology by 2020. We are nowhere close to these and might never get there.

Will the transformation of the European coal industry towards CCTS succeed? Based on analysing CCTS project information and the industrial strategies of the major players, there is a high probability that the IEA 2020 'Blue Map' targets will not be reached. Ironically, this may lead to a supply security paradox: while sufficient coal is available worldwide and can be supplied to Europe without severe danger of

secure

Security of Energy Considering its Uncertainty, Risks and Economic implications

SEVENTH FRAMEWORK PROGRAMME

Research for this paper was carried out in the context of the SECURE project (Security of Energy Considering its Uncertainties, Risks and Economic Implications), funded by the European Commission under the Seventh Framework Programme. The project develops appropriate tools for evaluating the vulnerability of the EU to the different energy supply risks, and for promoting the optimisation of EU energy insecurity mitigation strategies, including investment, demand side management and dialogue with producing countries.

At the time of writing this Policy Brief, Herold, Hirschhausen, and Rüster were with Dresden University of Technology, Chair of Energy Economics and Public Sector Management (EE^2); Herold and Hirschhausen are now with TU Berlin, and Rüster is with the European University Institute, Florence. Haftendorn Holz, and Neumann are with DIW Berlin. We thank Manfred Hafner for providing project leadership and the framework of the analysis, Christian Egenhofer and Arno Behrens for editorial assistance, and all SECURE colleagues and external experts for in-depth discussions. The usual disclaimer applies.

disruption, its use for electrification and other purposes may be restricted because the failure of CCTS forms a barrier to continued traditional use of steam coal.

The EU is hardly vulnerable to the potential external risks to its steam coal supplies. In particular, Europe imports from countries such as Russia, Colombia and South Africa, which are considered 'safe' suppliers and have not experienced serious disruptions in the past. Moreover, European importing countries diversify their imports, often complementing them with domestic production, which results in good scores in diversity indices.

The real concern with respect to supply security is the absence of an economically and politically sustainable use of coal for electricity generation, liquefaction, gasification, and in industry. According to the IEA Technology Roadmap, the next ten years are a 'make or break' period for CCTS (IEA, 2009a). However, we find that the ambitious development plans in CCTS demonstration are unlikely to be met. The reason is not the lack of funding for demonstration projects, but the underestimation of the technical and regulatory complexity of the whole CCTS process chain.[1] Further, strong public rejection of CO_2 storage and the decline in available storage potential have limited both suitable sites for demonstration projects and the future contribution of CCTS to a decarbonised electricity sector.

We argue that it is too early to abandon the IEA Roadmap, but that CCTS in Europe can only thrive when supported by stronger political determination on the part of the European Union and the respective member states. In particular, the financial and political uncertainty surrounding future projects should be reduced. This uncertainty stems from politically dependent CO_2 prices, the true abatement costs of commercial capture plants, the size, shape and provision of the transport and storage infrastructure, the performance of renewable energy technologies, and foremost the political commitment towards or against CCTS over the coming decisive years. The expectation of CCTS becoming a commercially available carbon abatement technology by the year 2020 or even 2030 should be significantly lowered. With a focus on Europe, the role of CCTS as a 'bridge' technology into an age of renewable electricity generation might be questioned. This does not apply to the use of CCTS in industrial applications or on a global scale.

[1] Similar problems were observed during an attempt to introduce hydrogen for the transport sector. Unresolved technical questions, the lack of the underlying network infrastructure and strong competitors have formed high market barriers for hydrogen technologies.

This Policy Brief summarises findings on the development and application of specific tools for energy security in the coal sector produced by the SECURE project. We identify the potential risks throughout the value chain for coal-based electricity and heat production, followed by policy recommendations to deal with the uncertainties of the CCTS value added chain.[2]

1. European supply with steam coal

Supply security issues have been subject to scant analysis in recent decades, despite the increased importance of coal as a primary energy source. In fact, amid concerns about global warming and CO_2 emissions reductions, coal is currently experiencing a renaissance due to its relatively low price and pressures upon primary energy markets such as oil. Power production based on steam coal input[3] has received more attention lately due to the advent of clean-coal technologies. Globally, the use of coal has risen considerably, mainly due to high energy demand growth in China and India. Only about 15% of the hard coal produced is internationally traded; from 2000 to 2005 the amount of yearly traded coal increased from 210 to 755 million tonnes.

