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Lost hopes for CCS

– added urgency for renewable energy

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Executive Summary

The combustion of fossil fuels has dramatically increased concentrations of carbon dioxide in the Earth's atmosphere. In addition to correlated global warming trends, ocean pH levels are steadily declining. To preclude the detrimental effects of manmade carbon emissions on the environment, a radical shift to low-CO_2 energy production is required.

The deployment of renewable energies has not yet succeeded in reversing the growth of fossil fuel usage. The implementation of carbon capture and storage (CCS) has therefore been proposed for trapping CO_2 emissions from power plants and other stationary installations and storing them permanently in subterranean geological formations. In this manner, existing generation and distribution infrastructures could remain intact, while carbon would be permanently removed from the biosphere.

However, no viable prospect exists for capturing CO_2 emissions on a scale sufficient to impact global warming.

- CCS technologies are suitable for only a small segment of fossil fuel emissions.
- Other greenhouse gases such as methane cannot be diminished with CCS.
- Geological CO_2 repositories are generally of no commercial value, while requiring significant expenditures to be established and maintained.
- By the time CCS could be routinely adopted for power plants worldwide, rapidly diminishing coal reserves would limit the extent and duration of their operation.
- Restricted water resources often do not allow the cooling demands of capturing and compressing CO_2 for transport and geological injection to be fulfilled.
- Since adequate returns on investment must be guaranteed for the life of the equipment and infrastructure to justify implementation, CCS cannot deliver competitive carbon-free power at current emissions trading prices.
- CCS may benefit certain industrial enterprises in fulfilling emissions regulations or for manufacturing products from carbon dioxide, but it is too expensive for general adoption without commercial purpose.

CCS is already being deployed in North America for increasing oil and natural gas production using CO_2 injection. Diminishing global reserves of these hydrocarbons are widening the application of this technique. However, the additional quantities of extracted fuels that make extraction profitable emit greater quantities of CO_2 when burned than the carbon dioxide captured to implement the process. This application of CCS therefore countervails the objective of inhibiting global warming.

Global coal reserves may be largely depleted by mid-century at forecast consumption rates. CCS would intensify demand, possibly depriving newly constructed power plants of adequate fuel supplies before the end of their normal service life.

However, commercial CCS technologies will not be widely available in the foreseeable future. They cannot deliver competitive CO_2-free power at projected emissions trading prices, while fuel, water, and geological sequestration requirements exclude them as a universal solution to global warming.

1. Carbon Imbalances in the Biosphere

Nearly 90% of the world's marketed energy is supplied by fossil fuels.[1] When coal, petroleum products, and natural gas are burned, atmospheric carbon captured over millions of years by photosynthesis re-enters the biosphere in a radically compressed time frame as carbon dioxide (CO_2) and methane (CH_4).

Only a negligible percentage of the CO_2 released by combustion is later assimilated by surface plant life for sequestration in humus, organic debris, and wooden construction materials. Nearly half of all fossil fuel emissions since the beginning of the Industrial Revolution have been dissolved in the world's oceans. The mean "airborne fraction" (AF) of carbon dioxide retained in the atmosphere during the years 1960 - 2007 has been determined at 57% from fossil fuels alone, or 48% for the sum of fossil fuel and land use emissions.[2] At the absorption rate of 25% - 30% determined in 2005, however, the sequestration capability of the North Atlantic has declined by more than 50% since the 1990's due to warming-induced stratification.[3] The ocean has thus become a "variable and decreasing sink for atmospheric CO_2".

With absorption capacities of the biosphere in decline, the carbon dioxide concentration in the atmosphere has risen by over 35% since the beginning of the 20th century (295 parts per million ppm) to more than 390 ppm in 2012 at rates exceeding 2 ppm/a.[4]

Atmospheric chemistry is likewise altered by the emission of methane from natural gas wellheads, faulty gas pipelines, and coal mines. Biogenic methane is additionally contributed by cattle farming, rice fields, and organic waste dumps, effectively multiplying the effects of carbon on the biosphere due to the greater radiation absorption of CH_4 compared with CO_2. Atmospheric methane concentrations have grown from 700 parts per billion (ppb) in 1750 to over 1850 ppb, a level higher than at any time in the past 400,000 years. Atmospheric nitrous oxide (laughing gas N_2O) concentrations from industrialised agriculture and other anthropogenic sources have increased by 16% over pre-industrial levels.

1.1. Ocean Acidification

The absorption of atmospheric CO_2 in water forms carbonic acid ($CO_2 + H_2O \rightarrow H_2CO_3$) that along with sulphur and nitrogen compounds in precipitation ("acid rain") is reducing the natural alkalinity of the world's seas and oceans. Average pH values have already diminished by 0.11 units compared with the pre-industrial level of 8.16, increasing hydrogen ion concentrations

1 Energy Information Administration (May 25, 2010): International Energy Outlook 2010 - Highlights. EIA: Washington.

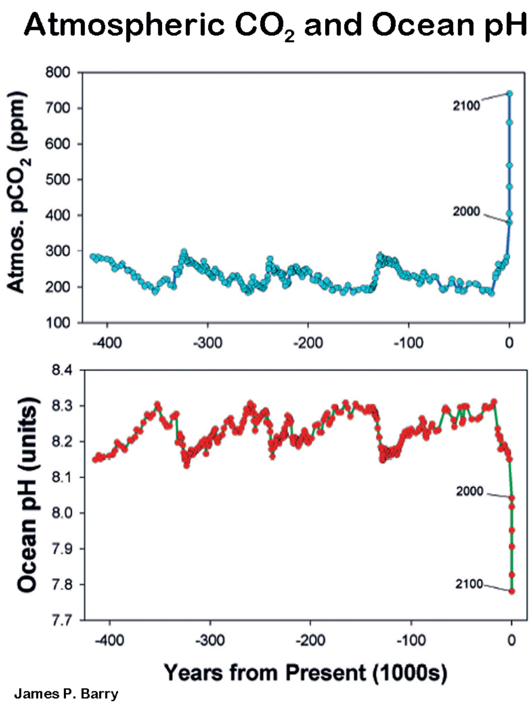
2 Kharecha, Pushker A. and James E. Hansen (2008): "Implications of 'peak oil' for atmospheric CO_2 andclimate". Global Biogeochemical Cycles, 22, GB3012, doi:10.1029/2007GB003142, p. 6.

3 Schuster, Ute and Andrew J. Watson (2007): "A variable and decreasing sink for atmospheric CO2 in the North Atlantic". Journal of Geophysical Research, Vol. 112, C11006, doi:10.1029/2006JC003941.

4 "Carbon Targets for Humanity". CO_2Now.org.

by nearly 30% due to the logarithmic measurement scale.[5] The reduction of aquatic calcium carbonate ($CaCO_3$) concentrations inhibits calcification in corals and shellfish. Under ongoing CO_2 emission trends, ocean pH values could decline by 0.17 - 0.46 units by the year 2100 and by as much as 1.4 units over the next three centuries.

Ocean acidification rising in correlation with atmospheric carbon dioxide concentrations is reflected in synchronous temperature trends. A study issued by the World Bank estimates that the "warming of 4°C or more by 2100 would correspond to a CO_2 concentration above 800 ppm and an increase of about 150 percent in acidity of the ocean". Without effective strategies of control or compensation, British climate researchers have predicted that atmospheric CO_2 concentrations "could reach about 600 ppm in 2050, rising to about 1,000 ppm in 2100".[6] "The observed and projected rates of change in ocean acidity appear to be unparalleled in Earth's history."[7]



The corresponding reduction of carbonate concentrations to the detriment of calcifying organisms foreshadows a "likely mass extinction of corals by the middle to end of this century".[8] Above atmospheric CO_2 levels of 450 - 500 ppm, hard corals will no longer be able to build the calcium carbonate skeletons of which ocean reefs are comprised.[9] Surveys of the International Coral Reef Initiative indicate that reefs support about 25% of all marine life, including over 4,000 species of fish.[10]

Corals depend on a highly evolved form of symbiosis with single-celled algae, known as zooxanthellae, with which nutrients essential to survival are

5 Federal Environment Agency of Germany (June 2009): Klimawandel und marine Ökosysteme. UBA: Dessau-Roßlau, p. 24.

6 Lenton, T. M. and N. E. Vaughan (January 28, 2009): "The radiative forcing potential of different climate geoengineering options". Atmospheric Chemistry and Physics: Norwich, p. 5545.

7 Potsdam Institute for Climate Impact Research and Climate Analytics (November 2012): Turn Down the Heat. The World Bank: Washington, p. xv.

8 Harrould-Kolieb, Ellycia et al. (December 2009): Ocean Acidification. Oceana: Washington, p. 1.

9 Dickey, Gwyneth (July 6, 2010): "Ocean acidification may make fish foolhardy". Science News: Washington; Turley, Carol (2010): Environmental Consequences of Ocean Acidification: A Threat to Food Security. United Nations Environment Programme (UNEP): Nairobi, p. 6.

10 Doyle, Alister (March 25, 2013): "Reef-building corals lose out to softer cousins due to warming". World Environment News: Sydney; www.icriforum.org/about-coral-reefs/status-and-threat-coral-reefs.

exchanged. Increased sea surface temperatures (SSTs) cause a reduction of these symbionts, initiating coral decline well before pH-induced dissolution of the carbonate skeletons ensues. The whitening of coral structures due to loss of the living organisms is termed "bleaching", which generally commences when warming exceeds an area's historical temperature norm by 1°C for more than four weeks.

The UN Secretariat of the Convention on Biological Diversity has determined that the measured trend toward ocean acidification "is irreversible on timescales of at least tens of thousands of years".[11] At current emission rates, "the surface waters of the highly productive Arctic Ocean will become under-saturated with respect to essential carbonate minerals by the year 2032, and the Southern Ocean by 2050 with disruptions to large components of the marine food web."

Reduced pH levels in combination with thermal stress and expanding hypoxia (oxygen depletion), all of which are linked to climate change from anthropogenic CO_2 emissions, "act together to constrain the window of performance for marine organisms".[12] Many nations responsible for the greatest carbon dioxide emissions are also among those potentially most affected by impoverished aquatic food chains due to their high nutritional and economic reliance on commercial fish production. Coastal life forms are additionally confronted by changes in circulation patterns and by the hypoxia resulting from fertiliser runoff. According to Ove Hoegh-Guldberg, director of the Global Change Institute at the University of Queensland, Australia, the Earth is "well on the way to the next great extinction event" in these realms.[13]

The absorption of CO_2 by the world's oceans is a cumulative and enduring process. The resilience of aquatic life forms subjected to moderate pH changes initially obscured the imperilment of their habitats by fossil fuel usage. However, the irrevocable reduction of seawater alkalinity at rates exceeding the progress of biological adaptation has now made non-carbon energy strategies a compelling global priority.

1.2. Climate Change

Solar irradiation and reflected terrestrial sunlight are absorbed in the troposphere at infrared frequencies by water vapour, carbon dioxide, methane, nitrous oxide, and various manmade fluoride compounds (SF6, CFCs, PFCs) as the dipole moment[14] of molecular bonds is changed. The ensuing resonant

11 Barnard, Nicola and Stefan Hain (2009): Scientific Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity. Secretariat of the Convention on Biological Diversity: Montreal, p. 9.

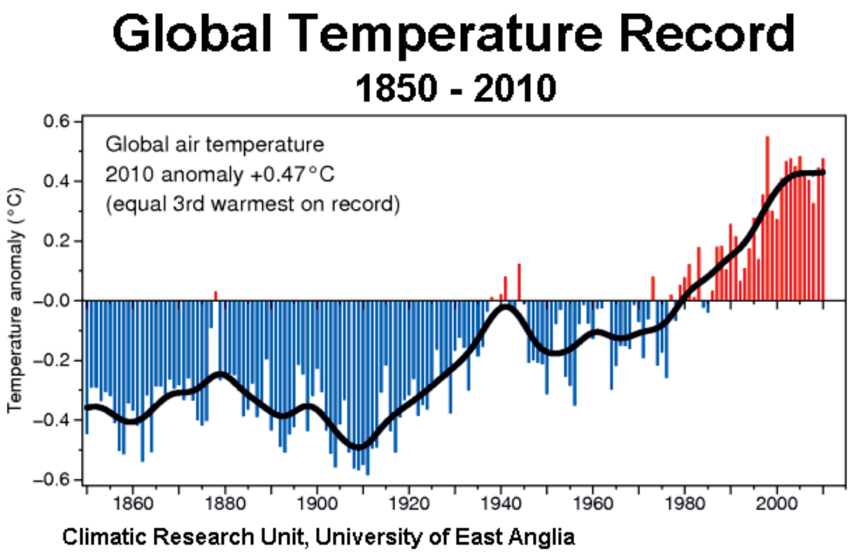
12 Barry, James P. et al. (2010): "Atmospheric CO_2 targets for ocean acidification perturbation experiments". In: Guide to best practices for ocean acidification research and data reporting. Publications Office of the European Union: Luxembourg, p. 61.

13 Perry, Michael (June 18, 2010): "Oceans choking on CO_2, face deadly changes: study". Thompson Reuters.

14 A dipole moment prevails when the centre of a negative charge does not coincide with the centre of positive charge. Symmetrically configured gas molecules such as oxygen (O_2) do not contribute to the greenhouse effect.

energy is radiated in equal parts toward outer space and the Earth. Rising temperatures resulting from this "greenhouse effect" stimulate the decay of organic matter, inducing further terrestrial emissions of water vapour, CO_2 and CH_4. Greenhouse warming thus becomes a positive feedback process that could increase dramatically if thawing Arctic permafrost released vast unstable stores of methane "more than 60 times as powerful as CO_2" in the first 20 years, although declining more rapidly.[15]

Until methane is ultimately oxidised to carbon dioxide and water, its greenhouse gas potential remains responsible for as much as a third of all global warming effects according to findings of the Goddard Institute for Space Studies.[16] The reduction of energy-related CO_2 is thus insufficient to prevent climate change. Methane additionally reacts with ozone to alter infrared atmospheric reflection coefficients that influence global surface temperatures.



The global warming occurring between 1850 and the end of the 20th century is equivalent to intensified solar radiation of about 2.5 Watts per square meter (W/m2).[17] The doubling of CO_2 from pre-industrial levels (280 ppm)[18] expected within a few decades would result in a corresponding warming increase of 4 W/m2.

Receding mountain glaciers, the migration of terrestrial vegetation and aquatic organisms, and insect species emerging in symbiosis with changing environments are symptomatic of global warming trends. An atmospheric CO_2 concentration of 350 ppm, which is considered by many researchers[19]

15 McCarthy, Michael (February 22, 2010): "Methane levels may see 'runaway' rise, scientists warn". The Independent: London.

16 Ramanujan, Krishna (July 18, 2005): "Methane's Impacts on Climate Change May Be Twice Previous Estimates". Goddard Space Flight Center: Greenbelt.

17 World Meteorological Organization: "Causes of Global Warming". www.wmo.int: Geneva.

18 www.physicalgeography.net/fundamentals/7h.html

19 Harrould-Kolieb, Ellycia et al. (December 2009), op. cit., p. 8.

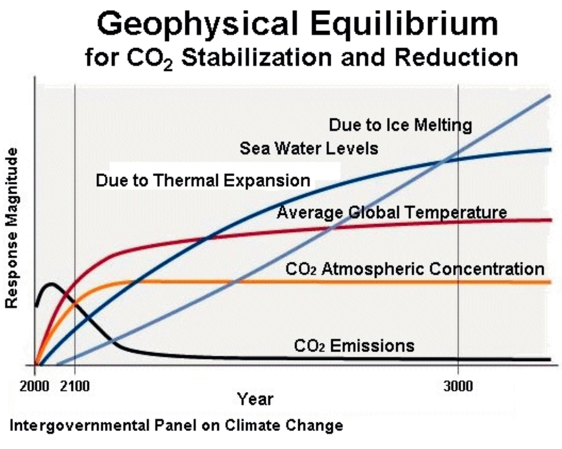
to constitute the maximum level consistent with biological diversity, was exceeded a quarter century ago. Levelling emissions at maximally 450 ppm could allow average global temperatures to stabilise around 2°C above pre-industrial concentrations. Greater temperature shifts may cause irreversible and ultimately disastrous changes in the global climate, a prospect recognised in July 2008 by leaders of the Group of Eight industrialised countries in agreeing to halve greenhouse gas emissions by 2050.[20]

Mathematical evaluations of global warming trends since 1750 indicate that doubling of CO_2 concentrations in the Earth's atmosphere corresponds with land warming of about 3.1 ±0.3°C, a result that "is broadly consistent with the IPCC estimates of 2-4.5°C warming (for land plus oceans) at doubled CO_2".[21] The global land mean temperature was found to have increased by 0.9±0.05°C over half a century (comparing 2001 - 2010 with 1951 - 1960).

In 2005, the Lawrence Livermore National Laboratory calculated that burning "the entire planet's available fossil fuels" by 2300 could increase median air temperatures by 7.8°C.[22] The temperature in the polar regions "would spike more than 20 degrees Celsius, forcing the land in the region to change from ice and tundra to boreal forests". Since these estimates were made before innovative shale gas and shale oil extraction technologies further increased the anthropogenic carbon inventory, the temperatures cited could ultimately be exceeded.

Temperature thresholds cannot be entirely extrapolated from ongoing energy usage, however, owing to uncorrelated emissions of CH_4, N_2O, and fluoride compounds. The warming effects of atmospheric CO_2 also diminish at concentrations above the first additional 50 ppm, while intensified terrestrial evaporation generally moderates rising temperatures.[23]

Ultimately, however, cumulative emissions will continue to alter the geophysical conditions of natural existence long after fossil fuel reserves have been depleted. Rising ocean levels resulting from melting glaciers and thermal expansion could displace millions of people from harbour cities, coastal areas, and island habitats.



20 Stolberg, Sheryl Gay (July 9, 2008): "Richest Nations Pledge to Halve Greenhouse Gas". The New York Times: New York.

21 Rohde, Robert et al. (2013): "A New Estimate of the Average Earth Surface Land Temperature Spanning 1753 to 2011". Geoinformatics and Geostatistics, Volume 1, Issue 1: Henderson, pp. 3, 5.

22 Lawrence Livermore National Laboratory (November 1, 2005): "Modeling of long-term fossil fuel consumption shows 14.5-degree hike in Earth's temperature". University of California: Livermore.

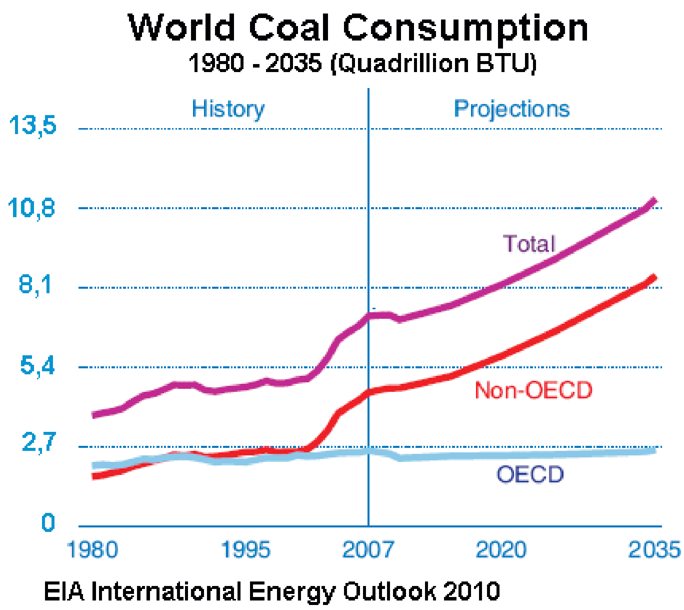
23 Kininmonth, William (November 2, 2006): "It's the cause of climate change that's in question". The Age: Melbourne.