Historically, there are two geographical markets: *i) the Pacific market* with exports from Australia, Indonesia and China, and to a lesser extent from South Africa, the US, Canada and East Asia, i.e. Japan, South Korea, Taiwan, etc., and *ii) the Atlantic market* with exports from South Africa and Colombia, and to a lesser extent from the US, Canada, Poland, Russia, Australia and Venezuela. Recent research points out that the traditional separation of the Pacific and Atlantic markets has faded (Ellerman, 1995; Warell, 2006; Li, 2008; Zaklan, et al., 2009). However, the spatial aspect of the global coal market plays a considerable role, with transport costs being an important factor in determining trade relations.

[2] Earlier drafts were discussed at the SECURE Stakeholder Workshop (November 2009, Paris), with experts from academia, the policy community, and industry, and in the internal SECURE workshop (June 2010, Brussels). More information is available at www.secure-ec.eu and in companion CEPS Working Documents (Herold et al., 2010c, and Mendelevich, et al., 2010).

[3] With hard coal, a distinction is drown between steam (thermal) and coking (metallurgical) coal, depending on its calorific content and other chemical properties. Steam coal, which is almost exclusively used for electricity production, can be considered a homogeneous good. This Policy Brief considers steam coal the most important type of coal. In some European countries, lignite is used domestically (generally, minemouth), but there is no risk to its domestic supply.

Most large coal consumers obtain a significant share of their demand on the world market, often because domestic reserves have declined. Important EU countries in this respect are Germany, the UK, and Poland. For these consumers imported steam coal becomes more attractive than exploiting indigenous, high-cost reserves. Global coal markets now provide relatively cheap supply, which has attracted new consumers like China and India.

Table ***1*** reports the import share of total consumption for the major consumers. Even though the import dependency rate of some European countries is relatively high, the share of imported steam coal in electricity production does not exceed 25% in any large coal-consuming country. This compares to somewhat higher import dependency for Japan, South Korea and Taiwan. Although China's import share is low, the amount of imported steam coal is substantial in absolute terms.

Table 1. Import dependency rates (in %) of major steam coal consuming countries in 2007

	Import dependency rate	Share of steam coal in electricity production	Share of imported steam coal in electricity production
Germany	77.8	20.8	16.2
Italy	98.6	14.1	13.9
Spain	70.5	21.3	15.1
UK	64.4	34.5	22.2
US	3.4	46.5	1.6
Japan	100	24.0	24.0
South Korea	93.5	36.9	34.5
Taiwan	100	48.8	48.9
China	2.2	80.3	1.7

Source: IEA (2009b, c).

Various external risks could impede European coal supplies. For instance, an oligopolistic supply structure would not endanger the supplies, but it would increase prices substantially beyond the competitive level. Little diversification and reliance on a single exporter would bring large risks of a total supply disruption in the short term after, e.g. a technical failure on the export side.

We use the Shannon-Wiener Index[4] to measure supply diversification. A second step extends the index to the Shannon-Wiener-Neumann Indices 1 and 2 that respectively include the political stability of the exporters and the internal supplies of a country.[5] As a rule of thumb, these indices lie between zero (complete import dependence upon one supplier) and two (broad diversification). Figure 1 shows the indexes for the major European and non-European importers and OECD Europe for 2007, the most recent year with available data. OECD Europe obtains virtually all of its imports from six sources, with South Africa and Russia making up for more than 60% of the total deliveries. About 60% of the total steam coal consumption in Europe is imported (in contrast, 99% of US domestic production supplies American consumption). China's domestic production makes that country a net exporter, while Japan lacks domestic production and receives more than 50% of its imports from Australia. The values – between 0.8 and 1.8 – for the European countries indicate a high degree of diversification, and thus security of supply.

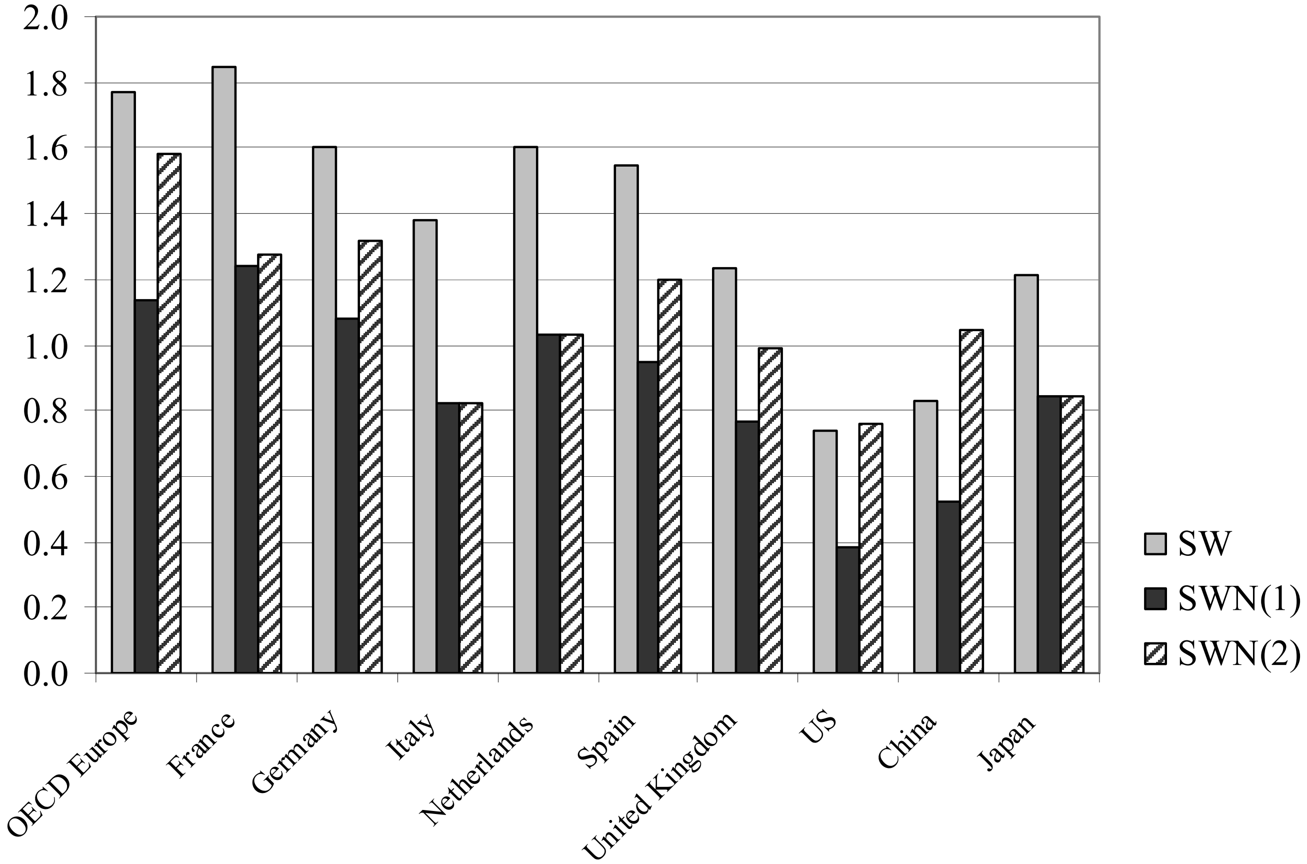
With respect to the market structure of supply, model-based analysis suggests relatively few worries about oligopolistic market power. The COALMOD model is a partial equilibrium model of international steam coal trade that is used to compare perfectly competitive and oligopolistic markets; for details see Haftendorn, Holz and von Hirschhausen (2009). In our COALMOD model, the simulated trade flows on the global steam coal market suggest that the competitive simulation better represents reality. The model also shows that the global market for steam coal is organised competitively and that strategic behaviour

[4] The Shannon-Wiener Index (SW) measures import supply diversification by taking into account both the number of suppliers as well as their repartition: the more suppliers there are and the more evenly distributed their respective quantities, the higher the Index.

[5] The Shannon-Wiener-Neumann Index 1 (SWN 1) adds a measure of political stability for each exporting country and the Shannon-Wiener-Neumann Index 2 (SWN 2) also includes domestic supplies in the formula. A lower measure of political stability decreases the value of the index, whereas domestic supplies increase it. For a description of the formulas see Neumann et al., 2009.

by the exporters cannot be significantly observed. The real prices are closer to the competitive level as shown in Figure 2. We perform likely scenarios of supply disruption, only to find that they have limited impact on EU countries. Our analyses of the supply structure confirm there is little risk for the security of supplies from the export markets serving Europe; this holds in the medium to long term, too.