Carbon dioxide enrichment in the atmosphere can promote vegetation growth to the benefit of agricultural productivity, while concurrently moderating greenhouse gas concentrations. However, enhanced growth rates will later subside as successive generations of green plants readjust to higher CO_2 levels by decreasing the stomata area required for photosynthesis. The relative numbers of stomata in plant fossils obtained from sedimentary rocks and peat deposits are thus measured by climatologists to ascertain prehistoric atmospheric CO_2 concentrations.

1.3. Global Carbon Trends

The US Energy Information Administration (EIA) predicts that worldwide energy consumption will be increasing by 49% between 2007 and 2035, most of it dependent on fossil fuels.[24] The acceleration of energy usage is most pronounced in the coal sector.

At the turn of the 21st century, the International Energy Agency (IEA) expected an annual 1.7% increase in global coal consumption, from 2,255 million metric tons (tonnes) of oil equivalent (Mtoe) in the year 1997 to 3,350 Mtoe in 2020,[25] corresponding to 3,221 and 4,786 million tonnes of coal equivalent (Mtce), respectively. By 2011, however, the produced tonnage of all types of coal already had risen to an estimated 7,678 million tonnes, of which 1,041 million tonnes was low-quality lignite.[26]



In China alone, coal demand is expected to attain 4.5 billion tonnes (Gt) by 2030,[27] while India anticipates quadrupling consumption to 2.5 Gt by 2031 - 32.[28] With imports indispensable to meeting domestic demand, foreign coal operations are now being acquired by both countries to secure long-term

24 Energy Information Administration (July 2010): International Energy Outlook 2010. EIA: Washington, p. 1.

25 International Energy Agency (2000): World Energy Outlook 2000. IEA: Paris, p. 91.

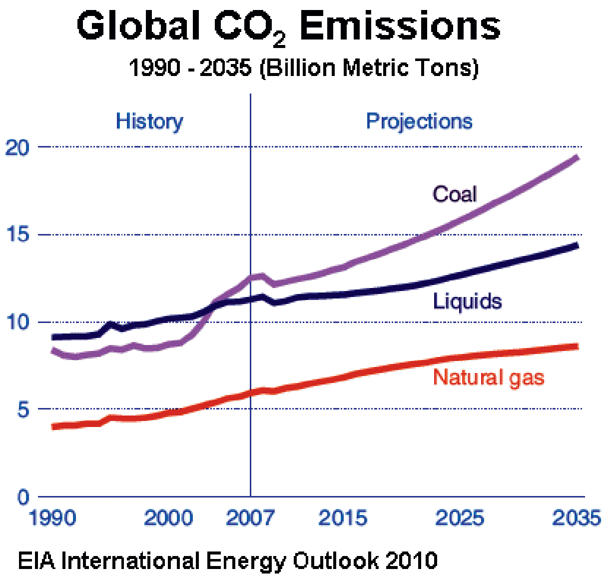
26 World Coal Association (August 2012): Coal Statistics. www.worldcoal.org/resources/coal-statistics.

27 Wei Tian (March 9, 2013): “Deputy appeals for greener coal mining policies”. China Daily: Beijing.

28 Katusa, Martin (September 12, 2010): “China and India: Still Hungry for Coal”. 321 Energy; Rakteem, Katakey and Tushar Dhara (September 24, 2010): “Indian Coal Demand May Triple in Next Two Decades, Minister Says”. Bloomberg; Singh, Ruchira (November 30, 2010): “India’s coal shortage to deepen next year”. Reuters.

delivery capabilities.[29] The most recent production figures indicate that coal may overtake liquid fuels as the world's most important energy source in the year 2013.

In 2010, coal was the mainstay of electricity production in South Africa (93%), Poland (92%), mainland China (79%), Australia (77%), Kazakhstan (70%), India (69%), the Czech Republic (60%), Greece (52%), the United States (49%), and Germany (46%).[30]



Global energy-related CO_2 emissions had earlier been predicted by the EIA to rise from 29.7 Gt in 2007 to 33.8 Gt in 2020 and 42.4 Gt in 2035.[31] Carbon dioxide emissions of 13 Gt in the year 2020 were expected for Asia, an increase of 38% over 2007. Yet on the basis of 2012 coal tonnages of 3.8 Gt in China and 0.64 Gt in India, the emissions from coal usage in these two countries have already attained that level using the common conversion factor of 2.93 tonnes of CO_2 to coal.

Under consideration of all greenhouse gas effluents, a study issued by the Belgian government in 2010 placed CO_2 equivalent emissions per year (termed $GtCO_2eq/yr$) at 48 Gt.[32] With reference to the Copenhagen Accord of 2009, it was noted that "today's emission levels exceed those envisaged as being desirable in 2020 by roughly 4 $GtCO_2eq/yr$ (±2 $GtCO_2eq$), requiring the peaking of global emissions by approximately 2015 in order to achieve at least a likely chance of limiting warming to below 2°C".

A report by the Netherlands Environmental Assessment Agency for the Joint Research Centre of the European Commission notes that a record amount of 34 billion tonnes of carbon dioxide was emitted in the year 2011, with emissions rising by an average of 2.7% per year over the last decade.[33] Maria van der Hoeven, Executive Director of the IEA, has concluded that because of "ever-increasing emissions of greenhouse gases" and undiminished carbon intensity "the global energy system is on an unsustainable path".[34]

29 Parker, Mario (November 18, 2010): "Alpha Says It Wants to Expand Coking Coal Resources"; Mehrotra, Kartikay and Rajesh Kumar Singh (December 21, 2010): "India to Seek Coal Mines in Africa to Plug Shortfall in Domestic Supplies". Bloomberg.

30 IEA statistics referenced at the website of the World Coal Association: www.worldcoal.org

31 Energy Information Administration (July 2010), op. cit., p. 123.

32 Johansson, Daniel J.A., et al. (October 2010): Scientific Perspectives after Copenhagen. Government of Belgium: Brussels, p. 12.

33 Olivier, Jos G.J. et al. (2012): Trends in global CO_2 emissions. PBL Netherlands Environmental Assessment Agency: The Hague, p. 6.

34 Van der Hoeven, Maria (April 16, 2013): "The push for clean energy has stalled". Huffington Post: New York.

2. Countermeasures for CO_2 Reduction

Renewable technologies and energy efficiency measures may supplement or alter existing strategies of energy deployment, but they have proved incapable of supplanting them. Fossil fuels offer the logistical advantage of incorporating their own storage medium, while all non-carbon energy sources except biomass require immediate consumption or ancillary storage, raising the final costs of energy utilisation.

While global reserves of fossil fuels may have been widely exhausted by the end of the 21st century, any restriction of their current deployment invariably leads to stockpiling, which is another advantage of inherent storage capability. Temporary price reductions subsequently enable former levels of market penetration to be regained and ultimately exceeded.

Anticipatory responses appropriate for inhibiting unrestrained market behaviour have been outlined in The Stern Review on the Economics of Climate Change contracted by the Chancellor of the Exchequer of the United Kingdom in 2006.[35] The report's fundamental premise is that climate effects may only be partially experienced "over the next 40 or 50 years", while "what we do in the next 10 or 20 years can have a profound effect on the climate in the second half of this century and in the next". The expense of the required proactive measures is estimated at 1% of yearly global gross domestic product (GDP), while the consequences of inaction might ultimately result in GDP burdens of 5%, or more.

The methodology employed for the Stern Review has been questioned by the Harvard economist Martin L. Weitzman for emphasising "optimistically-low expected costs of mitigation and pessimistically-high expected damages from greenhouse warming".[36] Nevertheless, the study provides substantial reasons for evaluating climate change and the means of controlling greenhouse gas emissions.

2.1. Planetary Engineering

Global warming trends might hypothetically be moderated by blocking a portion of the sun's rays using extraterrestrial reflectors, or by altering the albedo (reflection coefficient) of the Earth's surface to reduce infrared radiation. However, such techniques would not reverse biological imbalances caused by CO_2 and other anthropogenic effluents. Engineered global cooling might also lower average winter temperatures, promoting additional fossil fuel usage.

It would alternatively be possible to scrub carbon dioxide directly from ambient air using chemical conversion or gas separation processes. This approach would neutralise CO_2 emissions regardless of origin. Although corresponding technical proposals have existed for half a century, experiments at

35 Stern, Nicholas (2007): The Stern Review on the Economics of Climate Change. Cambridge University Press: Cambridge, p. xv.

36 Weitzman, Martin L. (2007): The Stern Review on the Economics of Climate Change. Department of Economics, Harvard University: Cambridge, p. 3.

the University of Calgary and the Idaho National Laboratory have thus far only demonstrated the functional plausibility of using sodium carbonate for the required gas capture arrays.[37]

Plant life serves as temporary CO_2 storage media until decay releases the captured carbon compounds. By harvesting trees, burying them in exhausted coal pits or other deep depressions, and permanently sealing these repositories, the carbon released into the atmosphere by fossil fuel combustion could be subsequently withdrawn.

For such proposals to be viable, however, the economic value of CO_2 remediation would need to exceed attainable forest product revenues. According to the German agricultural ministry, the wood commonly used in building construction sequesters about one tonne of carbon dioxide per cubic metre. With international trading prices for wood ranging up to several hundred dollars, any major strategic withdrawal of forest products for carbon encapsulation would not be commercially feasible. Enduring benefits for the environment may be more easily realised by substituting wood for cement and other high-energy building materials.

2.2. Policy Responses to Global Warming

The European Union is committed to diminishing greenhouse gas emissions by at least 20% by 2020, rising to 30% if countries in other parts of the world agree to achieve "comparable emission reductions" in the interest of climate protection.[38] The Emissions Trading Scheme (ETS) has been instituted by Directive 2009/29/EC to achieve "a predictable path" for controlling emissions in EU Member States.[39] All power plants and other stationary installations exceeding an annual threshold level of 25,000 tonnes of carbon dioxide equivalent (CO_2e) are allocated emission allowances totalling 21% less in the year 2020 compared with 2005. The Directive specifies that "full auctioning should be the rule from 2013 onwards" for power plants, with "the increased cost of CO_2" passed on to customers. Fossil fuel transactions are also taxed by individual Member States, increasing the cost of usage for lowering emissions from all sources.

In 2008, the GHG inventory of the EU-27 was 4.94 Gt,[40] only about a tenth of global totals estimated by the Belgian government.[41] Russian President

37 Mahmoudkhani M. et al. (2009): "Low energy packed tower and caustic recovery for direct capture of CO_2 from air". Energy Procedia, pp. 1535 - 1542.

38 Commission of the European Communities (January 23, 2008): 20 20 by 2020. Europe's climate Change opportunity. EU: Brussels, p. 2.

39 Commission of the European Communities (April 23, 2008): Directive 2009/29/EC amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community. Official Journal of the European Union: Brussels.

40 European Environment Agency (2010): Annual European Union greenhouse gas inventory 1990–2008 and inventory report 2010. Executive summary. EEA: Copenhagen, p. 10.

41 Johansson, Daniel J.A., et al. (October 2010), op. cit., p. 12.

Dmitry Medvedev's chief climate change adviser, Alexander Bedritsky, noted in 2010 that the 40 industrialised nations committed to the Kyoto Protocol represented only 28% of global emissions.[42] "28 percent of the world cannot change anything," Bedritsky concluded. "The burden on the climate will grow."

The Swiss Eidgenössische Technische Hochschule (ETH Zürich) has calculated that a maximum of 1,000 Gt of carbon dioxide may be released into the atmosphere between the years 2000 and 2050 before the critical 2ºC global warming limit is surpassed with a probability of 0.75.[43] By 2012, however, an additional 419 Gt of CO_2 had already been emitted. Ongoing usage trajectories indicate that all permissible carbon dioxide emissions will have been expended by 2030, with subsequent fossil fuel consumption raising global temperatures past the two degree limit.

In its annual Low Carbon Economy Index, PricewaterhouseCoopers LLP of the United Kingdom determined in 2012 that "the required improvement in global carbon intensity to meet a 2˚C warming target has risen to 5.1% a year, from now to 2050", adding that "not once since World War 2 has the world achieved that rate of decarbonisation".[44] The task now confronting Mankind was "to achieve it for 39 consecutive years".

Nations with the greatest greenhouse gas levels, notably China, the United States, and India, have declined to adopt overall emission ceilings. Efficiency programmes in non-compliant countries may diminish carbon intensity per unit of gross national product (GNP),[45] but their net effect is generally neutralised by ongoing economic growth.

Reduced carbon dioxide levels in the United States that reflect increased natural gas usage are expected by the EIA to return to 2005 levels by 2027.[46] California is pursuing greenhouse gas reduction policies in confronting climate-related precipitation changes in the Sierra Nevada mountain range.[47] The state has introduced an emissions trading scheme for electricity and industrial installations beginning in 2010, and for the distributors of fuels in 2015.[48]

However, carbon reduction is particularly difficult to achieve in regions of the world with abundant fossil fuel reserves, rising populations, or practiced

42 Humphries, Conor (September 23, 2010): "Kremlin Adviser Says Kyoto Can't Stop Climate Change". Reuters.

43 ETH Zurich (May 4, 2009): "Climate Change: Halving Carbon Dioxide Emissions By 2050 Could Stabilize Global Warming". Science News: Washington.

44 PricewaterhouseCoopers LLP (2012): Too late for two degrees? PwC: London, p. 1.

45 Stanway, David (January 13, 2011): "China Regions To Have Binding CO_2 Targets: Official". Reuters.

46 Energy Information Administration (December 16, 2010): AEO2011 Early Release Overview. EIA Washington, pp. 9 - 10.

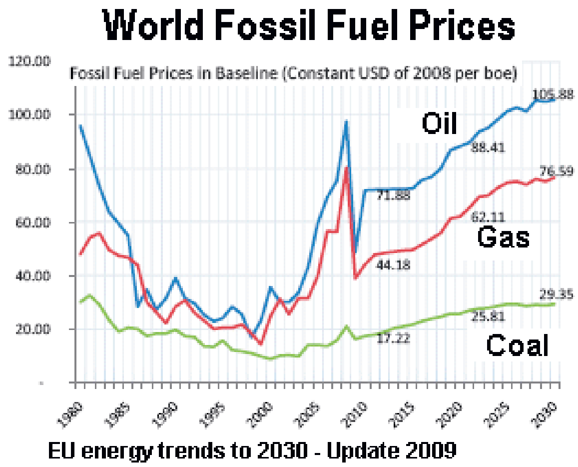
47 Gwynne, Peter (May-June 2008): "Preparing ground for global warming". Research-Technology Management: Arlington.

48 Air Resources Board (October 27, 2010): "ARB Emissions Trading Program Overview". California Environmental Protection Agency: Sacramento.

denial of global warming. Conversely, widespread resource deficiency in the European Union has stimulated price-driven efficiency strategies for reducing energy imports and associated emissions, as exemplified by the ETS.

In a March 2009 German study, McKinsey & Company assumed that CO_2e trading allocations (certificates) would cost 35 euro per tonne (€/t) in 2020 and 40 €/t in 2030.[49] The inherent inaccuracy of these expectations is indicated by the projection of 25 €/t for 2010, twice the ETS trading levels actually attained. An EU analysis released in August 2010 predicted allocation prices rising only to 16.5 €/t in 2020 and 18.7 €/t in 2030.[50]

McKinsey had relied on a significantly higher "median carbon price of € 35 per tonne CO_2" in assessing the international prospects of carbon reduction funding.[51] Ongoing allocation oversupply instead has continually diminished ETS revenues. On April 16, 2013, a plenary session of the European Parliament considered a recommendation of the European Commission to temporarily eliminate some of the excessive certificates responsible for the decline.[52] When the proposal was rejected by 19 votes, ETS prices at the European Energy Exchange (www.eex.de) immediately dropped from 4.67 €/t to 2.64 €/t the following day.



Under Article 10(a) 8 of the revised Emissions Trading Directive 2009/29/EC, 300 million allowances (NER300) have been dedicated to financing the research and development of technologies for reducing emissions. However, regular market responses to climate change continue to be impeded by the cost advantages of older, debt-free coal power stations, particularly at low ETS levels. Coal power generation is also becoming more competitive compared with increasingly costly oil and natural gas, overtaking oil in 2013 as the world's most widely used fuel. Eliminating coal from the energy equation requires cost-effective substitutes that are intricate to implement, since the centralised attributes of large-scale energy generation, storage, and distribution must be supplanted by a multiplicity of diminutively scaled substitutes requiring increased capital outlays.

In a market context, ETS allowance prices and the costs of remedial technologies can never exceed the combined monetary benefits they are capable of providing. In 2002, the British Department of Environment Food and Rural

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49 McKinsey & Company, Inc. (March 2009): Kosten und Potenziale der Vermeidung von Treibhausgasemissionen in Deutschland. McKinsey: Berlin, p. 5.

50 Capros, P. et al. (August 4, 2010): EU energy trends to 2030 - Update 2009. European Commission: Brussels, p. 38.

51 Nauclér, Tomas et al. (September 22, 2008): Carbon Capture and Storage: Assessing the Economics. McKinsey: London, p. 44.

52 Garside, Ben and Barbara Lewis (April 17, 2013): "EU parliament rejects carbon market rescue fix". World Environment News: Sydney.

Affairs (DEFRA) surveyed previous estimates of the Social Cost of Carbon (SCC) expressing the comprehensive effects of carbon emissions on social and economic existence.[53] By 2007, a SCC figure of 42 €/t CO_2 had been estimated for the year 2020,[54] which is higher than ETS projections.

The alternative Shadow Price of Carbon (SPC) is used to indicate the cost of technologies and policies necessary at a specific point in time for achieving a future atmospheric CO_2 concentration target.[55] The British SPC of £25/tCO_2e set in 2007 then corresponded to a price range of roughly 30 - 40 €/t CO_2e that would have been necessary for achieving a CO_2 concentration of between 450 and 550 ppm under the assumption of equitable international participation.

These earlier estimates have since been eclipsed by rising fossil fuel usage and accompanying carbon dioxide emission levels. The United Kingdom abandoned calculation of the SCC altogether in 2009, basing its carbon price estimates instead on mitigation costs in "a range of $41 - $124 per ton of CO_2, with a central case of $83".[56] However, submitting to current ETS penalties invariably proves less expensive than financing their avoidance. The global dimension of climate change nevertheless requires CO_2-reduced technologies that are affordable for less affluent regions, but which cannot be financed from expected carbon market proceeds.

Eastern European countries have been alleviated of equitable participation in emission-control strategies due to the decline of heavy industry and fuel-switching after 1990. The "metamorphosis of the Hungarian economy", for instance, has allowed Kyoto-based emission targets to be overachieved, so that "the country and its (energy) industry are not forced to implement any measures" similar to Western European fulfillment strategies.[57]

The European Commission has identified southern Europe, the Mediterranean basin, outermost regions, and the Arctic as being most vulnerable to climate change.[58] Mountain ranges, islands, coastal and urban areas, densely populated floodplains, and small island states are especially susceptible. Maritime nations are likewise confronted with the effects of ocean acidification. Many regions least responsible for the dominance of fossil fuel usage are particularly affected by its consequences. An appropriately calculated social cost of carbon could compensate for severe cases by postulating migration or

53 Clarkson, Richard and Kathryn Deyes (January 2002): Estimating the Social Cost of Carbon Emissions. Department of Environment Food and Rural Affairs: London.

54 O'Brien, Neil and Hugo Robinson (October 2008): The EU Climate Action and Renewable Energy Package: Are we about to be locked into the wrong policy? Open Europe: London, p. 2.

55 Price, Richard et al. (December 2007): The Social Cost Of Carbon And The Shadow Price Of Carbon: What They Are, And How To Use Them In Economic Appraisal In The UK. Economics Group, Department for Environment, Food & Rural Affairs: London, pp. 3 - 8.

56 Ackerman, Frank and Elisabeth A. Stanton (April 1, 2010): The Social Cost of Carbon. Economics for Equity and the Environment Network: London, p. 17.