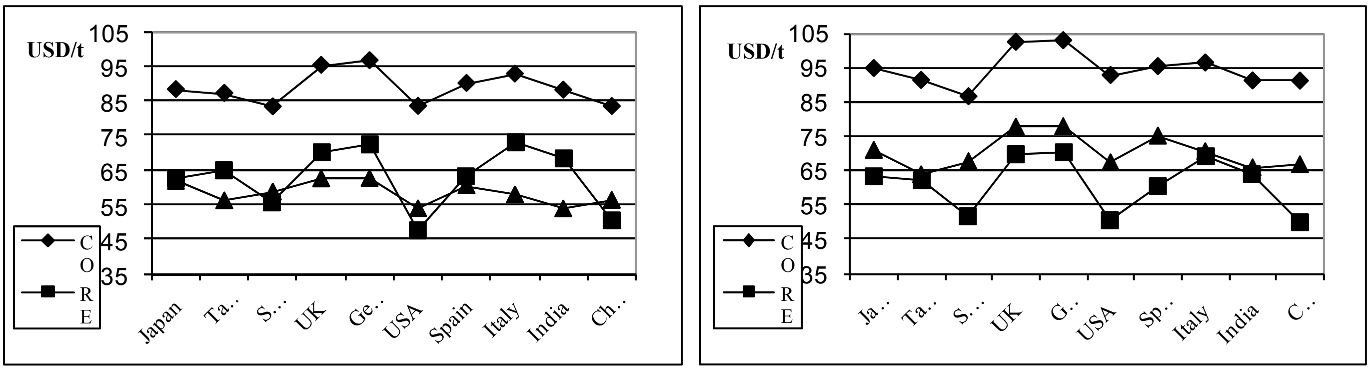
Figure 1. Diversification indices for major European and non-European importers in 2007



Source: Neumann et al. (2009).

SW: Shannon-Wiener Index, measure of import supply diversification.
SWN 1: Shannon-Wiener-Neumann Index1, in addition to SW including a measure of political stability for each exporting country.
SWN 2: Shannon-Wiener-Neumann Index2, in addition to SWN1 including the level of domestic supplies.

Figure 2. CIF prices in the perfect competition (PC) and Cournot scenario (CO) – model results, and reference data (RE) in 2005 (l) and 2006 (r)



Source: Haftendorn & Holz (2010).
CO: Cournot-assumption.
RE: Reference data, real prices observed.
PC: Perfect competition assumption.

2. Obstacles to a successful roll-out of CCTS

2.1 Upstream: CO_2 capture

Although the chemical industry has used CO_2 capture for decades, near-term available technologies vary in maturity and thus have different time horizons for commercial availability. This Policy Brief focuses on first-generation capture technologies. Scaling up the technology of CO_2 capture and the treatment of gases containing impurities demands dedicated research and development well before the technology can begin to achieve significant CO_2 emissions abatement. Currently, the following three capture technologies are under consideration:

Post-combustion chemical absorption technologies are commercially available. The technology was first applied in the 1980s to capture CO_2 from ammonia production plants. The captured CO_2 is used in food production to carbonate soft drinks and soda water. However, the technology is used only for the treatment of very clean gas mixtures (Kanniche et al., 2010). Including compression, this process leads to a 25% loss in the thermal efficiency of a coal-fired plant. Nonetheless, high compatibility in retrofitting existing plants makes this technology the most attractive mid-term option.

The *oxyfuel* process 'separates' the flue gas before combustion. CO_2 from conventional combustion processes is present as a dilute gas in the flue gas, resulting in costly capture using, e.g. amine absorption. Attempts to develop and apply the technology were initiated in the 1980s by the oil industry. The energy efficiency of a coal-fired oxyfuel power plant is 8-10% lower than air-based systems. Several technical questions still need resolution: the technology has not been demonstrated on a large scale, and the high temperatures of flue gas do not allow for the electric removal of ash but rather require costly ceramic filters.

Pre-combustion capture refers to the treatment of CO_2 and H_2 after the gasification of coal, biomass or the steam reformation of natural gas. Pre-combustion capture is not applicable to existing plants other than Integrated Gasification Combined Cycle (IGCC) and Integrated Reformer Combined Cycle (IRCC) plants. Therefore, the technology is mainly an option for industrial applications in the absence of IGCC plants. The energy penalty is around 22 points, dropping from 43% to 33.5% (Kanniche et al., 2010). The major barrier, however, is the high investment cost of approximately €2,700/kW for coal-based IGCC plants (Tzimas, 2009).

2.2 Midstream: CO_2 transport

Pipeline transportation is commonly considered the only economic onshore transport solution which can carry the quantities emitted by large-scale sources. Onshore transport faces few or no significant technological barriers and is usually in liquid or super-critical form in order to avoid two-phase flow regimes. CO_2 pipelines representing a typical network industry, characterised by very high upfront investment costs that are sunk; variable costs are comparatively insignificant and primarily include expenditures for fuelling compressors. CO_2 transportation costs vary between less than €1 and more than €20/tCO_2, a function of the transportation distance and the CO_2 flow (IPCC, 2005).

The level of uncertainty about the size and configuration of the pipeline network stems from the uncertainty about future policies and the suitability of geological formations to store captured CO_2. The solutions will correspond to the shape of the future network, which remains undefined and requires quantification and qualification of storage sites at the European level (Herold et al., 2010a). Important regulatory issues therefore include: network ownership; competition regulation; and the degree of vertical integration. The options for ownership range from completely private to completely public. In the case of regionally dispersed sources and sinks, and long transport distances, the benefits of an interconnected pipeline network increase. Southern European states lack geological formations suitable for CO_2 storage on a larger scale.

It is important to understand that the transport network will not evolve until storage sites are identified and the first capture plants are under construction, and that no investment in CCTS plants can be expected unless legal, regulatory and economic questions about the future network are answered.

2.3 Downstream: CO_2 storage

Injecting CO_2 into reservoirs has been practised for a few decades, but only a handful of operations permanently store CO_2, i.e. under the Sleipner Field (Norway) or at In Salah (Algeria). Storage comes with a portfolio of technology options, but not all are applicable in Europe for economic reasons or due to the lack of geologic formations. Enhanced oil recovery, practised for decades in the US, and enhanced gas recovery require oil and gas fields that still hold a significant quantity (60%). However, only a fraction of the injected CO_2 remains underground. Alternatively, storage can take place in depleted fields, yet without the monetary benefit of fossil fuel production.

Table 2. Cost estimation of CO2 storage options in €/tCO2

	Depth of storage (m)		
	1,000	2,000	3,000
Aquifer onshore	1.8	2.7	5.9
Aquifer offshore	4.5	7.3	11.4
Natural gas field onshore	1.1	1.6	3.6
Natural gas field offshore	3.6	5.7	7.7
Depleted oil field onshore	1.1	1.6	3.6
Depleted oil field offshore	3.6	5.7	7.7
	Low	**Medium**	**High**
EOR onshore	-10	0	10
EOR offshore	-10	3	20
ECBM	0	10	30

Source: Vallentin (2007).

Mature oil and gas reservoirs that have held crude oil and natural gas for millions of years have a lower risk of leakage. Storage in saline aquifers appears to have the best storage potential for Europe, followed by coal seams and fossil fuel reservoirs (Vallentin, 2007). Saline aquifers potentially could hold a global storage potential of 1,000 to 10,000 $GtCO_2$ (IPCC, 2005). They are also associated with high uncertainty concerning their pure physical potential, usable formations and timeframes. Due to environmental concerns, ocean storage of CO_2 is no longer considered. Yet storage in formations under the seabed offers an alternative to the NIMBY problem observed in many countries. Although seabed storage might gain public acceptance, its storage costs are far greater than onshore facilities.

New studies find a strong decline in estimated storage potential (Gerling et al., 2010 and Höller, 2010). For instance, the Federal Institute for Geosciences and Natural Resources (BGR) estimates that total annual storage potential in Germany is 50 to 75 $MtCO_2$. [6] This is equal to about 20% of the emissions covered under the German EU ETS allocation and highlights the limitations of CCTS, especially if the observed trend continues (Gerling, 2010).

Storing CO_2 in geologic formations requires routine monitoring throughout the entire storage period. The leakage rate of individual formations is unpredictable and varies between no leakage and unforeseen high rates. Low leakage must be monitored over a time horizon exceeding firms' planning horizons and makes governmental intervention necessary. The European Commission proposes that liability should be transferred to the public 20 years after storage closure. A former German proposal for CCTS legislation suggested that liability should be transferred 30 years after a site is closed and long-term safety has been proven. Perhaps the most significant barrier to large-scale carbon storage is public opposition. An educational effort by policy-makers and the industry could help to explain the costs, benefits and limits of all alternatives. A further decline in the usable storage potentials due to public opposition would increase transport and storage costs significantly (Mendelevitch et al., 2010).

2.4 Uncertain economics of the CCTS value added chain

Due to the energy penalty and the higher capital expenditure of CCTS plants, the costs of electricity production will increase if the technology comes into use. The true costs of CO_2 abatement with CCTS remain unknown in the absence of scaled-up demonstration plants; likewise, the expected benefits for electricity producers are uncertain, given future carbon price uncertainty (Tzimas, 2009).