57 Perger, András (November 2009): The role of coal in the Hungarian electricity sector. Energia Klub: Budapest, p. 29.

58 Commission of the European Communities (April 1, 2009): Adapting to climate change: Towards a European framework for action. EC: Brussels, p. 4.

financial compensation. Yet such considerations have been precluded by the failure of the European carbon market, which the British journal The Economist predicts “will reverberate around the world”.[59]

2.3. European Strategic Energy Technology (SET) Plan

The European Commission has predicted that under “business as usual” conditions, EU reliance on imported energy will have grown from 50% in the year 2007 to 65% in 2030. Imports of gas are “expected to increase from 57% to 84% by 2030, of oil from 82% to 93%”.[60] Since domestic resources are in decline, reducing import dependency would inevitably diminish fuel usage and accordingly lower greenhouse gas emissions. The Commission has commensurately formulated state-of-the-art policies for “transforming Europe into a highly energy efficient and low CO_2 energy economy”. The resulting European Strategic Energy Technology (SET) Plan announced in 2007 is intended to “put EU industry at the forefront of the rapidly growing low-carbon technology sector”.

The SET-Plan consists of large-scale programmes that link research, development, and deployment among the Member States. Up to €31 billion are to be devoted by 2020 to renewable energy technologies.[61] An additional €5 - €10 billion have been earmarked for “sustainable nuclear energy”, and €12 - €14 billion for implementing smart energy infrastructures designed to accommodate changing conditions of supply and demand. As CO_2-free technologies are increasingly deployed, up to 35% renewable electricity must be fed into the power grid within the current planning timeframe.

These measures alone would be insufficient to eliminate continuing EU dependency on fossil fuels for over three-quarters of energy usage. Switching to low-carbon natural gas could enable CO_2 emissions to be reduced in particular applications. However, considerably lower prices for coal and particularly domestic lignite (brown coal) continue to inhibit this transition. The cost differences are diminished to some degree by the greater capital expenditures necessary for sulphur dioxide and dust filters in solid-fuel power plants. On the other hand, the plants can often be located near coal and lignite mines (“mine-mouth” or “pithead” plants), greatly reducing transportation and bunkering costs. Many mining regions commensurately prevail as centres of electrical power distribution, contrasting with the multiple grid architectures inherent to intermittent and widely distributed renewable power generation.

59 The Economist (April 20, 2013): “ETS, RIP?”. Economist: London, p. 61.

60 Commission of the European Communities (January 10, 2007): An Energy Policy for Europe. EC: Brussels, pp. 3 - 8.

61 Commission of the European Communities (October 10, 2009): Communication on Investing in the Development of Low Carbon Technologies (SET-Plan). A Technology Roadmap. Staff Working Document. SEC(2009) 1295. EC: Brussels, p. 8.

3. Carbon Capture and Storage (CCS)

Rather than abandoning fossil fuel infrastructures, the EU is striving to sustain them by diminishing their contribution to climate change. The European Commission has asserted that "coal can continue to make its valuable contribution to the security of energy supply and the economy of both the EU and the world as a whole only with technologies allowing for drastic reduction of the carbon footprint of its combustion".[62] Carbon dioxide may be prevented from reaching the atmosphere by capturing the emissions at the point of combustion using suitable filter technology and transporting them to a storage repository or sink, generally a deep geological formation that is subsequently sealed for permanent isolation (sequestration) from the biosphere.

The SET-Plan provides for funding of up to 12 innovative large-scale carbon capture and storage (CCS) projects. Budgeting projected at €10.5 to €16.5 billion encompasses both public subsidies and private capital outlays. The demonstration projects are intended for investigating a wide range of technologies ahead of commercial implementation, which is anticipated after 2020. On December 9, 2009, funding for six projects was announced,[63] each with a Community allocation of up to €180 million.

A CCS symposium at the Massachusetts Institute of Technology (MIT) in 2009 simultaneously concluded that there is "no credible pathway towards stringent GHG stabilisation targets without CO_2 emissions reduction from existing coal power plants, and the United States and China are the largest emitters."[64]

However, coal-based installations possess widely different prerequisites for CCS implementation. The Carbon Capture Journal has noted that "current CCS projects have the luxury of conveniently positioning themselves within arm's reach of their most essential resources (fuel sources, CO_2 sources, and suitable storage sites)".[65] As additional ventures develop, however, "it will become more and more difficult to avoid intersections with population, land development, and local resource scarcity". The costs of conventional coal generation remain quantifiable, but the economic possibilities of subsequent CO_2 reduction involve highly divergent capacities for local storage, as shown in the following table compiled for the European Commission:[66]

62 Commission of the European Communities (January 10, 2007): Sustainable power generation from fossil fuels: aiming for near-zero emissions from coal after 2020. EC: Brussels, p. 4.

63 Commission of the European Communities (December 9, 2009): Commission approves over €1.5bn for 15 CCS and offshore wind projects to support European economic recovery. EC: Brussels.

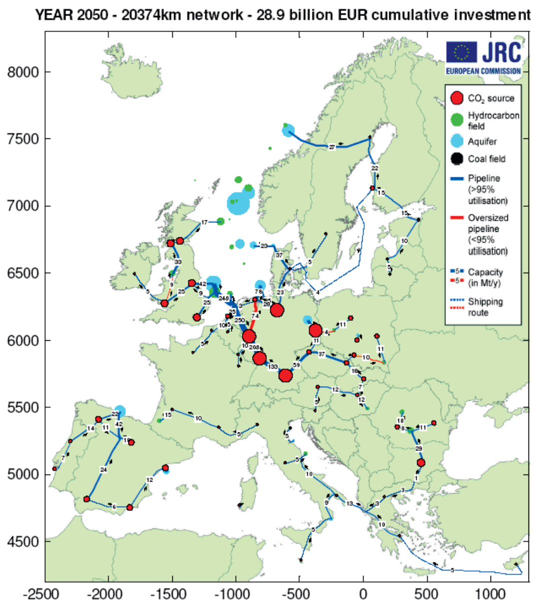
64 MIT Energy Initiative (March 23, 2009): Retrofitting of Coal-Fired Power Plants for CO_2 Emissions Reductions. Massachusetts Institute of Technology: Cambridge, p. 5.

65 Forbes, Sarah (January 10, 2011): "China's growing CCS activities in action". Carbon Capture Journal. Global CCS Institute: Canberra.

66 Morbee, Joris (July 6 - 8, 2011): "International transport of captured CO_2: Who can gain and how much?". International Energy Workshop, Stanford: Palo Alto, p. 3.

Potential EU CO_2 Capture and Storage Capacities in 2050, Mt/a

	CO_2 capture	CO_2 storage		CO_2 capture	CO_2 storage
Austria	8	0	Netherlands	52	40
Belgium	30	0	Norway	0	636
Bulgaria	25	0	Poland	147	17
Czech Republic	62	0	Portugal	17	0
Denmark	15	14	Romania	43	88
France	27	17	Slovakia	16	0
Germany	337	111	Slovenia	6	0
Hungary	17	9	Spain	80	108
Italy	89	61	United Kingdom	173	315
Total				1145	1416



Due to the geographic distances between many emission sources and the geological formations considered suitable for CO_2 storage, the European Commission has drawn up plans for an interconnecting "trans-European CO_2 transport network".[67] By the year 2050, a 20,347 km pipeline network has been envisioned to convey 900 Mt of carbon dioxide from power plants and industrial installations largely to offshore locations, equivalent to three-quarters of the total CO_2 emitted by the EU power sector. Cumulative capital costs estimated at 28.9 billion euro (2010 value) would be apportioned according to relative emissions levels, predestining Germany as the main capital source with 58% to 66% of total investments.[68] Norway, by contrast would accrue revenues as the chief CO_2 sink of 11.7 to 16.6 billion euro, constituting 42% to 59% of all outlays rendered by source countries.

3.1. CCS Realisation Costs

The 2009 MIT symposium projected that retrofitting existing power stations using "current and evolutionary amine-based capture technology" would involve costs "generally in the \$50-70/ton of CO_2 range for the Nth-plant" for capturing CO_2 alone, without subsequent transport and storage.[69] The ex-

67 Morbee, Joris et al. (2010): The evolution of the extent and the investment requirements of a trans-European CO_2 transport network. European Commission. Directorate General, Joint Research Centre, Institute for Energy: Petten, pp. 9 - 10.

68 Morbee, Joris (July 6 - 8, 2011), op. cit., p. 11.

69 MIT Energy Initiative (March 23, 2009), op. cit., p. 6.

pense of an entire CCS process chain in the United States has been estimated at $125 per ton of CO_2.[70] The US Department of Energy (DOE) projects that "carbon capture will add over 30 percent to the cost of electricity for new integrated gasification combined cycle (IGCC) units and over 80 percent to the cost of electricity if retrofitted to existing pulverised coal (PC) units".[71]

The German Advisory Council on the Environment (SRU) quotes figures from various studies between 30 and 64 €/t of avoided CO_2 for new installations and 53 to 97 €/t for retrofits.[72] A study group at the Technical University in Berlin has determined that economical geological CO_2 storage could be achieved in Germany for industrial installations only at an allocation price of at least 50 €/t for selected industrial installations and 75 €/t for the power sector.[73] The German Institute for Economic Research (DIW) calculates that electricity generation costs would increase by 48 - 92% when produced by coal plants with CO_2 capture.[74]

An investigation coordinated by the VTT Technical Research Centre of Finland has determined that a reduction of that country's carbon dioxide emissions by 10 - 30% "could be achieved with CCS technology by 2050" only if "the price level for emission allowances rises to 70 - 90 euros per tonne carbon dioxide" by that time.[75]

The Bellona Foundation, a Norwegian-based NGO, likewise substantiates the adoption of CCS with an ETS model rising to 50 €/t in 2030 and 90 €/t in 2050.[76] These forecasts are assumed to reflect a "relatively conservative future EU climate policy, which imposes a slow and steady reduction in the European cap on CO_2 emissions through 2050". Nonetheless, Bellona notes that raising emissions prices to the level required for CCS investments has proved to be "incredibly difficult" as a political objective.[77]

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70 Aston, Adam (November 13, 2009): "China and U.S. Energy Giants Team Up for 'Clean Coal'". Business Week.

71 U.S. Department of Energy: "Retrofitting the Existing Coal Fleet with Carbon Capture Technology". www.fossil.energy.gov/programs/powersystems/pollutioncontrols/Retrofitting_Existing_Plants.html.

72 German Advisory Council on the Environment (April 2009): Abscheidung, Transport und Speicherung von Kohlendioxid. Stellungnahme. SRU: Berlin, p. 27.

73 Oei, Pao-Yu et.al (2011): "CO_2 Speicherung in Deutschland Eine Brückentechnologie als Klimalösung?". Workgroup for Economic and Infrastructure Policy, Technische Universität Berlin: Berlin, p. 1.

74 Herold, Johannes and Christian von Hirschhausen (September 8, 2010): "Hohe Unsicherheiten bei der CO_2-Abscheidung: Eine Energiebrücke ins Nichts?". German Institute for Economic Research (DIW): Berlin, p. 4.

75 VTT Technical Research Centre of Finland (November 11, 2010): "VTT: CCS technology could have significant role in reducing Finnish greenhouse gas emissions". VTT: Espoo.

76 Bellona Environmental CCS Team (2010): A Bridge to a Greener Greece. Bellona Foundation: Greece, p. 16.

77 Helseth, Jonas (December 2010): "Die Kohle für CCS". Politische Ökologie 123: Munich, p. 28.

All pricing assumptions issued for CCS thus greatly exceed the attainable prerequisites for power plant investments. The European Commission concluded in a communication released in March 2013 that at "current ETS prices well below €40/tCO_2, and without any other legal constraint or incentive, there is no rationale for economic operators to invest in CCS".[78] Although higher calculations for the shadow cost of carbon could provide greater impetus for developing the corresponding technologies, the number of countries capable of financing the necessary equipment purchases would be conversely reduced.

Conventional coal power stations continue to be constructed under the pretext that future corrective technologies will ultimately make coal combustion environmentally tolerable. However, only "capture ready" plants with the necessary technical prerequisites would qualify for retrofits. Processing over a thousand tonnes of emissions per hour requires a separate chemical factory as large as an airplane hangar that exceeds the space available at many sites. The parasitic energy losses incurred by CO_2 capture and compression necessitate supplementary generation, additional fuel, and disproportionally greater amounts of cooling water to restore original grid capacity.

3.2. CCS Precedents

The production and use of carbon dioxide is established practice in a broad range of commercial applications. The World Coal Institute (WCI) has emphasised that "CCS is not a new or emerging technology". [79] It instead employs "a suite of component technologies from the petroleum, chemical, and power generation industries that already exist and are commercially available. CCS is simply the novel integration and optimisation of these technologies for the purpose of climate change mitigation." Existing processes nevertheless require considerable public subsidies for CCS pilot applications that will become superfluous only if less costly technologies evolve or commercial revenue streams ensure operating profitability.

CO_2 capture is already employed to purify natural gas and to improve the efficiency of hydrocarbon extraction. In the Algerian Sahara, carbon dioxide is separated from natural gas produced at the In Salah field with a multi-stage, proprietary aMDEA (activated methyl diethylamine) process licensed by BASF.[80] The raw natural gas stream contains an average CO_2 volume concentration of 5.5% that is reduced to 0.3% for meeting export specifications, a process known as natural gas sweetening. The high underground gas pressure provides the energy required for carbon dioxide separation and for subsequent pipeline transport.

78 Commission of the European Communities (March 27, 2013): Communication on the Future of Carbon Capture and Storage in Europe. COM(2013) 180 final. EC: Brussels, p. 16.

79 World Coal Institute (November 6, 2009): Securing the Future. Financing Carbon Capture & Storage in a Post-2012 World. WCI: London, p. 6.

80 www.insalahco2.com.

The carbon dioxide concentration of raw natural gas in North America must be reduced to 2 - 4% depending on pipeline product specifications.[81] The CO_2 obtained from gas processing and, to a lesser extent, from industrial sources is routinely injected into natural gas formations and (together with water) into oil fields to maintain extraction pressure and increase production volumes. The corresponding techniques are respectively termed Enhanced Gas Recovery (EGR) and Enhanced Oil Recovery (EOR). An analogous Enhanced Coalbed Methane (ECBM) process is widely employed in China, where 30 Gt of CO_2 might ultimately be injected for extracting CH_4 from deep coal seams.[82] All such processes are covered by the term Enhanced Hydrocarbon Recovery, which also includes pressurising techniques such as steam injection and underground oxidation for extracting residual amounts of fossil fuels from geological formations.

In Germany, an EGR project was announced in 2007 by Vattenfall Europe Technology Research GmbH for providing carbon dioxide from lignite power generation in Brandenburg to a largely depleted gas field in Saxony-Anhalt operated by Erdgas Erdöl GmbH.[83] Following feasibility verification using tank truck deliveries, a 300-km CO_2 pipeline was to be constructed for extracting an additional 20 billion cubic metres of natural gas. The project was subsequently terminated due to local protests over possible leakages along the transport route as well as from undetected geological faults and well holes abandoned after earlier gas drilling operations.

EOR is also termed "tertiary oil recovery", since CO_2 miscible flooding is additionally employed after the conventional extraction and water injection phases. In a survey published in 2010, there were 129 CO_2 EOR projects operating around the world, 114 of which were located in the USA.[84] 280,000 barrels of crude oil were being recovered per day by CO_2 injection in the American Midwest and Gulf Coast regions, constituting 6% of total domestic production,[85] and 1.3% of national consumption.[86]

CCS project proposals largely reflect expected EOR returns, with Canada leading new investment due to the proximity of oil fields to industrial operations.[87] In 2010, more than 13,000 CO_2 EOR wells and 3,900 miles (over 6,200 kilometres) of high-pressure CO_2 pipelines were already in operation

81 Foss, Michelle Michot (December 2004): Interstate Natural Gas - Quality Specifications & Interchangeability. Center for Energy Economics: Sugar Land, p. 15.

82 Pan, Kexi (August 22, 2005): "The Depth Distribution of Chinese Coal Resource". Fudan University: Shanghai.

83 Thiel, Holger (October 17, 2007): "Kohlendioxid kann Erdgasförderung in der Altmark verlängern". Volksstimme: Magdeburg.

84 Dooley, J.J. et al. (July 2010): CO_2-driven Enhanced Oil Recovery as a Stepping Stone to What?, Pacific Northwest National Laboratory: Richland, p. 4.

85 Meyer, James P.: Summary of Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR) Injection Well Technology. American Petroleum Institute: Houston, pp. 5 - 6.

86 Denbury Resources, Inc. (May 2011): Annual Report. Shedding Light on a Transformed Denbury. www.denbury.com, p. 7.

87 Enhance Energy: The Alberta Carbon Trunk Line Project Fact Sheet. Enhance Energy, Inc.: Alberta.

in the United States. The CO_2 employed in these operations has usually been separated from natural gas during extraction, with only 17% originating from manmade sources such as petrochemical processing. More than half of the injected CO_2 returns to the surface mixed with extracted oil, enabling it to be recycled for subsequent EOR cycles until permanently retained in the geological oil formations. The requirement for fresh CO_2 is correspondingly reduced.

A survey of US oilfields has indicated that an average of 3.6 additional ("incremental") barrels of oil could be produced by injecting one ton of CO_2 under present best practices, and 4.5 barrels for next generation technologies.[88] In the Texas Gulf Coast region, about 1.5 billion stock barrels of oil would be recoverable by flooding candidate fields with 200 million tons of CO_2,[89] an EOR ratio of 1 to 7.5.

At the Great Plains Synfuels lignite gasification plant in Beulah, North Dakota USA, captured CO_2 is transported through a 350-mile (about 600-km) pipeline system across the Canadian border for injection at the Cenovus oil field in Weyburn and Apache at Midale in southeast Saskatchewan. An additional 155 million barrels of crude oil can be extracted by 2035 at Weyburn using 30 million tons of CO_2.[90] The Midale field will be storing 10 Mt of CO_2 for recovering 60 million barrels of oil. In the Canadian province of Alberta, the current CO_2 flooding ratio is 1 to 3.25.[91]

In China, the production of 28 oil wells at the Jilin formation is increased using 10 injection wells with carbon dioxide separated from natural gas exhibiting 10% - 14% CO_2 content.[92] The carbon dioxide at the Daqing Oil Field has been separated from natural gas with 20% CO_2, at the Shengli Oil Field from a power plant exhaust stream containing 13.5% CO_2.

Injection may also be performed to avoid carbon taxes, which were introduced in Sweden in 1991 ($100 per ton of CO_2 at that time) and subsequently in Norway. The Sleipner West gas field in the North Sea was dedicated in 1996 as the world's first offshore CCS plant for this purpose. About one million tonnes of carbon dioxide per year are sequestered in a high-injectivity saline aquifer, termed "Utsira Sand", at a depth of 1,000 metres for yearly tax savings of €43 million.[93] The sand is not conjoined with the hydrocarbon reservoirs at 3,500 metres, which deliver natural gas at a

88 Advanced Resources International (March 10, 2010): U.S. Oil Production Potential from Accelerated Deployment of Carbon Capture and Storage. Department of Energy: Reston, p. 12.

89 Essandoh-Yeddu, Joseph and Gürcan Gülen (2009): "Economic modeling of carbon dioxide integrated pipeline network for enhanced oil recovery and geologic sequestration in the Texas Gulf Coast region". Energy Procedia 1, p. 1604.

90 Carbon Capture Journal (July 21, 2010): "U.S. and Canada renew funding for Weyburn-Midale project". Global CCS Institute: Canberra.

91 Alberta Carbon Capture and Storage Development Council (March 2009): Accelerating Carbon Capture and Storage Implementation in Alberta. Alberta Energy: Edmonton, p. 27.

92 Energy Information Administration (July 2010), op. cit., p. 215.

93 Anwar, André (July 20, 2009): "Norwegens CO_2 bald unter der Erde". Foundation for Global Sustainability: Zürich.

pressure of 100 bar with CO_2 content varying between 4 - 9.5% by volume. The CO_2 is absorbed in an amine contact column and then stripped from the amine in a desorption column for injection into the site aquifer.