[6] This is due to the restriction in the injection rate.

Table 3. Investment cost of different systems with and without CO_2 capture

Technology	Investment costs demonstration project in €$_{08}$/kW	Efficiency [%]
IGCC-carbon capture	2,700	35
PF	1,478	46
PF-carbon capture	2,500	35
Oxyfuel	2,900	35
NGCC-carbon capture	1,300	46

Source: Tzimas (2009).

Our project database (Herold & Hirschhausen, 2010b) shows that among the 69 CO_2 capture projects, only eight are operating on a pilot scale and that large-scale demonstration projects, i.e. SuperGen in the US, and the UK tender, are behind schedule. It is not certain whether the European Recovery Programme could jumpstart the development of its six large-scale capture projects.

Mendelevitch et al. (2010) introduce a mixed integer, multiperiod, cost-optimizing CCTS network model to analyse the future potential of the technology for CO_2 reduction at the European level. It incorporates endogenous decisions about carbon capture, pipeline and storage investments, ejection and flow quantities based on given costs, certificate prices, storage capacities and point source emissions. The results indicate that CCTS can theoretically contribute to the decarbonisation of Europe's energy and industry sectors. This requires a CO_2 certificate price rising to €55 in 2050, and sufficient CO_2 storage capacity for both on- and offshore sites. However, CCTS deployment is highest in CO_2-intensive industries where emissions cannot be avoided by fuel switching or alternative production processes. In all scenarios, the importance of the industrial sector as a first-mover to induce the deployment of CCTS is highlighted.

By contrast, a decrease of available storage capacity or a more moderate increase in CO_2 prices will significantly reduce the role of CCTS as a CO_2 mitigation technology, especially in the energy sector. Continued public resistance to onshore CO_2 storage could only be overcome by constructing expensive offshore storage.

3. Conclusion and policy recommendations

This Policy Brief suggests that the real issue in European steam coal supply security is not resource availability, but rather the absence of an economically and politically sustainable use of coal for electricity generation, liquefaction, gasification, industrial applications, etc., due to obstacles in the implementation of a CCTS value-added chain.

On the coal supply side, we find that virtually all major exporters[7] can be considered 'safe' countries in geopolitical terms and no sudden supply disruption on political grounds can reasonably be expected. Short-term supply disruptions may occur due to natural disasters, or to social tensions that lead to strikes. Yet efficient supply management with stockpiling and supply diversification can reduce the short-term risk of disruption for European import countries. Therefore, we suggest that:

- market monitoring should continue, particularly for developments and prices in specific regions (e.g., China);
- competition authorities should continue to monitor international coal markets, with a special focus on mergers and acquisitions of large coal and mining companies;
- while coal-buying utilities should be urged to implement efficient risk management, we see no need for additional policy intervention.

On the utilisation side, there is an implicit supply security threat, i.e. that coal will no longer be an essential element of European energy supply, because the CCTS rollout will be delayed or never carried out. There is justified concern that the ambitious development plans in CCTS demonstration as outlined in the IEA Technology Roadmap over the next decade will not be met. This is based on a lack of determination by public authorities to overcome the significant obstacles inherent in the complexity of the CCTS chain, and the difficulties of the power sector embracing a technology that challenges the business model of coal electrification. With a focus on Europe, the economic use of coal in the power sector and in industry could be threatened. CO_2 emissions from the industrial sector are responsible for 22.3% of Europe's CO_2 emissions (European Commission, 2010). One-third is directly linked to fossil fuels or chemical processes. The substitution of coal in industrial processes could present even larger challenges than the substitution of coal for electricity production.

In addition to transport infrastructure, recent estimations find a significant decline in European storage potential. Further, increased public opposition to onshore storage will most likely necessitate

[7] Major exporters are Australia, South Africa, Indonesia, the US, Russia, China and Colombia.

offshore solutions. This will raise the costs and the technical complexity of the CCTS chain and will therefore raise questions on the role of CCTS as a bridge technology to an age of renewable based energy production. We therefore recommend the following:

- The potential contribution of CCTS to a decarbonised European electricity sector should be reconsidered given new data available on CCTS costs, a better understanding of the complexity of the process chain and the lowered CO_2 storage potential. The idea that CCTS could constitute an 'energy bridge' to a new, largely renewable-based energy system should be discontinued.