3.3. CCS Perspectives in Industry

About 11% of total CO_2 emissions in the EU are ascribed to the four industrial sectors indicated in the table.[94]

Industrial CO_2 Emissions in the European Union, 2007

Sector	Refining	Iron and Steel	Chemicals	Cement	Total
Million tonnes	134.6	115.6	30.3	173.6	4,186.7
Contribution	3.2%	2.8%	0.7%	4.1%	100%

Since industrial installations are generally smaller than electrical power stations, the avoidance of ETS obligations using emissions mitigation technologies would generally involve higher specific costs. Individual plants may also be distant from CO_2 transportation infrastructures and storage sites, imposing disproportionate financial risks on CCS implementation. While domestic electrical power generation is integral to the economic security of most countries, relocation or outsourcing could become an attractive option for manufacturing industries unable to bear the costs of emissions remediation.

A study commissioned by the German Green Party has projected the use of CCS for crude steel and cement clinker production after 2030, potentially contributing 4% of total greenhouse gas emission reductions in the EU from 2008 to 2050.[95] The EU ULCOS (Ultra Low CO_2 Steelmaking) consortium, founded in 2004 as "a consortium of 48 companies, universities and laboratories across Europe", originally intended to achieve a 30 - 70% reduction of carbon dioxide emissions in steel making by 2050 using a variety of technologies.[96]

In October 2011, an application of consortium partner ArcelorMittel was approved for geological storage research in saline aquifers over 1,000 metres below a steel plant at Florange in the French Lorraine.[97] The venture was later suspended "for technical reasons" at the end of 2012.[98] ArcelorMittel emphasised that the decision "in no way means the Ulcos project is being abandoned". However, EU parliamentarian Chris Davies observed "that not one single new CCS scheme is set to proceed", since governments in the Netherlands, Romania, and Poland had already withdrawn project funding.

94 Schmid, Victoria and André Lacerda (November – December 2010): "CCS perspectives in energy intensive industries". Carbon Capture Journal. Global CCS Institute: Canberra, pp. 11 - 12.

95 Matthes, Felix Christian et al. (January 2011): The Vision Scenario for the European Union 2011 Update for the EU-27. Öko-Institut: Berlin, p. 44.

96 AlcalorMittel Flat Carbon (November 2009) Update. ArcelorMittal Flat Carbon Europe S.A.: Luxembourg,p. 21.

97 Tageblatt.lu (October 19, 2011): "Auf der Suche nach einer CO_2-Lagerstätte". Tageblatt: Luxembourg.

98 EurActiv (December 6, 2012): "ArcelorMittal buries Europe's carbon storage hopes."

3.4. Unfounded Expectations for CCS

The Swedish state corporation Vattenfall GmbH operates four lignite power stations in eastern Germany that emit a total of 57 Mt of CO_2 per year.[99] In view of both ETS penalties and anticipated market opportunities for remedial technologies, Vattenfall has actively supported power plant research at Chalmers University of Technology in Gothenburg, Sweden and at Brandenburg Technical University (BTU) in Cottbus, Germany. However, many of the initial claims made for CCS[100] have been subsequently weakened or disproved.

For instance, Vattenfall's original contentions in 2001 that the cost for capture and liquefaction could be reduced to "10-13 €/ton of CO_2" and that "the avoidance cost for a whole system can be calculated to about 30 €/ton of CO_2" have not been verified. A renewed evaluation made in 2003 revealed the commercial necessity of reducing CCS costs to as low as 20 €/ton, estimated as the price of ETS allowances in 2015.[101] Since that time, however, the necessary power plant technologies have proved far more expensive to develop and deploy, resulting in a number of project cancellations worldwide.

Many proposed CO_2 repositories are also unsuitable for large-scale ventures. The Scottish Centre for Carbon Storage has established "that most oilfields in the northern North Sea cannot easily be used solely for CO_2 storage because sea water injection, commonly used to maintain field pressure during oil production, significantly reduces the amount of storage capacity for CO_2".[102]

Vattenfall maintains that CO_2 storage "would create a possibility of using coal as a fuel and still showing concern for the climate change issue". Similarly, the International Performance Assessment Centre for the Geologic Storage of Carbon Dioxide (IPAC-CO_2) in Canada has projected "that applying a CCS strategy can account for 19 per cent or almost one in every five tonnes of greenhouse gas emissions that are targeted to be eliminated by the year 2050".[103] Representatives of the coal and lignite industry routinely justify the continued research and development of CCS technologies as an appropriate response to growing coal usage in China and India. Such expectations imply that laboratory experiments may be rapidly transformed into global commercial ventures, even though the many thousands of power plants currently in operation are generally unsuitable for economical CCS implementation.

99 Michel, Jeffrey H. (February 2008): Status and Impacts of the German Lignite Industry. Swedish Air Pollution & Climate Secretariat: Gothenburg, p. 37.

100 Strömberg, Lars (October 26, 2001): "Combustion in a CO_2/O2 mixture for a CO_2 emission free process". Vattenfall: Stockholm.

101 Strömberg, Lars (October 2 - 3, 2003): "CO_2 Capture and Storage for coal based power generation – technology and economics". Vattenfall: Stockholm.

102 Glover, Anne (April 2009): Opportunities for CO_2 Storage around Scotland. Scottish Centre for Carbon Storage: Edinburgh

103 International Performance Assessment Centre for the Geologic Storage of Carbon Dioxide (January 2011): "Frequently Asked Questions". IPAC-CO_2: Regina.

A 2007 MIT study on the future of coal has speculated that China could "optimistically" become "the world's largest market for clean coal technologies".[104] It is cautioned, however, that "these technologies will add considerably to the cost of coal use, and, in the case of carbon capture and sequestration, are unlikely to be deployable on a large scale for decades". While in the case of India "there may be time to introduce cleaner, more efficient generating technologies before the greatest growth in coal use",[105] solid fuel demand in that country will likely surpass that of the United States around 2020, well before commercial CCS technologies could be broadly implemented.

A decade ago, Vattenfall's thesis that treating emissions would prove "less expensive than almost all other options including wind power, biomass, and small hydropower plants" appeared plausible due to incomplete performance evaluations of alternative technologies. By 2012, however, CO_2-neutral renewable power in Germany already constituted one quarter of total electricity supplies, often undercutting the price of conventional generation.

Vattenfall has referred to coal as "an energy source which is found all over the world, is relatively cheap, does not have the obvious security problem of oil and gas and, last but not least, is so plentiful that it will last for several hundred years". The European Commission likewise communicated to the Parliament in 2007 that coal "represents the fossil fuel with by far the largest and most widely distributed global reserves, estimated to last for some 130 years for lignite and 200 years for hard coal".[106] Under the assumption of continuing reliance on coal, it was determined in 2009 that "in scenarios without CCS, the costs for achieving climate stabilisation in 2050 are at least 70% higher than scenarios that include CCS".[107] Projections had shown that "EU emissions can be reduced by 400 million tonnes CO_2/year through CCS. This is less than energy efficiency (500 million tonnes CO_2/year) but more than renewables (200 million tonnes CO_2/year). By 2050, CCS could reduce EU emissions by up to 1.7 billion tonnes CO_2/year, depending on the extent of use of CCS." The Commission estimated that "between now and 2070 the EU will need to store about 20 billion tonnes of CO_2". That figure, however, is less than two-thirds of the total carbon dioxide emissions registered globally in a single year.

The IEA has estimated that half of the iron and steel, cement, pulp and paper and ammonia plants, and almost 80% of all fossil power plants would need to apply CCS by 2050 in order for 19% of total CO_2 savings to be realised in a comprehensive global climate protection strategy.[108] Since an additional 1,000 Gt of carbon dioxide will have likely been emitted between the begin-

104 Ansolabehere, Stephen et al. (2007): The Future of Coal. Massachusetts Institute of Technology: Cambridge, p. 70.

105 ibid., pp. 74 - 75.

106 Commission of the European Communities (January 10, 2007), op. cit., p. 4.

107 The European Commission (2009): "CO_2 Capture and Storage". EC: Brussels, p. 4.

108 International Energy Agency (2008): CO_2 Capture and Storage. A key carbon abatement option. IEA: Paris, p. 211.

ning of the century and 2030, however, an estimated 3,400 large-scale CCS operations would already be required by that time, or one new plant very two days. A report presented by the IEA in April 2013 to the "Clean Energy Ministerial" (governments representing 4.1 billion people and 80% of global CO_2 emissions) indicates that any such strategy would be unachievable.[109] There are currently only 13 large-scale CCS demonstration projects worldwide, and not one commercial plant with carbon dioxide separation.

4. CO_2 Capture Technologies

The flue gases of a coal-fired power plant typically consist of about 14% carbon dioxide, 5% oxygen (O2), and 81% nitrogen (N_2).[110] Efficient carbon capture and disposal therefore requires the CO_2 concentration of the exhaust stream to be increased sevenfold. Since coal power generation produces about one tonne of carbon dioxide per hour for each megawatt of generating capacity, a large CO_2 capture plant must be capable of processing around 200 tonnes of flue gases per minute and separating over 25 tons of carbon dioxide.

By comparison, the smokestack effluents of a natural gas power plant may contain only 4% CO_2, since the methane-based fuel consists of four hydrogen atoms bonded to a single carbon atom. Correspondingly greater flue gas volumes must be processed at higher energy losses to obtain a pure CO_2 stream for storage. Since gas-powered plants are generally smaller than coal-fired designs and operate in response to varying electricity demand, even higher costs per tonne of carbon dioxide separation may be incurred. Conversely, the effluents of a cement kiln can consist of about one-third carbon dioxide entailing lower separation costs.

In North America, where advanced flue gas treatment processes are termed "clean coal" technologies, less efficient methods of CO_2 separation are frequently employed. Partially CO_2-reduced coal plants can simulate combined cycle gas power generation under the California Greenhouse Gas Emission Performance Standard, which specifies electricity contracts with maximally 1.1 pounds (499 grams) of CO_2 per kilowatt-hour.

Partial separation is also inherent to many manufacturing and EOR operations. For instance, a 582 MW mine-mouth lignite gasification (IGCC) plant being constructed in Kemper County, Mississippi, is designed with a 65% separation efficiency for supplying three million tons of CO_2 per year to an oilfield near the Gulf of Mexico.[111] Significant quantities of sulphuric acid (135,000 t/a) and ammonia (20,000 t/a) will also be produced at the internal syngas cooling stage used for CO_2 separation. Although construction costs of $2.4 billion amount to over $4,100 per kW generating capacity, the technol-

109 Chestney, Nina (April 18, 2013): "Clean energy progress too slow to limit global warming: report". World Environment News: Sydney.

110 Chakravarti, Shrikar (May 15 – 17, 2001): Advanced Technology for the Capture of Carbon Dioxide from Flue Gases. Praxair: Tonawanda, p. 2.

111 Nelson, Matt (September 16, 2010): "CO_2 Capture at the Kemper County IGCC Project". Southern Company: Atlanta.

ogy is being studied for adoption in China,[112] where low-grade coal potentially suitable for gasification comprises nearly half the remaining domestic shallow reserves of 115 billion tons.[113]

4.1. Biofixation

Carbon dioxide capture by photosynthesis is employed in greenhouse agriculture when effluents from natural gas heaters are used to enhance plant productivity. The absorbed CO_2 ultimately returns to the biosphere in subsequent phases of organic decay. About 40% of the dry plant matter of most species consists of carbon.

In the electrical power industry, the same principle may be applied by passing smokestack effluents through an algae solution bathed in sunlight, generating organic waste used for manufacturing biodiesel fuel and ethanol, with residues suitable for animal feed.[114] High removal rates of 80% for CO_2 and 86% for NOX have been reported.

In a project termed green MiSSiON (Microalgae Supported CO_2 Sequestration in Organic Chemicals and New Energy), Vattenfall is testing various strains of microalgae for capturing carbon dioxide from lignite power plant emissions.[115] According to a company statement, the biomass produced in the process could potentially be used to produce biodiesel for motor vehicles, as a fuel for biogas power plants, or as a supplementary nutrient in fish food. In all cases, however, the captured carbon would not be permanently stored, but instead ultimately enter a subsequent oxidation process with CO_2 re-emission.

Hypothetically capturing the nearly 24 Mt of carbon dioxide emitted each year by the 3,000 MW Vattenfall lignite power station at Jänschwalde has been estimated to require a 600-square-kilometre expanse of biogeneration arrays,[116] which is 30 times the size of Germany's Frankfurt Airport, or two-thirds the area of Berlin. Implementation would therefore be impractical unless costly high-rise configurations were employed.[117]

Since the original Vattenfall project announcement refers only to sunlight used for algae photosynthesis,[118] supplementary artificial lighting would technically be required for nighttime operation owing to the continuous (base

112 Swogetinsky, Steve (December 23, 2010): "Ground broken on Kemper coal plant". The Neshoba Democrat: Philadelphia (Mississippi).

113 Heinberg, Richard and David Fridley (November 18, 2010): "The end of cheap coal". Nature. Volume 468: London, p. 369.

114 Stern.de (October 15, 2007): "Mit Algen das Klima retten". Stern: Hamburg.

115 The Local (July 22, 2010): "Vattenfall plant tests CO_2-scrubbing algae". AFP.

116 Blankennagel, Jens (July 23, 2010): "Algen fressen Kohlendioxid". Berliner Zeitung: Berlin.

117 Wick, Hanna (August 5, 2009): "Treibstoff aus Algen – mehr als ein Hype". Neue Zürcher Zeitung: Zürich.

118 Vattenfall Europe Mining AG et al. (April 6, 2010): "Bau mit Algenzucht mit Rauchgas begonnen". Vattenfall: Cottbus.

load) operation of lignite power plants. However, the theoretical maximum efficiency of photosynthesis is 6.7%, and for C3 plants such as algae merely 3.3%.[119] If electrical light is provided by a lignite power plant with 40% efficiency, scarcely more than 1% of the energy originally contained in the fuel would be available for combining flue gas carbon dioxide with water to produce glucose ($C_6H_{12}O_6$).

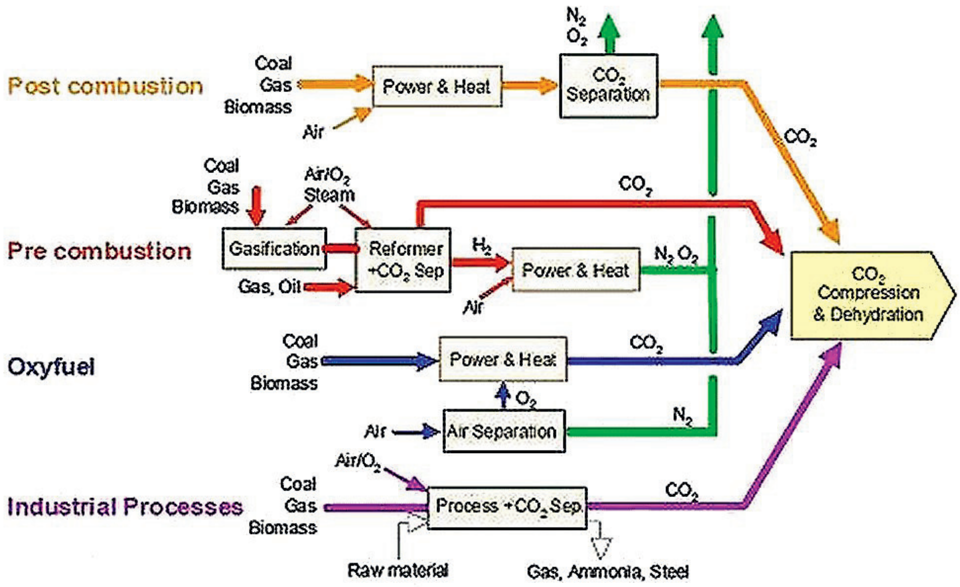
While permanent CO_2 sequestration might plausibly be implemented by increasing the growth rate of saltwater algae using chemical fertilisation, the dying biomass would need to sink to the ocean floor rather than being reintroduced into carbon cycles. In practice, enhanced algae growth instead serves to enrich prevailing food chains.

4.2. Chemically Reactive Capture

A diagram issued by the Intergovernmental Panel on Climate Change (IPCC)[120] summarises the main alternative approaches to capturing carbon dioxide from large-scale thermal plants using chemical processes.

As shown, carbon may be separated either by:

- washing carbon dioxide out of the flue gases (post-combustion),
- gasifying the fuel to oxidise the carbon in manageable form while extracting hydrogen for thermal generation (pre-combustion), or



Intergovernmental Panel on Climate Change

- burning the fuel in oxygen to obtain a pure stream of CO_2 that is suitable for storage (oxyfuel).

Alternatively, looping processes may be employed for capturing flue gas CO_2 in a chemical compound that is heated to separate the gas for storage, and

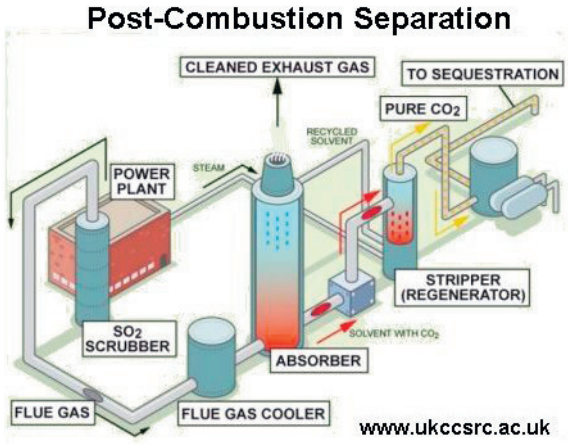
119 Hall, David O. et al. (1993): "Biomass for Energy: Supply Prospects". Renewable Energy. Sources for Fuels and Electricity. Island Press: Washington, p. 599.

120 Intergovernmental Panel on Climate Change (2005): IPCC Special Report on Carbon Capture and Storage. IPCC: Cambridge, p. 108.

subsequently recycled.

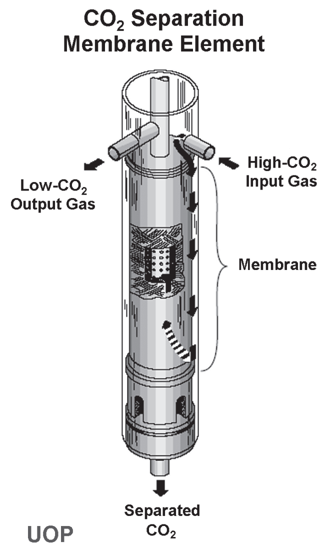
4.2.1 Post-Combustion

CO_2 separation performed in power plant flue gas streams requires no modifications of the original combustion process. Comparable technologies are employed to separate carbon dioxide from natural gas for achieving required purity specifications. The gas emerging from a power plant or a wellhead is passed through a solvent in an absorption column, followed by a desorption or stripping column to isolate the CO_2 for subsequent compression and transport.



Since post-combustion technologies enable CO_2 separation to be retrofitted at existing power plants, any comprehensive CCS strategy would depend on their widespread deployment to avoid stranded assets. Compared with processes integrated into the combustion cycle, however, post-combustion flue gas treatment is relatively energy-intensive due to the auxiliary heat input required for effective desorption.

The achieved efficiency of CO_2 separation is determined by the quality and purity of the solvent, which is generally a sterically hindered amine such as monoethanolamine (MEA). The amine must be protected from rapid degeneration that can be caused by even minute quantities of oxygen in the flue gas. A solvent regeneration stage is therefore integral to a post-combustion separation system, supplemented by MEA replenishment of up to several tonnes daily. To reduce solvent deficits, Siemens AG has developed an amino acid salt solution for "high selectivity, high absorption capacity, low chemical and thermal degradation, low energy demand for solvent regeneration and near-zero solvent slip" that is currently being tested in Germany.[121]



In Alstom's patented chilled ammonia process for post-combustion CO_2 capture, the flue gases are first chilled, allowing byproduct water to be removed for recycling.[122] Ammonium carbonate $(NH_4)2CO_3$ is then employed for carbon dioxide absorption. The resulting ammonium bicarbonate NH_4HCO_3 is regenerated under heat and pressure to ammonium carbonate for reuse, while

121 Jockenhövel, T. et al. (November 16 - 18, 2008): "Development of an Economic Post-Combustion Carbon Capture Process". 9th International Conference on Greenhouse Gas Control Technologies: Washington, p. 10.

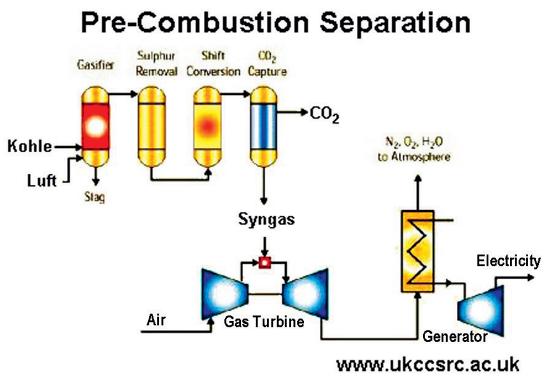
122 Spitznogle, Gary O. (December 9, 2010): "AEP CCS Program Overview". American Electric Power: Columbus.

releasing the captured CO_2 for storage. Lower efficiency losses than alternative separation technologies are claimed. At the 1,300 MW Mountaineer power plant in New Haven, West Virginia USA, the Alstom process was intended to capture more than 90% of flue gas CO_2 (1.5 Mt/a) in a 235 MW generating block until the project was prematurely terminated in July 2011.

Non-porous diffusion membranes may also be used to capture carbon dioxide from gas streams.[123] Cellulose acetate membranes are routinely employed for natural gas purification and EOR. Since they do not require periodic removal and handling of spent solvents or adsorbents, they are suitable for remote applications. Compact membrane configurations are capable of integrated dehydration, CO_2 and H_2S removal, dew-point control, and mercury removal, contrasting with conventional CO_2 separation that requires separate process stages. Improvements in mechanical strength, durability, chemical and thermal resistance as well as aging effects would be necessary, however, before routine employment in electrical power stations could become practical.[124]

4.2.2. Pre-Combustion

High-efficiency power plants employing integrated coal gasification and combined gas/steam cycles (IGCC) offer the capability of integration into industrial strategies involving gas manufacturing. In a pre-combustion CCS power plant, coal is thermally gasified into synthesis gas (syngas) consisting primarily of carbon monoxide (CO) and water (H_2O). The subsequent reaction of carbon monoxide with steam produces hydrogen (H) for burning in a gas turbine to generate electricity, and CO_2 that is compressed for geological storage, EOR, or use in subsequent chemical processes. Product manufacturing and coal liquefaction installations employing gasification may therefore be designed for climate-neutral operation.



Although conceptually attractive, the gasification of coal to produce syngas requires intense reaction conditions.[125] Temperatures up to 1,700 °C and pressures approaching 30 times ambient levels impose high demands on equipment and process control. The complexity of IGCC designs restricts their ability to respond to changing power grid loads.[126] To achieve

123 Dortmundt, David and Kishore Doshi (1999): “Recent Developments in CO_2 Removal Membrane Technology”. UOP LLC: Des Plaines.

124 Scholes, Colin A. et al. (2008/1) “Carbon Dioxide Separation through Polymeric Membrane Systems for Flue Gas Applications”. Recent Patents on Chemical Engineering: Oak Park, p. 64.

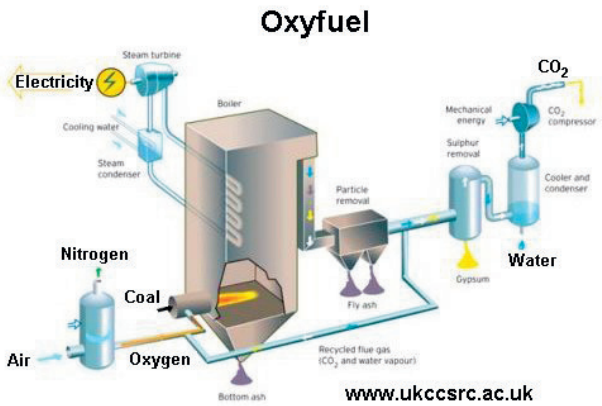
125 Roberts, Daniel (undated). “Coal gasification: from fundamentals to application”. Queensland Centre for Advanced Technologies: Kenmore.

126 Starr, Fred. et al. (July 2006). Near-Term IGCC and Steam Reforming Processes for the Hydrogen Economy: The Development Issues. European Commission. Directorate Gen-

low residual nitrogen in the output gas streams, oxygen instead of air combustion may be preferred despite additional energy penalties.[127] While IGCC designs comprise both CO_2 capture and hydrogen production, the combined configuration lowers the attainable plant efficiency to around 35%, or less. This disadvantage may be offset by the gasification of inferior-grade coal available at a reduced price.

4.2.3. Oxyfuel

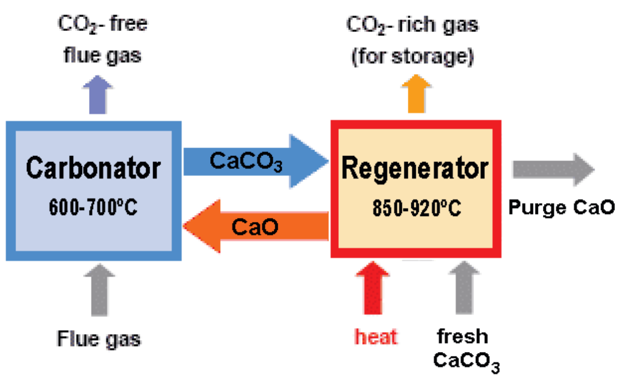
The oxyfuel process produces a highly concentrated stream of capture-ready CO_2.[128] Since pure oxygen is employed, the combustion unit can be reduced to a fraction of the size required for air-fired plants. The configuration replicates many components of conventional plant design. On the other hand, process control imposes exacting requirements on mass and heat stream regulation. Sulphur and nitrous oxides as well as oxygen must be removed from the output CO_2 stream to avoid possible impairment of geological storage.



While other capture processes exhibit high water demand, oxyfuel combustion produces water as an output product. It is suitable for use with lignite and other low-grade fuels without requiring oil or gas injection to maintain combustion. However, the process depends on a dedicated oxygen supply requiring additional energy and considerable upscaling for commercial use. The largest oxygen production plants currently in operation have a capacity approaching 800 tonnes daily, which would be adequate to react with 300 tonnes (800 * 12/32) of carbon. On a yearly basis, about 400 thousand tonnes of carbon dioxide could be treated. Large-scale coal and lignite power plants, by contrast, emit between 5 and 25 million tonnes of CO_2 annually.

4.2.4 Chemical Agent Looping

The carbonate looping process (or lime-loop CO_2-reduction procedure) is an alternative post-combustion method employing carbon dioxide to transform calcium oxide



eral, Joint Research Centre, Institute fo

127 Starr, Fred (February 11, 2009). "IGCC plus CCS – an Objective Analysis". Claverton Group, London.

128 Birkestad, Hendrik (2002): "Separation and Compression of CO_2 in a O2/CO_2-fired Power Plant". Chalmers University of Technology: Göteborg.

CaO into limestone $CaCO_3$. Calcination of the $CaCO_3$ reconverts it to fresh sorbant. The carbonator and calcinating regenerator operate at temperatures between 650 - 900 °C, allowing both units to deliver steam for greater power generation than with low-temperature methods of CO_2 separation.

Evaluations conducted by the Canadian CanmetENERGY organisation have shown carbonate looping to reduce power plant generation efficiency by only 7.4% (from 43% to 35.6%) compared with 11% for the oxyfuel process.[129] However, repeated looping cycles result in sintering of the CaO that successively reduces efficiency, thus necessitating $CaCO_3$ replenishment. In the presence of SO_2, furthermore, the formation of $CaSO_4$ may impair carbonator operation, making pre-stage sulphur removal desirable. The carbonate looping process appears to be moderately less effective than other capture technologies. Initial evaluations indicate that a CO_2 separation level of 86% can be achieved, compared with the 95% potentially attainable by the oxyfuel process.

On the basis of tests conducted at its 1 MW carbonate looping test facility, the Technical University of Darmstadt, Germany, has reported a parasitic energy loss of only 6% that includes CO_2 compression.[130] A second chemical looping process using a metal oxide oxygen carrier employs component temperatures of 950 - 1050 °C with energy losses reduced to 4%. The first commercial installations are expected in 2017 for power plants in the 10 - 50 MW range.[131] Plant configurations up to 1,050 MW are under consideration.

A similar calcium-based approach might be used for the CO_2-free combustion of natural gas, producing hydrogen ($CH_4 + 2H_2O + CaO = 4H_2 + CaCO_3$) as an output product for use in fuel cells. Alternatively, chemical looping systems achieve the advantages of the oxyfuel process without requiring an external source of oxygen.[132] The carbon-based fuel is used as a reduction agent to bond with the oxygen of a metal oxide. As in conventional oxyfuel processes, CO_2 and water are produced. The reduced metal is re-oxidised in a separate reactor and recycled to the fuel reactor, explaining the term "chemical looping".

4.2.5. Conventional Separation Technology Comparisons

In contrast with the employment of post-combustion separation for retrofits of existing facilities, new plant construction follows broader selection criteria. The following comparison of available technologies has been derived from findings of American Electric Power (AEP), a US utility company investigating alternate approaches to CCS.[133]

129 Anthony, E.J.: "Ca Looping: a New Technology for CO_2 Capture". CanmetENERGY, Natural Resources Canada: Ottawa.

130 Epple, Bernd (2010): "Zero Emission Power Plant". Technische Universität: Darmstadt.

131 Jopp, Klaus (November 12, 2010): "Zwei Loopings für weniger Kohlendioxidemissionen". VDI nachrichten: Darmstadt.

132 Siriwardane, Ranjani (April 2008): "Chemical-Looping Combustion Research Shows Promising Results". Netlog. National Energy Technology Laboratory: Albany.

133 Braine, Bruce (September 2007): "AEP, Climate and Carbon Capture and Storage". American Electric Power: Columbus; Spitznogle, Gary O. (December 9, 2010), op. cit.

CO_2 Separation Technologies

	Advantages	Penalties
Post-combustion	Amine technologies commercially available	High parasitic demand: Conventional amine 28 - 32% Chilled ammonia target 15 - 22% Amines need very clean flue gas
Pre-combustion IGCC with Water-Gas Shift	Very pure CO_2 stream Parasitic demand of 20% lower than post-combustion or oxy-coal	IGCC plant costs higher CO_2 capture costs lower than pulverised coal
Oxyfuel	Creates stream of very high CO_2 concentration	Not yet commercially proven High parasitic demand > 25%

Post-combustion processes are the only CO_2 separation technologies widely proven in commercial environments. Vattenfall regarded oxyfuel plants a preferred lignite option for more than a decade, but the intended construction of a 250 MW CO_2 separation pilot plant by 2010 at Jänschwalde in the eastern German state of Brandenburg was ultimately not realised.[134] Instead, only a 30 MW test facility had been dedicated by that time at Schwarze Pumpe.[135]

Vattenfall was subsequently granted €180 million under the SET-Plan for CO_2 separation testing at Jänschwalde using a modified configuration that included a 50 MW retrofitted post-combustion generator and a new 250 MW oxyfuel plant. The installations, dimensioned for CO_2 separation quotas of 10% and 90% respectively,[136] were considered preliminary to "future commercial power plants, with capacities up to 1,000 MWe".[137] More than 300 Mt of CO_2 storage would have been required over the typical lifespan of 40 years for the project, which was cancelled in December 2011 due to unresolved local conflicts on geological storage. Vattenfall has officially cited "insufficient will in German federal politics" for the failure to implement EU Directive 2009/31/EC as intended.[138]

The company nevertheless intends to "continue further development of CCS" at the Ferrybridge Power Station in West Yorkshire, United Kingdom, while also working "for the development of a European storage infrastructure" that would require a long-distance CO_2 pipeline network. The Ferrybridge project involves capturing 90% of the carbon dioxide from a 1% slipstream (equivalent to 5 MWe, or 14 MWth) of the total plant emissions.

Due to the frequent availability of inferior-grade or contaminated coal at reduced prices following the cessation of regular mining activities, as well as the growing potential of ancillary chemical product manufacturing, IGCC

134 Strömberg, Lars (October 21 - 22, 2004): "A future 'CO_2 Free' Power Plant for Coal". Vattenfall: Stockholm.

135 Preuss, Olaf (July 23, 2008): "'Saubere' Kohlekraftwerke und Windparks auf See sollen die Stromversorgung sichern". Hamburger Abendblatt: Hamburg.

136 Schuster, René (October 25, 2010): Vattenfall's planned CCS demonstration plant is not a sustainable energy solution. Grüne Liga: Potsdam, p. 2.

137 Vattenfall AB (October 2008): "Factsheet CCS. Demonstration Plant in Jänschwalde". Vattenfall: Stockholm.

138 Vattenfall AB (December 5, 2011): "Uncertainties with CCS law stop Vattenfall investment in demo plant". Vattenfall: Stockholm.

is being considered for CCS power plant installations worldwide. As indicated in the table, the high technology outlays that may be unwarranted for conventional generation may provide relatively economical CO_2 separation capabilities.[139]

Comparative Costs of Coal Power Generation ($/MWh)

USA 2005	Without CO_2 Separation		With CO_2 Separation	
Coal grade	Conventional	IGCC	Conventional	IGCC
Bituminous	46.6	45.8 - 48.3	75.4	61 - 67
Sub-bituminous	44	48 - 54	64 - 97	61

These figures have been calculated for the US electrical power industry in 2005. Subsequent technological improvements capable of lowering costs may also prolong implementation schedules due to greater process complexities. In the Canadian province of Alberta, capture costs as high as $225 per ton of CO_2 have been ascertained for natural gas combustion.[140]

4.3. Capture of Biogenic Carbon Dioxide

If biomass is employed for heat or power generation, CO_2 capture provides ETS offsets that reverse the effect of emissions in allocation accounting. The Belgian Government has determined that technologies resulting in "negative CO_2 emissions" such as "biomass energy with carbon capture and storage may be crucial for maintaining a 2°C limit".[141]

However, the generally modest generation capacity of biomass power plants may not justify CCS infrastructure costs unless a nearby CO_2 pipeline or storage site is available. Biomass co-firing in an existing fossil fuel plant would permit more efficient utilisation of capital resources. Biomass fuel may be imported from other countries or even other continents due to the frequent limitations of domestic biomass procurement.

4.4. CO_2 Compression

At 20 °C and atmospheric pressure (atm), one ton of carbon dioxide occupies a volume of 510 m^3. For manageable transportation, therefore, CO_2 is compressed after separation to produce a supercritical fluid that continues to behave like a gas, while exhibiting the density of a liquid. The purified carbon dioxide stream must be thoroughly dried to prevent corrosion of pipelines and sequestration equipment. Hydrate crystals resulting from subsequent water penetration can block pipeline equipment and valves, necessitating temporary shutdown of the CO_2 disposal chain.

At supercritical temperatures exceeding 31.1 °C and pressure of at least 73.9 bar, corresponding to 7.39 megapascals (MPa) or 72.93 atm, a ton of CO_2 will be compacted to a volume of about 2.1 m^3. Maintaining these specifica-

139 Utilis Energy (February 2005): Coal Gasification 2005: Roadmap to commercialization. UE CG/05. Utilis Energy USA: New York, p. 22.

140 Alberta Carbon Capture and Storage Development Council (March 2009), op. cit., p. 23.

141 Capros, P. et al. (August 4, 2010), op. cit., p. 6.

tions for subterranean storage requires the gas to be injected to a level of at least 800 metres below ground level to ensure adequate geological pressure.

4.5. CO_2 Capture Rates and Purity Requirements

The achievable CO_2 capture rates for commercial power plants commissioned after 2020 have been estimated at 67% - 85% for hard coal firing, 78% - 95% for lignite, and 67% - 75% for natural gas.[142] Attempts to increase capture performance above these levels may introduce excessive contaminants into the gas stream.

When CO_2 is separated from natural gas for pipeline transport to EOR applications, it is devoid of manmade impurities. By contrast, the smokestack effluents of CCS power plants contain products of high-temperature combustion that may include sulphur oxides (SOx), nitrous oxides (NOx), particulates, hydrochloric acid (HCl), hydrogen fluoride (HF), mercury (Hg) and other metals, as well as trace organic and inorganic substances.[143] These contaminants must be kept at minimum concentration not only to prevent equipment corrosion, but also to avoid the additional energy expenditures necessary for compressing impure CO_2 to preclude transitions to two-phase gas flows during transport and storage.[144] Such phase changes may result in pump cavitation and performance detriments leading to system deterioration.

Residual water vapour in the CO_2 stream must be completely removed to prevent corrosion and hydrate formation during transport that may cause valve malfunctions and blockage.

Transient conditions inherent to start-up, shutdown, and irregular flow must likewise be examined with respect to potential phase changes.

The IPCC has determined that commercially available CO_2 capture technologies are capable of achieving a purity level occasionally exceeding 99%, while purity reductions to 95% may be tolerated at commensurately lower cost.[145] The Dynamis and Ecofys projects have established standard carbon dioxide concentrations and maximum trace contaminants for CO_2 pipeline transport to ensure a sufficiently high degree of gas purity.[146]

CO_2 Pipeline Stream Specifications

142 Esken, Andrea et al. (August 9, 2010): RECCS plus. Comparison of Renewable Energy Technologies with Carbon Capture and Storage (CCS). Wuppertal Institute: Wuppertal, p. 202.

143 Intergovernmental Panel on Climate Change (2005), op. cit., p. 114.

144 Seevam, P. N. et al. (2007): “CO_2 Transport Infrastructure”. Newcastle University.

145 Intergovernmental Panel on Climate Change (2005), op. cit., p. 124.

146 Pershad, Harsh et al. (April 27, 2010): CO_2 pipeline Infrastructure: An analysis of global challenges and opportunities. International Energy Agency: Cheltenham, p. 102.

<table>
<tr><th rowspan="2"></th><th colspan="2">Dynamis</th><th rowspan="2">Ecofys</th></tr>
<tr><th>CCS</th><th>EOR</th></tr>
<tr><td>CO_2</td><td colspan="2">> 95.5%</td><td>> 95%</td></tr>
<tr><td>H_2O</td><td colspan="2">500 ppm</td><td>< 500 ppm</td></tr>
<tr><td>SOx</td><td colspan="2">100 ppm</td><td>Not critical</td></tr>
<tr><td>NOx</td><td colspan="2">100 ppm</td><td>Not critical</td></tr>
<tr><td>H_2S</td><td colspan="2">200 ppm</td><td>< 200 ppm</td></tr>
<tr><td>CO</td><td colspan="2">2000 ppm</td><td>< 2000 ppm</td></tr>
<tr><td>H_2</td><td rowspan="5">< 4 vol%</td><td rowspan="3">< 4 vol%</td><td rowspan="5">< 4 vol%</td></tr>
<tr><td>Ar</td></tr>
<tr><td>N_2</td></tr>
<tr><td>O_2</td><td>100 - 1000 ppm</td></tr>
<tr><td>CH_4</td><td>< 2 vol%</td></tr>
</table>

5. CO_2 Transport

Captured carbon dioxide may sometimes be sequestered in the immediate vicinity of power plant sites. A study commissioned by the US Congress has noted that "77% of the total annual CO_2 captured from the major North American sources may be stored in reservoirs directly underlying these sources, and that an additional 18% may be stored within 100 miles of additional sources".[147] In Europe, CCS installations close to the North Sea or the Alps would be availed of comparable geological prospects. Some CO_2 point sources in China are located near potential storage locations, while India has conducted no geological investigations in response to rising emission levels.[148] In Australia, all proposed CO_2 capture power plants are located in the vicinity of sedimentary basins considered feasible for storage.[149]

5.1. Ship, Rail, and Pipeline Transport Options

For power plants in coastal regions and on major waterways, semi-pressurised tank carrier ships allow economical CO_2 removal to offshore locations. The semi-pressurised/semi-refrigerated gas is typically transported at -55 °C and 6.5 bar.[150] On the basis of current ship designs, a capacity of up to 45,000 tons may be realised. Multi-purpose tankers delivering liquefied natural gas (LNG) to industrialised countries could return to the Middle East with CO_2 for enhanced hydrocarbon recovery, or for underground storage

147 Parfomak, Paul W. and Peter Folger (April 19, 2007): Carbon Dioxide (CO_2) Pipelines for Carbon Sequestration: Emerging Policy Issues. Congressional Research Service: Washington, p. 6.