- Europe has an important role to play in keeping the technology options open and avoiding premature IP appropriation. The EU-co-funded projects should make new knowledge widely available, and a competition between projects should be promoted that yields the highest chances of achieving technical progress (Newbery et al., 2009).

- Money does not seem to be a significant constraint to CCTS projects. The readily available billions of euros and dollars should be invested immediately.[8] In cases where industry does not respond, the legal and regulatory framework should be readjusted and the level of incentives should be raised. In the absence of a credible CO_2 price path, forcing utilities into a capture-ready option will raise the costs of the standard plants but will not encourage CCTS investment (Geske & Herold, 2010).

- The strong focus on the implementation of CCTS in the power sector observed in the past should be extended to industrial applications, which can be highly vulnerable to an abandonment of coal. Due to a larger number of small emissions sources, this will pose higher challenges to network development.

- Early planning of transport routes is of paramount importance should large-scale CCTS deployment be implemented. At least in this phase, the state will be needed as a major provider in the development of transportation infrastructure, including planning and siting.

- Construction and operation can be tendered to the private sector, or carried out by state-owned network firms. Routing pipelines along existing networks can lower costs and, to a limited extent, mitigate public rejection. Thus synergies with other energy network infrastructure (gas, electricity) should be considered.

- Future regulation should specify the allocation and financing principles and access for third parties. It is unlikely that the private sector has sufficient incentives to develop the network, given the political, regulatory, technical and economic uncertainties.

- If Europeans fail to fill their role as CCTS pioneers, new strategies for the global roll-out of CCTS are needed. The inclusion of CCTS under the Clean Development Mechanism could help bring the technology to the markets. However, this would also imply outsourcing potential risks associated with the technology.

[8] The EU has commissioned €1.05 billion from the EERP plus the revenues from 300 million certificates. The expected €6-9 billion will co-finance 8-12 CCTS projects and 34 renewable energy projects. The US has announced that US$2.4 billion from the American Recovery and Reinvestment Act will be used to expand and accelerate the commercial deployment of CCTS. Canada has commissioned US$2 billion in funding by the provinces for four large-scale CCTS projects. Australia has allocated Aut$2.4 billion to partially fund CCTS flagship projects.

References

Apotheker, D.F. (2007), "The design of a regulatory framework for a carbon dioxide pipeline network," Mas.ter Thesis, TU Delft.

Buhre, B.J.P., L.K. Elliott, C.D. Sheng, R.P. Gupta and T.F. Wall (2005), "Oxy-fuel combustion technology for coal-fired power generation," *Progress in Energy and Combustion Science*, Vol. 31, pp. 283-307.

Celia, M.A., S. Bachu and S. Gasda (2002), "A framework to estimate CO_2 leakage associated with geological storage in mature sedimentary basins," *American Geophysical Union*, Fall Meeting.

Chrysostomidis, I., P. Zakkour, M. Bohm, E. Beynon, R. de Filippo and A. Lee (2009), "Assessing issues of financing a CO_2 transportation pipeline infrastructure," *Energy Procedia*, Vol. 1, No. 1, pp. 1625-1632.

DOE (2009), http://www.energy.gov/7405.htm [23.10.2010].

European Commission (2003), Guidelines for successful public-private partnerships, DG Regional Policy, March, Brussels.

European Commission (2010), EU Energy in Figures 2010. CO_2 Emissions by Sector, Brussels.

Ellerman, D.A. (1995), "The world price of coal," *Energy Policy*, Vol. 23, No. 6, pp. 499-506.

Geske, J. and J. Herold (2010), *Carbon Capture and Storage Investment and Management in an Environment of Technological and Price Uncertainties,* Working Paper WP-RD-05, Dresden University of Technology.

Gerling, J.P., S. Knopf, C. May and C. Müller (2010), "Neuberechnung möglicher Kapazitäten zur CO_2-Speicherung in tiefen Aquifer-Strukturen," *Energiewirtschaftliche Tagesfragen*, Vol. 60, No. 4.

Gerling, J.P. (2010), "CO_2 storage – German and international perspective," presentation at the Berlin Seminar on Energy and Climate Policy, 3 June.

Groenenberg, H. and H. de Coninck (2008), *Technical support for an enabling policy framework for carbon dioxide capture and geological storage,* Task 3: Incentivizing CO_2 capture and storage in the European Union, Report for the Directorate-General Environment of the European Commission.

Haftendorn, C., F. Holz, and C. von Hirschhausen (2009), "Oligopolistic supply in coal markets? Modeling the international steam coal trade," SECURE Deliverable 5.3.4.