148 Ansolabehere, Stephen et al. (2007), op. cit., pp. 55 - 57.

149 Cook, Peter J. and Dennis R. Van Puyvelde (January 2008): "Australia's CCS Technology Roadmap". Cooperative Research Centre for Greenhouse Gas Technologies (CO_2CRC): Canberra.

150 Schulze, Anders (March 31, 2010): "Maersk Tankers – a pioneer in CO_2 shipping". Carbon Capture Journal, Global CCS Institute: Canberra.

that would permit the sale of credits to an emission trading platform.[151]

Rail transport from isolated emission sources requires stringent logistical planning, since the carbon dioxide tonnage leaving a power plant would constitute several times coal deliveries.[152] The CO_2 cannot be stockpiled but instead must be withdrawn continuously by up to two tank freight trains per hour for large plants. Major congestion could result on rail lines not intended for such frequency of service. Another two trains per power plant would leave the CO_2 repository every hour with empty tanks, with additional trains dispatched for longer distances. Frequent road traffic interruptions could be experienced at railway crossings along heavily travelled routes.

The larger the power plant, the greater the economic rationale for constructing a pipeline for transporting compressed CO_2 to storage sites. However, pipeline network geometry becomes increasingly complex when multiple emission sources are interconnected with geological repositories.[153] The efficiency of a single trunk pipeline branching between CO_2 sources and sinks can degenerate as soon as individual injection sites attain storage saturation. The economic justification of ETS avoidance may prove insufficient whenever unanticipated pipeline rerouting becomes necessary.

The Kiel Institute for the World Economy has accordingly determined the "problem of network externality" to be crucial for pipeline realisation.[154] While CCS operators will share CO_2 pipelines, "the spatial complexity of the network (upstream-downstream structure)" may prevent the market from finding "the efficient pricing levels of pipeline use, and by extension, the socially optimal structure of pipeline network. When coupled with other externalities, such as the externality of research and development and the carbon (climate change) externality, the externality problem of pipeline network design poses a substantial need for coordination – this is, in fact, a problem that needs a public solution."

Experience in the United States indicates that routing "through a highly populated area, a wetland or a waterway can increase the ROW (right of way) cost by 10-15 times".[155] If pipeline infrastructures are aligned with the most promising revenue streams, remote CO_2 point sources may be excluded. Supplementary rail transport networks or a system of offset payments for isolated installations could then become necessary for retaining overall conceptual integrity at inevitably greater cost.

Pipeline transport prevails over local storage options when separated carbon

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151 Parkinson, Giles (December 6, 2010), op. cit.

152 This relationship reflects the molecular weight of carbon (12) compared with carbon dioxide (44). In addition, pressurized railroad tanks have a lower capacity than coal hopper cars.

153 Hunt, Paul et al. (April 27, 2010): CO_2 pipeline Infrastructure: An analysis of global challenges and opportunities. Element Energy Limited: Cambridge, pp. 122 - 124.

154 Heitmann, Nadine et al. (November 2010): "Embedding CCS infrastructure into the European electricity system: A policy coordination problem". Kiel Working Paper No. 1657. Kiel Institute for the World Economy: Kiel, p. 3.

155 Essandoh-Yeddu, Joseph and Gürcan Gülen (2009), op. cit., p. 1606.

dioxide can be sold to EOR operations. The 24 inch (61 cm) 320 mile (515 km) Denbury Resources "Green Pipeline" to be completed in 2014 between Louisiana and the West Hastings oilfield in Texas will transport up to 44 thousand tons of CO_2 daily from natural gas production as well as from a local coking plant and other anthropogenic sources. An existing pipeline network in Mississippi may be extended over one of two proposed routes to link coal powered plants in Illinois, Indiana, and western Kentucky with the Gulf Region.[156] Payments made to CO_2 suppliers for EOR are tied to crude oil revenues. Rising energy prices therefore improve the commercial prospects of CO_2 separation.

Additional cost benefits may be achieved by connecting multiple plants to a single pipeline. The Canadian Government and Alberta Province originally allocated C$495 million over 15 years for the Alberta Carbon Trunk Line (ACTL),[157] a 240 km (149 mile) pipeline for delivering carbon dioxide from energy-intensive companies to increase the production of mature oil fields.[158] In contrast with CO_2 pipelines in Europe proposed for avoiding ETS obligations, the Canadian venture was intended to promote energy industry turnover, with funding outlays for project realisation regained from tax revenues on oil sales. The subsequent development of shale gas and shale oil, however, has indefinitely delayed project realisation.

5.2. CO_2 Pipeline Risks

Public anxiety over the possible dangers of CO_2 transport visibly contrasts with the widespread toleration of explosive natural gas fed into homes and office buildings, and of pipelines for hazardous substances that interconnect chemical factories near urban settlements. Uneasiness over CO_2 pipeline networks may be interrelated with perceived deficiencies in the economic or ecological value of CCS. Furthermore, established practices and safety records may be of limited value in determining future transport risks. The rarity of recorded incidents on the extensive North American EOR pipeline network reflects operational practices adequate for sparsely inhabited regions. Routing in population centres imposes additional demands on pipeline materials and monitoring. Intermittent operation may raise liability insurance costs.

While natural gas pipelines are designed for a pressure of 60 to 80 bar,[159] a CO_2 pipeline must be constructed of thicker material for transporting supercritical CO_2.[160] The use of corrosion-resistant steel with continuous pressure monitoring and automatic stop valves prevents rupturing. Mechani-

156 Lydersen, Kari (February 8, 2011): "With no sources of CO_2, Midwest pipeline project in limbo". Midwest Energy News.

157 Enhance Energy, op. cit.

158 CBC News (January 12, 2011): "Sask. CO_2 leaks raise questions in Alberta". Canadian Broadcasting Company.

159 Serpa, Joana et al. (2011): Technical and Economic Characteristics of a CO_2 Transmission PipelineInfrastructure. European Commission. Joint Research Centre. Institute for Energy: Petten, p. 15.

160 National Energy Technology Laboratory (August 2010): Impact of the Marcellus Shale Gas Play on Current and Future CCS Activities. Department of Energy: Washington, p. 24.

cal arrestors every 1,000 feet (300 metres) inhibit the propagation of pipeline fractures induced by the highly compressed gas. CO_2-resistant elastomers around valves and joint fittings are specified. Gas odorants may be employed to facilitate leak detection.

If multiple CO_2 sources are connected to the same pipeline, the respective pressures, temperatures, and impurity concentrations must be synchronised. However, the monitoring data required to ensure pipeline integrity may be constrained by participating operators as confidential information of potential value to competitors.

Any CO_2 decompression via pipeline leaks or ground fissures at storage locations could release expanding gas that would flow over the surrounding terrain rather than dissipating into the air like volatile natural gas. Supercritical CO_2 changes phase as its pressure is reduced, causing a sudden temperature drop. Escaping CO_2 from a defective pipeline or valve may thus instantaneously solidify and fall to the ground as dry ice snow. Carbon dioxide could ultimately accumulate to hazardous and potentially lethal levels in landscape depressions or poorly ventilated substructures.

Investigations of American submarine crews submitted to a CO_2 concentration of 30,000 ppm (3%) in ambient air showed only slight adverse reactions as long as an adequate supply of oxygen was available.[161] A 5% concentration caused increased respiration, while 6 - 10% variously induced shortness of breath, headaches, dizziness, sweating, and general restlessness. Increasing the CO_2 concentration to 10 - 15% led to impaired coordination and abrupt muscle contractions. Loss of consciousness and convulsions may ensue at 20 - 30%, while higher levels are ultimately fatal. Appropriately, the FutureGen pipeline and storage infrastructure in Illinois USA includes monitoring plans both from space satellites and by detection sensors on the ground.[162]

5.3. Pipeline Energy Losses

Separated carbon dioxide is compressed to a dense supercritical state for transport to achieve the lowest possible volume and thus the most cost-effective pipeline size. The overall efficiency of the CCS process chain is reduced by the inherent parasitic energy losses, calculated at 0.089 kWh/kg for compressing pure CO_2 to 12 MPa (120 bar).[163] The corresponding efficiency penalty of a power plant required to deliver this compression performance depends on the fuel quality and plant design. For instance, an advanced lignite power plant typically emits 900 grams of CO_2 per generated kilowatt-hour, resulting in 1.11 kWh/kg CO_2. Compression to 120 bar

161 Schaefer, K. E. (1951): Studies of carbon dioxide toxicity. Navy Department, Bureau of Medicine and Surgery, Medical Research Laboratory, U.S. Naval Submarine Base: New London, Vol. 10, Report No. 181, pp. 156-189.

162 Thoele, Cathy (November 18, 2010): “Officials believe area right for FutureGen”. Effingham Daily News: Effingham.

163 Kuckshinrichs, Wilhelm et al. (March 2010): Weltweite Innovationen bei der Entwicklung von CCS-Technologien und Möglichkeiten der Nutzung und des Recyclings von CO_2. Institut für Energieforschung - Systemforschung und Technologische Entwicklung (IEF-STE): Jülich, pp. 35 - 37.

entails 8% (0.089/1.11) of available output power. Restoration of the original grid capacity thus requires expending an additional 8.7% (1/0.92) of plant generation.

Transport friction causes the compression pressure to drop by about 30 kPa/km in a typical 20-inch pipeline under adiabatic (constant temperature) conditions.[164] Therefore, a CO_2 compression level of 13 - 14 MPa (130 - 140 bar) is typically maintained to preclude phase transition to a gaseous state within the pipeline. Greater pressures of up to 200 bar may be employed over extended distances to minimize the need for a high-powered booster station along the transport route. However, thicker wall materials will be required, increasing pipeline costs. Since upstream (power plant) compression also heats the CO_2 medium above the ambient temperature, a somewhat larger pipeline diameter is often employed. Additional compression may be ultimately unavoidable depending on the amount, type, and mixture of impurities in the gas stream.[165]

6. CO_2 Storage

The stabilization of global carbon cycles requires that any CO_2 produced from fossil fuels not be absorbed by the biosphere. Instead, the gas must be rendered either inert or inaccessible. It also must be prevented from releasing entrapped hydrocarbons that could be transformed into additional greenhouse gas emissions, as is the case with EOR.

The German Green Party has postulated that CCS can only serve as “a fallback option if it is not possible in coming decades to reduce the share of process-related emissions from the steel, cement and chemical industries (about 10 percent of total emissions in Germany), or alternatively to decrease them significantly with alternative materials”.[166] If these installations are not ultimately equipped with CO_2 separation technologies, however, any incurred expenses of capture-ready engineering and planning would be lost. The absence of proportionate returns may invariably forestall the required investments.

6.1. Carbon Dioxide Usage

The use of power plant CO_2 for chemical manufacturing is termed carbon capture and usage, or utilisation (CCU). An investigation by the Centre for Low Carbon Futures has established that, due to cost and energy implications, CCS by itself represents “a mitigation technology without payback”.[167] However, supplementary post-capture chemical conversion and refining processes can deliver “products from CO_2 with various degrees of added value”. The Global CCS Institute estimates that “most of the emerging reuse tech-

164 Essandoh-Yeddu, Joseph and Gürcan Gülen (2009), op. cit., p. 1607.

165 Seevam, P. N. et al. (2007), op. cit.

166 Krischer, Oliver (February 23, 2011): “Stand und Bewertung zum neuen CCS Gesetzentwurf”. Federal Parliamentary Fraction of the German Green Party: Berlin.

167 Styring, Peter et al. (July 2011): Carbon Capture and Utilisation in the green economy. The Centre for Low Carbon Futures: York, p. 25.

nologies still have years of development ahead before they reach the technical maturity required for deployment at commercial scale".[168]

In Germany, byproduct CO_2 from chemical manufacturing is used for the production of urea (107 Mt of CO_2 per year), methanol (2 Mt/a) and salicylic acid (25,000 t/a).[169] Reactively inert output products such as plastics provide enduring sequestration opportunities. Since CO_2 is thermodynamically stable, however, significant energy expenditures are required for synthesizing hydrocarbons. High purity products synthesised from gases are appropriate for specialised applications, but they usually cannot be produced economically for general use.

Bayer AG has commissioned a pilot plant for manufacturing polyurethane plastic using an innovative catalytic reaction.[170] A chemical precursor is produced into which CO_2 is integrated as a substitute for petroleum. The carbon dioxide is obtained from a RWE Power lignite power plant in Niederaussem.

The carbon dioxide produced by fossil fuel combustion could hypothetically be recycled indefinitely by chemical synthesis. In the United States, research conducted at the Los Alamos National Laboratory has demonstrated the viability of absorbing CO_2 into a liquid solution of potassium carbonate for subsequent petrochemical conversion.[171] Carbon Sciences, Inc., of Santa Barbara, California, is now developing processes for manufacturing gasoline and other fuels from carbon dioxide.

The US coal corporation Peabody Energy is cooperating with China's Huaneng Group and California-based Calera Corporation for capturing CO_2 from a 1,200-MW supercritical power plant in Inner Mongolia to manufacture green construction materials.[172] The Mineralization via Aqueous Precipitation (MAP) process employs brine of high calcium content to transform a ton of captured CO_2 into two tons of building cement.

The mineralisation of CO_2 into commercially marketable carbonates is confronted with existing production capacities. For instance, converting the emissions from lignite power generation in Germany into building materials could result in an output volume over ten times as large as domestic cement production.

168 Parsons Brinckerhoff (March 2011): Accelerating the Uptake of CCS: Industrial Use of Captured Carbon Dioxide. Global CCS Institute: Canberra, p. XII.

169 Kuckshinrichs, Wilhelm et al. (March 2010), op. cit., p. 110.

170 Bayer AG (February 17, 2011): "Bayer starts pilot plant for plastic manufacturing with CO_2". Bayer: Leverkusen.

171 Chang, Kenneth (February 19, 2008): "Scientists Would Turn Greenhouse Gas Into Gasoline". The New York Times: New York.

172 Peabody Energy Corp. (January 20, 2011): "China Huaneng, Peabody and Calera Agree to Pursue Development of Low-carbon Emissions Clean Coal Project in Inner Mongolia". Peabody: St. Louis.

6.2. Geological CO_2 Storage

In the European Union, "carbon dioxide capture and geological storage (CCS)" is designated by Directive 2009/31/EC[173] as "a bridging technology that will contribute to mitigating climate change". Three types of subsurface formations are under consideration for permanent geological storage:

- oil and gas reservoirs
- sedimentary saline aquifers (porous sandstones permeated with salt water)
- deep coal beds.

Extrusive igneous rocks (volcanic igneous rock) are also being investigated in North America for sequestration due to their widespread prevalence.[174] Their "high porosity and mineralogy offer opportunities for high volume storage and reactive chemistry that could convert the CO_2 into solid carbonates and essentially trap the CO_2 in the rocks forever". However, proposals for commercial implementation have not yet been announced.

Industry experience with underground natural gas storage indicates that saline aquifers would constitute the most expensive repositories of captured greenhouse gases. Compared with depleted oil and gas reservoirs, the detailed characteristics of aquifer formations are not previously known. All geological structures must be capable of retaining large quantities of CO_2 indefinitely and without leakage, preferably with multiple low-permeability layers forming an upward barrier to gas migration.

A geological storage depth exceeding 800 metres is necessary to maintain a supercritical gas pressure of 73.9 bar (7.39 MPa, 72.93 atm). Supercritical CO_2 is an aggressive solvent that can dissolve portions of injection formations. It is less dense than water and tends to rise to the top of storage reservoirs due to buoyancy forces, as well as moving laterally as allowed by structural geometry. Injection of the CO_2 increases pore pressure, inducing variations of permeability and porosity. Separate monitoring wells are therefore necessary to track resulting migration patterns, particularly if uncontrollable containment may occur.

Geological investigations comparable to oil and gas exploration are necessary for appraising the composition and porosity, fault structures, and prevailing pressure of storage formations. Geological modelling and seal analysis techniques help preclude fault reactivation and seismic disruption under the high pressure of supercritical CO_2. Storage characteristics are ultimately evaluated during the injection phase. Porous rocks used for deposition must be highly permeable, while defined storage field boundaries are required to prevent CO_2 interaction with groundwater and atmospheric leakage.

Oil and gas fields lie below impermeable caprocks (typically clay or salt layers) that prevent these fossil fuels from dissipating. By contrast, saline

173 Commission of the European Communities (April 23, 2009): Directive 2009/31/EC on the geological storage of carbon dioxide. Official Journal of the European Union: Brussels.

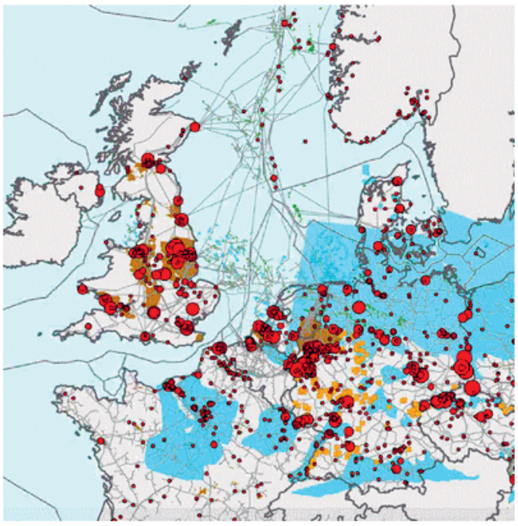
174 National Energy Technology Laboratory (September 2010): Geologic Storage Formation Classification: Understanding Its Importance and Impacts on CCS Opportunities in the United States. Department of Energy: Albany, p. 15.

aquifers and coal formations can lack suitable seals.[175] Some of the injected CO_2 may therefore escape from the primary formation, necessitating retrieval by secondary collector wells.

The injection rates achieved for EOR in oil reservoirs are best-case figures. An investigation of the candidate Tay saline aquifer in the North Sea has indicated a maximum CO_2 well injection rate of 6 Mt/a if water is simultaneously allowed to flow out of the formation for pressure relief.[176] The storage capacity of 375 Mt achieved in this case is reduced to155 Mt for no-flow boundaries, since the CO_2 injected into closed saline aquifers encounters pressure gradients of typically 3,000 psi (211 kg/cm2), "with injectivity reduced as reservoir pressure increases".[177] Multiple injection wells are therefore required for CO_2 storage in typical saline aquifers, compared with the single-well configuration of the Sleipner field.

The Scottish Centre for Carbon Storage has determined that only Scotland and Norway have CO_2 storage capacities of approximately equal size to make the North Sea "a major hub for CO_2 transport and storage in Europe".[178] With 2% storage efficiency (or injectivity), an assumption expressing the high pressure levels prevailing in reservoirs with no-flow boundaries, 46 billion tons of carbon dioxide might ultimately be deposited in Scotland's offshore aquifers that consist of deep sandstone formations filled with seawater. This undersea capacity is "greater than Netherlands, Denmark and Germany combined". Any carbon storage strategy in those countries would largely be restricted to onshore regions. A 20% storage efficiency was assumed for Germany in a 2007 evaluation issued by the federal government,[179] while later studies have quoted lower figures.

EU GeoCapacity Map of CO_2 Sources and Sinks



The German National Organization of the Energy and Water Industry (BDEW) estimates that the storage of 350 Mt of CO_2 a year from domestic electricity generation would correspond to a "CO_2 volume of 14 billion tons with a fluid volume of 20 billion m^3" over the interval of 40 years.[180] "With

175 www.dur.ac.uk/earth.sciences/research/research_groups/res_groups/duccs/background.

176 Glover, Anne (April 2009), op. cit., pp. 23 - 24.

177 Xie, Xina and Michael J. Economides (March 2009): "The Impact of Carbon Geological Sequestration". Society of Petroleum Engineers: Houston, pp. 2 - 9.

178 Glover, Anne (April 2009), op. cit., Foreword.

179 Federal Ministry for Economics and Technology et al. (September 19, 2007): Entwicklungsstand und Perspektiven von CCS-Technologien in Deutschland. BMWi, BMU, BMBF: Berlin, p. 10.

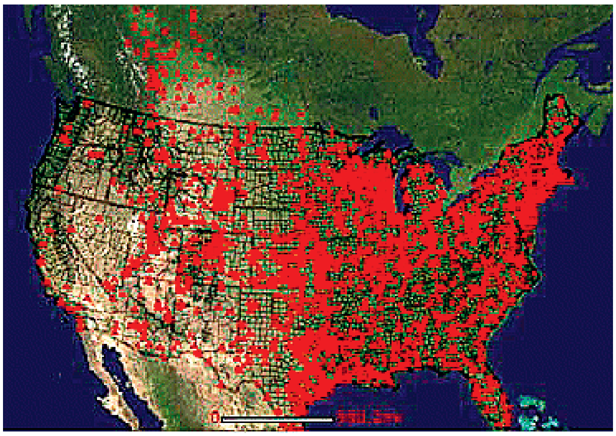
180 Bundesverband der Energie- und Wasserwirtschaft (April 21, 2010): "Stellungnahme der norddeutschen Wasserwirtschaft zur Umsetzung der Richtlinie 2009/31/EG über die geologische Speicherung vonKohlendioxid in deutsches Recht". BDEW Landesgruppe Wasserwirtschaft: Hamburg, p. 2.

a mottled sandstone porosity of 15% (2-18%), an expanse of 133 billion m^3 of stone would be necessary, corresponding to a land area of 5,320 km2 for a geological thickness of 25 m." This expanse, which is approximately twice the size of Luxembourg, would be confronted with formation irregularities and usage conflicts.

The CO_2 storage locations determined by the EU GeoCapacity study group in 2006 - 2008 may therefore prove less contiguous than indicated by the low-resolution depiction provided in the final report.[181] In Germany, the Federal Institute for Geosciences and Natural Resources (BGR) has repeatedly reduced estimated storage capacities, from 23 to 43 billion tons of CO_2 in 2003 to 12 to 28 billion tons in 2005.[182] By 2011, merely 6 to 13 billion tons of storage was considered achievable. Due to limitations of injectivity and infrastructure, only a fraction of some 350 Mt of carbon dioxide emitted each year by CCS-capable fossil fuel plants (lignite 174 Mt/a, hard coal 136 Mt/a,[183] plus CO_2 capture and compression emissions) might be stored in these formations. In other cases, therefore, power plant operators could switch off CO_2 capture equipment and sell the electricity rescued from parasitic losses.

The German state of Brandenburg, with CO_2 emissions of 23 tons per inhabitant, has actively pursued CCS for electrical power generation. Under the CO_2SINK pilot storage project, up to 30,000 t/a CO_2 was to be stored at Ketzin west of the city, with field testing of different technologies that include two observation wells.[184] While the project was intended to "accelerate the public acceptance of geological storage of CO_2 as a greenhouse gas mitigation option for the benefit of Europe", local concerns over possible groundwater contamination ultimately prevailed against further ventures.

US NatCarb Data Base of Carbon Sequestration



In the United States, sequestration locations are mapped at the NatCarb Data Base.[185] Potential CO_2 traps determined from oil and gas exploration are distributed in non-uniform three-

181 Vangkilde-Pedersen, Thomas (December 31, 2008): Assessing European Capacity for Storage of Carbon Dioxide. Geological Survey of Denmark and Greenland (GEUS): Copenhagen, p. 13.

182 Schrader, Christopher (February 15, 2011): "Wohin mit dem Treibhausgas?". Süddeutsche Zeitung.

183 Krupp, Ralf E. (November 18, 2010): Geologische Kurzstudie zu den Bedingungen und möglichen Auswirkungen der dauerhaften Lagerung von CO_2 im Untergrund. Bund für Umwelt und Naturschutz Deutschland e.V.: Berlin, p. 19.

184 GeoForschungsZentrum Potsdam (2005): "CO_2 Storage by Injection at a Saline Aquifer in Ketzin". GFZ: Potsdam.

185 National Carbon Sequestration Database and Geographical Information System (NatCarb), administered by the Department of Energy.

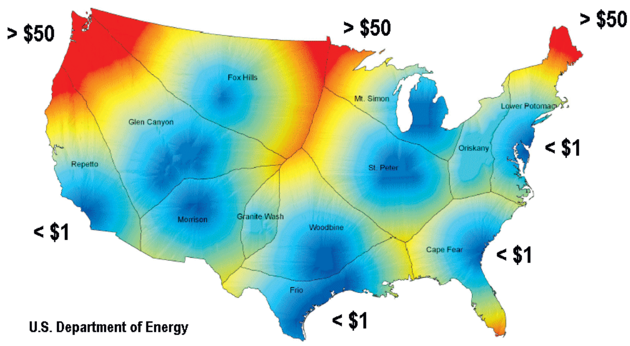
dimensional patterns with appreciable intervening zones. After depth and integrity parameters have been evaluated, the locations at which economical carbon dioxide sequestration is possible diminish to only a few suitable areas.

According to Bill Shefchik, chief geologist at Burns & McDonnell Engineering in Missouri, storage exploration requires “a similar level of effort which has been conducted over the past 150 years to extract oil and gas out of the ground”.[186] The deposition capacity required for major CO_2 point sources would be substantially greater than all of the country’s oil fields combined.

Storage evaluation is complicated by dispersal of injected carbon dioxide. Because of interactions in saline aquifers, “rapid dissolution of carbonate and other minerals could ultimately create pathways in the rock seals or well cements for CO_2 and brine leakage”.[187] Toxic metal contaminants and organic compounds may then be mobilised that subsequently migrate into potable groundwater. The dissolution processes are not permanent, with self-sealing chemical reactions ultimately causing CO_2 plume immobilisation. Nonetheless, any proximity of drinking water reservoirs presents a residual risk of contamination.

The US Office of Fossil Energy has established Regional Carbon Sequestration Partnerships (RCSPs) as a “public/private cooperative effort tasked with developing guidelines for the most suitable technologies, regulations, and infrastructure needs for CCS in different regions of the U.S. and Canada”.[188] A data bank developed by the National Energy Technology Laboratory (NETL) characterises “the different depositional environments with drilling, subsurface geophysics, chemical analysis, and geomechanical analysis of the rocks”.[189] After identifying suitable formations, it conducts “both small- (<500,000 tons) and large-scale (>1,000,000 tons) CO_2 injections”.

Minimum CO_2 Source-to-Sink Costs USA



The Frio Formation, an extensive saline sedimentary aquifer along the Gulf Coast of Texas, may enable particularly economical CO_2 storage due to porosity ranging from 28% to 35% in sand layers 300 metres thick. The initial sequestration costs encompassing sources to sinks in such regions

186 Stower, John, et al. (February 2010): “Siting Process for Coal-fired Power Generation: How to Address CO_2 Sequestration?”. Burns & McDonnell: Kansas City.

187 Kharaka1, Y.K. et al. (July 2006): “Gas-water-rock interactions in Frio Formation following CO_2 injection: Implications for the storage of greenhouse gases in sedimentary basins.” Geological Society of America: Geology, July 2006, v. 34; no. 7, pp. 577 – 580.

188 Office of Fossil Energy (2008): Carbon Sequestration Atlas of the United States and Canada. National Energy Technology Laboratory. Department of Energy: Albany, p. 8.

189 National Energy Technology Laboratory (September 2010), op. cit., p. 47.

may lie below one dollar per ton,[190] although this figure would be negated by early exploitation of the most favourable sites.

CO_2 sources located in regions of low subsurface porosity can make long-distance pipeline transport less expensive than local storage. If the additional costs cannot be offset by lower outlays for fuel or cooling water, however, remote locations will remain at a disadvantage for CCS deployment. The Kiel Institute for the World Economy has prudently noted that "it is relatively easy to find some positive evidence of the viability of long-term CO_2 storage", including "the general knowledge of geology about some mechanisms that could seal gas in selected geological structures (trapping), the existence of a range of geological analogues and element technologies (e.g., geologically stable oil and gas fields, natural gas storage, gas pipeline, and gas separation techniques), and the experiences made by demonstration projects".[191]

Despite the unparalleled cost-effectiveness of the Frio Formation, Susan D. Hovorka, Senior Research Scientist at the Bureau of Economic Geology in Austin, Texas, has compiled an extensive directory of experiments considered necessary before commercial-scale CO_2 storage is initiated.[192] The majority of issues are considered "problematic" and expensive, encompassing large-volume storage and geological effects, monitoring by flux towers, lasers, aircraft, and extraterrestrial satellites, complex gas injection, and long-term chemistry. Initial injection tests have verified plume immobilisation within a few days, empirically validating the geological models employed.[193]

The Lawrence Berkeley National Laboratory observes that monitoring will be important "during the 30 to 50 year injection phase of a storage project, both for the purpose of assuring worker and public safety and confirming that the storage project is performing as expected".[194] The time frame for subsequent monitoring "could be as short as a few years in a depleted gas reservoir with a well defined geological trap". Without a closed trap, however, "more time may be needed before a combination of capillary trapping and solubility trapping (dissolution of CO_2 in the salt water) eventually immobilise the CO_2. Model studies indicate that this can take anywhere from decades to centuries, or longer, before the CO_2 is immobilised."

6.3. Geological Storage Conflicts

190 Fritze, Kevin (April 2009): Modelling CO_2 Storage Pipeline Routes in the United States. Duke University, p. 8.

191 Heitmann, Nadine et al. (November 2010), op. cit., p. 2.

192 Hovorka, Susan D. (May 2005): "Update on the Frio Brine Project". The University of Texas: Austin.

193 Airhart, Mark (November 15, 2006): "Scientists deepen confidence in technique to reduce greenhouse gas emissions". The University of Texas: Austin.

194 Benson, Sally M. (April 2, 2006): Assessment of Risks from Storage of Carbon Dioxide in Deep Underground Geological Formations. Lawrence Berkeley National Laboratory: Berkeley, p. 24.

Exploration activities for storage in North America have evoked little public concern due to the established use of CO_2 for hydrocarbon extraction, the low population density of many sequestration regions, and the allotment of royalty income to affected landowners. However, state authorities such as the Mississippi Department of Environmental Quality only regulate CO_2 storage unrelated to EOR.[195] The Sierra Club has cautioned that "tens of thousands of property owners" would lie above any "cavity large enough" to accommodate the expected volume of emissions.

In Europe, public opposition has formed against CCS implementation due to the infringement of property rights with little or no indemnification, unresolved issues of storage integrity, and the suspected collusion of governments with power companies over CCS ventures. Many potential storage sites in Germany were unknown until Greenpeace obtained a classified list of 408 locations from the mining research authority BGR in February 2011.[196] Real estate values have declined by up to 20% in some regions due to prospective geological storage.[197] The enduring devaluation of private property in entire communities could outweigh the transient commercial benefits of avoiding ETS obligations.

While the immediate risks of CO_2 pipelines and injection wells are covered by operator insurance, latent hazards imperilling future generations are difficult to quantify and impossible to predict. Geological evaluations compiled by the British Geological Survey indicate that "a sudden release of CO_2 (a blow-out) from a subsurface storage site is practically zero", particularly when "thorough investigations of the storage reservoirs and caprocks prior to storage" have been conducted.[198] It is conceded, however, that migration of CO_2 could occur along undetected or incorrectly interpreted faults in caprocks, or in faults "that have become transmissive because of mechanical reactivation or elevated reservoir pressures".

The high-pressure storage of carbon dioxide may induce seismic disturbances similar to those experienced with other geological intrusions including mining, hydroelectric reservoirs, and geothermal power plants. Kinetic energy is transferred to subterranean formations by CO_2 injection, enhancing prevailing instabilities. The geologist Ralf E. Krupp calculates that 10-year operation of the 20 MW injection pump at the In Salah gas field generates 2.1 billion kWh of energy, which is "equivalent to the explosive power of 1810 kilotons of TNT".[199] This energy transfer corresponds to "an earthquake of magnitude 6.2 on the Richter scale" and is thus sufficient to cause "considerable seismic events".

195 Byrd, Shelia (February 4, 2011): "Mississippi considering bills on carbon storage". Associated Press.

196 Totz, Sigrid (February 13, 2011): "CO_2-Endlager unter Berlin und Hamburg?". Greenpeace: Hamburg.

197 Thiel, Holger (December 18, 2010) "CO_2-Lager: Politische Stimmung kippt". Volksstimme: Magdeburg.

198 Chadwick, Andy et al. (2008): "Best practice for the storage of CO_2 in saline aquifers". British Geological Survey: Nottingham, pp. 67 - 68.

199 Krupp, Ralf E. (November 18, 2010), op. cit., p. 54.

The German BDEW has noted that "rising saline water today already presents a danger to the public water supply" that would be "additionally imperiled for centuries by CO_2 storage".[200] Fresh and salt water aquifers must be separated by a clay layer for CO_2 sequestration to be considered. However, channels etched by prehistoric glaciers may allow salt water to rise from the lower formation under injection pressure, endangering drinking water supplies at distances up to 100 kilometres from the wellhead.[201] The natural presence of surface salt water has already been catalogued at some 100 locations in Brandenburg alone, mainly by botanists during the 19th and 20th centuries.[202] A number of CO_2 storage projects have nevertheless been proposed for this region.[203]

A CO_2 repository planned by RWE near the Danish border was decisively rejected by local administrations and the government of the northern federal state of Schleswig-Holstein. In a letter to the Upper House of German Parliament (Bundesrat) on July 16, 2009, the county commissioner of Schleswig-Flensburg, Bogislav-Tessen von Gerlach, cited Paragraph 54 of the German mining law (Bundesberggesetz) that empowers local planning authorities to set subsurface licensing requirements. Since water utility companies and private property owners have already discounted CO_2 storage on grounds of uncertain geological integrity and long-term liability, these authorities would be obligated to enforce appropriately protective standards for project proposals.

Carbon dioxide storage could be relegated to offshore sites. In coastal salt domes, however, drinking water may still be contaminated even at a distance of 100 kilometres.[204] The injection of 0.6 tons of CO_2 into such a geological formation will displace one cubic metre of highly concentrated saltwater.

In addition to deep wells essential for drinking water supplies, certain regions possess formations suitable for storing natural gas or compressed air. Geothermal sources could reportedly supply Germany's electricity needs 600 times over".[205] The required wells are drilled to a depth of 2,500 to 3,500 metres in bedrock that is not generally suited for CO_2 storage.

7. Fundamental CCS Limitations

200 Bundesverband der Energie- und Wasserwirtschaft (April 21, 2010), op. cit., p. 3.

201 Krupp, Ralf E. (January 24, 2011): "Gutachten zur geplanten Kohlendioxid-Einlagerung (CCS) in der Antiklinal-Struktur Neutrebbin, Ostbrandenburg". Amt Barnim-Oderbruch: Wriezen, pp. 18 - 19.

202 Hannappel, Stephan et al. (2007): "Aufbau von Sondermessnetzen zur geogenen Grundwasserversalzung in Brandenburg". Brandenburgische Geowissenschaftliche Beiträge: Kleinmachnow, 14 (1-2007), p. 3.

203 Wendler, Simone (Februar 7, 2011): "CO_2-Speicher-Ausstieg durch die Hintertür". Lausitzer Rundschau: Cottbus.

204 Krupp, Ralf (August 2011): Risiken der Verpressung von Kohlendioxid unter der Nordsee. Bund für Umwelt und Naturschutz Deutschland: Berlin, p. 64.

205 Burgermeister, Jane (June 2, 2008): "Geothermal Electricity Booming in Germany". RenewableEnergyWorld.com.

The European Commission has noted that some 30% of the EU's electricity is generated using coal, and that "most of the future growth in energy consumption in a number of large emerging economies is expected to be met from coal".[206] It is considered imperative to align future power plant technologies with this global trend. The climate change secretary of the United Kingdom, Chris Huhne, has stated flatly: "It would be impossible for any new coal power station to be built without being equipped with carbon capture and storage" under that country's proposed Emission Performance Standard (EPS).[207] On a global scale, Kharecha and Hansen have determined that if coal use can be phased out by 2030 except where the CO_2 is captured, "it is possible to keep maximum 21st-century atmospheric CO_2 less than 450 ppm, provided that the EIA estimates of oil and gas reserves and reserve growth are not significant underestimates".[208]

Regardless of the technologies employed, however, CCS underlies a number of elementary restrictions that make its wide application improbable. Beside process energy and water expenditures, additional CO_2 compression penalties are incurred by pipeline losses and by injection at the storage site. The emissions reduction infrastructure encompasses a wide geographic expanse, crossing countless property lines, undermining entire regions, and imposing far-reaching planning requirements.

Restricted scalability. Decentralised and mobile applications (excluding land use and agriculture) are responsible for at least one-third of all CO_2 emissions in industrialised countries. The complex equipment required for eliminating carbon from power plant effluents would be difficult to downsize to urban infrastructures. If motor vehicles or ships were fitted with post-combustion membranes for tailpipe emissions, the captured CO_2 weighing 3.15 times as much as the gasoline producing it would have to be transported and disposed.

At the same time, most CCS demonstration projects are currently limited to individual steam turbines of modest capacity. Subsequent upscaling to full-size installations requires gas handling and compression capabilities in an unprecedented dimension. The world's three largest long-term CO_2 storage projects – Weyburn-Midale in Saskatchewan, Canada, the Sleipner saline aquifer CO_2 storage project in the North Sea, and the In Salah EGR project in Algeria – cumulatively inject an amount equal to only about one fourth of the carbon dioxide emitted by a single large lignite-fired power plant.

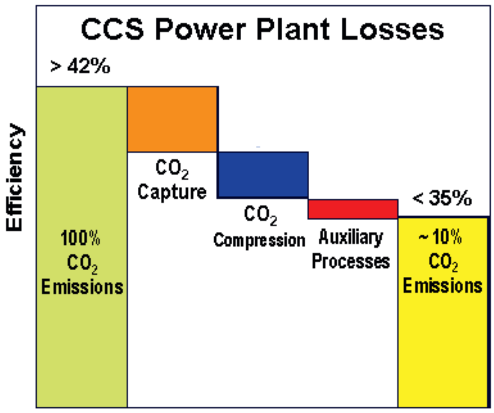
Energy intensity. Immense volumes of CO_2 must be separated from other gases in the power plant, dried thoroughly to prevent the formation of corro-

206 Commission of the European Communities (January 10, 2007): op. cit., p. 4

207 Wan, Kwok W. (August 17, 2010): "UK Needs Clean Coal For New Energy Policy: Government". World Environment News: Sydney.

208 Kharecha, Pushker A. and James E. Hansen (2008), op. cit., p. 8.

sive carbonic acid, and then compressed into a supercritical liquid state to permit pipeline transport to a geological repository. A significant portion of the fuel normally devoted to electrical generation is diverted to power the flue gas treatment processes. This "parasitic energy" reduces the electrical output to (1 – x) of its original value, where x is the decimal value of the diverted fuel quantity. To restore the power formerly fed to the grid, the total fuel consumption must be commensurately increased by a factor of 1/(1 – x).



For instance, diverting 20% (0.2) of the input fuel to CO_2 capture requires 25% more fuel to restore rated output generation. If the original electrical efficiency of the plant had been 42%, the increased fuel demand of 25% will reduce the overall efficiency to 42*100/125 = 33.6%.