Haftendorn, C. and F. Holz (2010), "Modeling and analysis of the international steam coal trade," *Energy Journal*, Vol. 31, No. 4. pp. 201-225.

Hazeldine, Stuart (2009), "UK CCS competition 'dead on its feet' says expert," (http://www.businessgreen.com/business-green/news/2252733/uk-ccs-competition-dead-feet).

Herold, J., S. Rüster and C. von Hirschhausen (2010a), "Vertical integration along the extended value added chain including carbon capture, transport, and sequestration (CCTS)," SECURE Deliverable 5.3.2.

Herold, J. and C. von Hirschhausen (2010b), "Carbon capture, transport, and sequestration (CCTS) – The real threat to European supply security with coal," SECURE Deliverable 5.3.5.

Herold, J., S. Rüster and C. von Hirschhausen (2010c), *Carbon Capture, Transport, and Storage in Europe*, CEPS Working Document, (http://www.ceps.eu).

Höller, S. (2010), "Ablagerung von CO_2 im geologischen Untergrund: Wie viel Platz gibt es in Deutschland?," *Bild des Monats*, Wuppertal Institute for Climate, Environment and Energy.

IEA (2008), *CO_2 capture and storage. A key carbon abatement option. Energy technology analysis,* OECD, Paris.

IEA (2009a), *Technology Roadmap – Carbon Capture and Storage*, OECD, Paris.

IEA (2009b), *Coal Information,* OECD, Paris.

IEA (2009c) *Electricity Information,* OECD, Paris.

IPCC (2005), *IPCC Special Report on Carbon Dioxide Capture and Storage,* Cambridge: Cambridge University Press.

Kanniche, M., R. Gros-Bonnivard, P. Jaud, J. Valle-Marcos, J.M. Amann and C. Bouallou (2010), "Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO_2 capture," *Applied Thermal Engineering*, Vol. 30, pp. 53-62.

Li, R. (2008), "International steam coal market integration," Department of Economics, Macquarie University, Australia.

Mendelevitch, R., P.Y. Oei, A. Tissen and J. Herold (2010), *CO_2 Highways for Europe: Modeling a Carbon Capture, Transport and Storage Infrastructure for Europe,* DIW Discussion Paper 1052.

MIT (2007), *The future of coal,* Massachusetts Institute of Technology, Cambridge, MA.

Neumann, A., C. Haftendorn, F. Holz and C. von Hirschhausen (2009), *A quantification of the diversification of European coal supplies*, SECURE Deliverable 5.3.3.

Newbery, D., D. Reiner, T. Jamasb, R. Steinberg, F. Toxvaerd and P. Noel (2009), *Carbon Capture and Storage (CCS): Analysis of Incentives and Rules in a European Repeated Game Situation,* University of Cambridge, EPRG Report to DECC.

Rezvani, S., Y. Huang, D. McIlveen-Wright, N. Hewitt and J. Deb Mondol (2009), "Comparative assessment of coal fired IGCC systems with CO_2 capture using physical absorption, membrane reactors and chemical looping," *Fuel,* Vol. 88, pp. 2463-2472.

Rubin, E.S., S. Yeh, M. Antes, M. Berkenpas and J. Davision (2006), "Estimating future costs of CO_2 capture systems using historical experience curves," *Proceedings 8th International Conference on Greenhouse Gas Control Technologies (GHGT-8)*, June 19-22, 2006, Trondheim, Norway.

Thurber, M.C., R. Varun and D.G. Victor (2009), "Carbon capture and storage at scale: Lessons from the growth of analogous energy technologies," Program on Energy and Sustainable Development, Stanford University, CA. Working Paper No. 81.

Tzimas, E. (2009), *The cost of carbon capture and storage demonstration projects in Europe,* JRC Scientific and Technical Reports, European Commission.

Vallentin, D. (2007), *Inducing the international diffusion of carbon capture and storage technologies in the power sector*, Wuppertal Institute for Climate, Environment and Energy.

Warell, L. (2006), "Market integration in the international coal industry: A cointegration approach," *Energy Journal*, Vol. 27, No. 1, pp. 99-118.

WCI (2010), World Coal Institute. (http://www.worldcoal.org).

Zaklan, A., A. Cullmann, A. Neumann and C. von Hirschhausen (2009), *The globalization of steam coal markets and the role of logistics: An empirical analysis*, DIW Discussion Paper No. 956, DIW Berlin.

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