When an existing power plant is retrofitted with CO_2 capture equipment, the rated output capacity is diminished. Although the size and performance of the internal turbine remain the same, part of the generated electricity is devoted to gas separation and compression. A second plant is then required to provide substitute power grid capacity.

The estimated energy requirements for CO_2 capture retrofits of existing coal-fired power plants equal 10% - 30% percent of original energy output.[209] To restore nameplate capacity, the final parasitic fuel demand could therefore lie as high as 43%. However, the energy of compression required for pipeline transport and injection, as well as additional electricity for mining further reduce the effective efficiency.

In evaluating the world's largest CCS pilot project in 2008, DONG Energy determined that separating one ton of carbon dioxide required an additional energy expenditure of 3.7 gigajoules (GJ).[210] As a consequence, the generation efficiency of the test power plant at Esbjerg, Denmark, was reduced from 45% to about 30%. In this case, 50% more fuel would have been necessary to restore the original grid power capacity, even disregarding external energy losses.

A 464 MW experimental plant has been developed by Foster Wheeler for the Spanish government's Fundación Ciudad de la Energía (CIUDEN).[211] The 43.5% efficiency attained in non-capture operation is reduced to 33.5% in oxyfuel mode for capturing 91% of the plant's CO_2 emissions,[212] increasing the fuel requirement per kWh of output power by about 32%. The carbon dioxide content of the flue gases is reduced in this mode of operation from 878

209 Ramezan, Massood et al. (November 2007): Carbon Dioxide Capture from Existing Coal-Fired Power Plants. National Energy Technology Laboratory: Pittsburgh, p. ES-5.

210 Wolff, Reinhard (November 24, 2008): "Abscheidung kostet richtig viel Kohle". Die Tageszeitung: Berlin.

211 Carbon Capture Journal (March 10, 2010): "CIUDEN awards Foster Wheeler contract for CCS plant Capture". Global CCS Institute: Canberra.

212 Eriksson, Timu et al. (May 26 - 28, 2009): "Development of Flexi-Burn™ CFB Technology Aiming at Fully Integrated CCS Demonstration". Foster Wheeler Energia Oy: Varkaus, p. 17.

to 90 g/kWh. The unit is part of the Integrated CCS Technology Development Plant (TDP) located near the existing ENDESA Compostilla power plant in Ponferrada, the location of one of the projects subsidised under the EU SET-Plan.

This efficiency loss does not include the additional power required for compressing the CO_2 for transport, which is accomplished by separate equipment located outside the capturing facility.[213] If 50% more fuel is required overall to capture, transport, and store CO_2 emissions, two CCS facilities would require a third plant of similar capacity to compensate for all parasitic energy losses.

In actual practice, even greater losses may be incurred. The \$2.2 billion IGCC power plant being constructed by the Summit Power Group at Penwell, Texas, will separate 90% of smokestack CO_2 to supply regional EOR operations.[214] In addition, 99% of effluent sulphur, over 95% of the mercury and 90% of nitrogen oxides will be removed. Of the 400 MW generation capacity, only 214 MW remains as grid power after all parasitic process losses are deducted.

Efficiency improvements achieved with advanced supercritical plant designs could become expensive to maintain due to the dwindling availability of high-grade coal. The Energy Watch Group has determined that the energy content of US coal production peaked in 1998 and has since declined despite the continuous rise in produced volumes.[215] In addition, after prime CO_2 repositories have become saturated, the use of less accessible geological formations would likely entail greater energy expenditures.

Cooling water intensity. The parasitic energy losses of CO_2 separation impose increased water demands, both for delivering additional steam to supplementary generating turbines (possibly at a different location) to restore the original grid capacity, and for cooling the added thermal losses dissipated by the process chain.[216] Depending on the plant design, CCS may require as much as twice the cooling water per kilowatt-hour of marketed electricity. This consideration is of relevance at any power plant site where water withdrawal already limits the maximum permissible generation capacity.

Installations such as the Vattenfall Moorburg coal fired power station (1,730 MW, 8.5 Mt of CO_2/a) in Hamburg, Germany, which has been licensed under stringent environmental limitations (river water withdrawal maximally

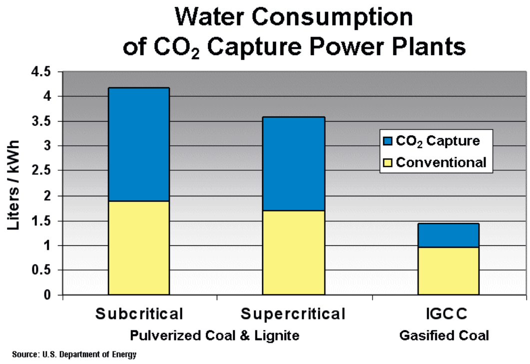
213 Ibid., p. 13.

214 Smith, Jack Z. (December 29, 2010): "West Texas 'clean coal' plant leaps big obstacle". Star-Telegram: Forth Worth.

215 Zittel, Werner and Jörg Schindler (July 2007), op. cit., p. 30.

216 Shuster, Erik (September 30, 2008): Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements. Department of Energy: Washington, p. 27.

64.4 m^3/s, O2 concentration minimally 4.0 mg/l),[217] might not attain sufficient profitability with the added water requirements and the diminishment of output grid power entailed by a CO_2-capture retrofit. To preclude overheating of the Elbe River even during conventional operation, the Moorburg plant has now being equipped with a hybrid cooling tower instead of a less expensive continuous withdrawal system.



CCS lignite power plants would impose additional demands on local water tables due to groundwater displacement precedent to mining. This prospect is particularly critical in the German Lusatian region that contends with water deficiencies of 4.5 billion cubic metres.[218] The entire water deficit of Germany is estimated at 80 billion m^3. Depending on the data source referenced, the water demand of thermal power stations in the country lies between 10% - 15% of total water usage. In the United States, power plant withdrawal is contributing to excessive water stress in 80 of 2,106 watersheds.[219] The Union of Concerned Scientists notes that in "much of the Southwest, even low water withdrawals can spell trouble, particularly when they come from diminishing aquifers".

Restrictive centralisation. The inclusion of municipal-scale gas power plants into CCS strategies would necessitate disproportionate capital outlays, since natural gas emits only about one third the CO_2 emissions of coal generation per kWh. The majority of gas power plants are employed only for intermittent operation, further reducing the ratio of carbon dioxide to CCS investment costs. The purchase of CO_2-free electricity from third parties would be less costly, as renewable grid power becomes increasingly available and competitively priced. Most municipalities possess no means of on-site sequestration. The same restriction applies to cement factories and other energy-intensive operations. The viability of CCS for such installations may therefore depend on their distance from pipelines or industrial centres with a multiplicity of emission sources.

Tenuous financing. To offset the additional expenses of technological implementation, a suitable "carbon-pricing environment" is to be established in the EU by 2020 - 2025.[220] Thereafter, ETS trading prices could not be allowed to fall below the costs of CCS realisation to preserve economic incentives for capturing CO_2. This stipulation predicates that all alternative CO_2-free technologies would become equally as expensive as CCS coal

217 City of Hamburg, water rights permit Nr. 4/5 AI 43 of 30. September 2008.

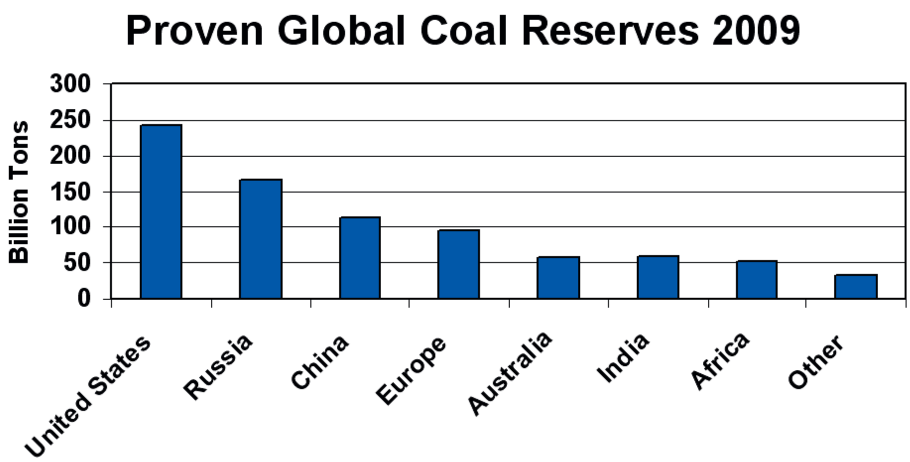
218 Michel, Jeffrey H. (February 2008), op. cit., p. 57.

219 Averyt, Kristen et. al. (November 2011): Freshwater Use by U.S. Power Plants. Union of Concerned Scientists: Cambridge, pp. 3 - 4.

220 Commission of the European Communities (October 10, 2009), op. cit., p. 6.

power plants for maintaining equitable competition. That prospect is highly improbable, however, because renewable energies are not rendered more expensive by ETS pricing, but instead become more competitive. High-risk insurance premiums would be inevitable for financing CCS process chains. Furthermore, the precautionary avoidance of "non-CCS technology lock-in" recommended by the European Commission[221] would make power plants inordinately expensive if capturing and storing CO_2 did not prove economically viable.

Illusions on global coal reserves. While CCS is hypothetically capable of harmonising power generation with climate protection strategies, increasingly limited coal deposits will ultimately restrict implementation to a very



few regions. A study published in 2007 by the European Commission has noted: "The lion's share of world proven coal reserves is concentrated in a few countries. Six countries (USA, China, India, Russia, South Africa, Australia) hold 84% of world hard coal reserves. Four out of these six (USA, Russia, China, Australia) also account for 78% of world brown coal reserves."[222] The report cites a proven reserves-to-production ratio of 155 years, but this figure assumes constant usage throughout the remaining Coal Age. Two years later, the World Coal Institute acknowledged coal reserves for only 122 years at current production levels.[223]

The website of the World Coal Association (www.worldcoal.org) notes that 130 years of global coal output had been estimated in 2011 by the German Federal Institute for Geosciences and Natural Resources (BGR), which in turn was being "used by the IEA as the main source of information about coal reserves". However, reserves reported by the World Energy Council (WEC) "are much lower – 861 billion tonnes, equivalent to 112 years of coal

221 ibid., p. 7.

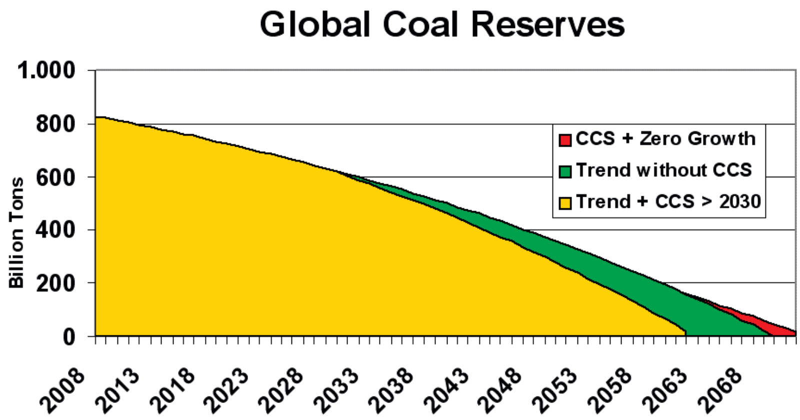
222 Kavalov, B. and S. D. Peteves (February 2007): The Future of Coal. European Commission: Brussels, p. 4.

223 World Coal Institute (2009): Coal Facts. WCI: London.

output".

Many coal supplies assumed for CCS implementation may therefore be prematurely depleted due to accelerating Asian usage and geological limitations on accessible resources.[224] The Energy Watch Group determined in a 2007 report that global coal estimates had already been downgraded by an overall 50% between 1980 and 2005.[225] China is now mining half the coal used by the world, yet imports have become indispensable for satisfying steadily increasing demand. Tom Whipple of the Post-Carbon Institute has concluded that if China's domestic coal production is thus already peaking, "then this event could turn out to be as serious as the peaking of oil".[226] By contrast, conventional business-as-usual projections show coal attaining maximum usage only around 2077,[227] even though most economically recoverable reserves will likely have been depleted beforehand.

In 2006, the EIA forecast that world coal consumption would be attaining 7,069 billion metric tons in the year 2015,[228] but this figure was surpassed by 2008. An increase in annual consumption of another billion tonnes appeared inevitable by 2012. This level of coal demand might appear to leave a comfortable margin against statistical global reserves of over 800 billion tonnes. However, the extrapolation of current trends leads to the hypothesis that economically accessible coal deposits could be exhausted by the year 2070. The general deployment of CCS after 2030 with assumed parasitic losses of 30% would deplete global reserves by 2062, or later only if demand could be rigidly capped. Coal exporting countries may become increasingly restrictive in supplying the world market, critically limiting fuel availabilities for CO_2-reduced generation. China and India have already begun buying coal mines in foreign countries to ensure adequate supplies of fuel for newly constructed power plants over their entire lifespan.



Promotion of intensified coal usage. Even as clean-coal technologies

224 Heinberg, Richard and David Fridley (November 18, 2010): op. cit., pp. 376 - 369; Behrmann, Elisabeth (November 24, 2010): "Coal Running Out, Prices to Soar, Nature Reports". Bloomberg.

225 Zittel, Werner and Jörg Schindler (July 2007): Coal: Resources and Future Production. Energy Watch Group: Berlin, p. 5.

226 Whipple, Tom (December 1, 2011): "Peak Coal is Moving Closer Too". Falls Church News-Press: Falls Church.

227 Kharecha, Pushker A. and James E. Hansen (2008), op. cit., p. 4.

228 Energy Information Administration (June 2006): International Energy Outlook 2006. EIA: Washington, p. 3.

remain too costly to become commercially competitive, publicly funded research implies continuing fossil fuel usage. CO_2 emissions are therefore likely to rise more rapidly than if CCS had never been proposed.

Disregard of Proportionality. A German Federal Government study quotes a 2006 IEA projection that commercial CCS implementation could prevent 2 Gt/a CO_2 by 2030.[229] This result would represent only about 5% of the emissions anticipated by that time, a result fully inadequate for fulfilling international climate protection accords.

If CCS could be used to fulfil the Kyoto requirement of reducing CO_2 emissions to 90% of 1990 levels, and considering the added coal usage that this technology entails, an American research team has calculated the required elimination of over 20 billion tons of carbon dioxide in the year 2030. This result is based on an EIA prediction that global CO_2 emissions will exceed the Kyoto target by 17.7 billion tons in 2030.[230] Depending on prevailing geological conditions, as many as 890,000 wells might have to be drilled worldwide by 2030 for emissions storage, or five wells per hour beginning in 2010. However, CCS commercialisation is only expected after 2020, while suitable regions have yet to be dedicated as storage locations. Atmospheric CO_2 concentrations are already increasing at a higher rate than foreseen by the Kyoto Protocol due to accelerated fuel consumption.

The World Coal Institute argues that for "every year that the widespread use of CCS is delayed after 2020 the long-term atmospheric stabilisation level of CO_2 is increased by 1 ppm".[231] Yet the disproportional relationship between individual demonstration projects and the geophysical scale of climate change cannot be overcome without commercial incentives in the required global dimension.

8. Project Assessments

CCS technologies will remain unsuitable for ongoing CO_2 remediation strategies if they cannot be economically implemented. Additional cost burdens result from intensified process requirements for fuel, water, and geological formations. The correspondingly increased demands on project payback must be justified by the decreased "carbon footprint" of power plant emissions despite the denial of these natural resources to competing ventures.

8.1. Dedicated Projects

In the EU, six of the intended 12 SET projects were approved in 2009 for

229 Federal Ministry for Economics and Technology et al. (September 19, 2007): op. cit., p. 5.

230 Xie, Xina and Michael J. Economides (March 2009), op. cit., pp. 2 - 3.

231 World Coal Institute (November 6, 2009), op. cit., p. 9.

European Commission funding: Jänschwalde (Germany, oxyfuel and post-combustion technology, with two transport and storage options), Porto-Tolle (Italy, 250 MW CCS flue gas treatment, storage in offshore aquifer), Rotterdam (Netherlands, 250 MW CCS chain, storage in a depleted offshore gas field), Belchatow (Poland, 250 MW supercritical lignite CCS chain, three saline aquifer exploration sites), Compostilla (Spain, 30 MW pilot, later above 320 MW oxyfuel CCS chain, saline aquifer storage), and Hatfield (United Kingdom, 900 MW IGCC intended for a regional CCS infrastructure, storage in an offshore gas field).[232] Each project received €180 million funding, with the exception of Porto-Tolle (€100 million). By the end of 2012, however, it had become apparent that none of the projects would be receiving funding adequate for completion as originally planned due to technological inadequacies or lack of public acceptance.[233]

In the United States, the EPA has expanded Clean Air Act permitting criteria to include climate change.[234] Effective July 2011, the act covers all new facilities with greenhouse gas emissions of at least 100,000 tons per year and modifications that would increase GHGs by at least 75,000 tons annually. Particular CCS projects directed toward precluding these obligations are receiving funding from the American Recovery and Reinvestment Act (ARRA).[235] Federal subsidies totalling $575 million were dedicated in 2010 to 22 projects for accelerating CCS research and associated industrial applications.[236] A year later, additional development grants totalling $41 million were provided for 16 advanced post-combustion technologies to reduce energy requirements and costs.[237] Mitsubishi Heavy Industries Ltd. has equipped a 25 MW CCS installation at Southern Company's Plant Barry that is owned and operated by Alabama Power.[238] The coal-fired plant captures approximately 150,000 tons of CO_2 annually (500 t/d) at a rate exceeding 90%, becoming the world's first CCS facility in continuous operation not dedicated to EOR. The CO_2 is injected into a deep saline geologic formation for permanent storage. In August 2011, the first large-scale industrial CCS facility in the United States was announced in Decatur, Illinois.[239] Since one million tons of carbon dioxide annually will be captured and stored from the

232 European Commission (October 9, 2009): "List of 15 energy projects for European economic recovery". EC: Brussels.

233 Schaps, Karolin and Barbara Lewis (December 19, 2912): "EU competition finds no carbon storage winner". World Environment News: Sydney.

234 Environmental Protection Agency (December 23, 2011): "Clean Air Act Permitting for Greenhouse Gas Emissions – Final Rules. Fact Sheet". EPA: Washington.

235 Sissine, Fred et al. (March 3, 2009): Energy Provisions in the American Recovery and Investment Act of 2009 (P.L. 111-5). Congressional Research Service: Washington, p. 12.

236 Department of Energy (September 2, 2010): "Industrial Carbon Capture Project Selections". DOE: Washington.

237 Department of Energy (August 25, 2011): "Department of Energy Announces $41 Million Investment forCarbon Capture Development". DOE: Washington.

238 Mitsubishi Heavy Industries (June 18, 2011): "Mitsubishi begins CO_2 capture at plant Barry". Carbon Capture Journal, Global CCS Institute: Canberra.

239 Department of Energy (August 25, 2011): "Energy Department Applauds Nation's First Large-Scale Industrial Carbon Capture and Storage Facility". DOE: Washington.

biologic fermentation of corn into fuel-grade ethanol, the plant exhibits a negative carbon footprint.

In Australia, industrial-scale CO_2 remediation efforts are regulated under the Offshore Petroleum and Greenhouse Gas Storage Act of 2008.[240] The National Low Emissions Coal (NLEC) Strategy has been designed "to ensure that low emissions technologies for coal, including CCS, are demonstrated at commercial scale from 2015 and are available for commercial deployment by 2020". In 2009 - 2010, the CCS Flagships programme was budgeted with 2 billion dollars of federal funding, for which four projects were initially considered: Wandoan (334 MW IGCC for sequestering 2.5 Mt CO_2/a), ZeroGen (400 MW IGCC, 2.5 Mt CO_2/a), Collie South West Hub (3.3 Mt CO_2/a from nearby industry), and CarbonNet Hub (3 - 5 Mt CO_2/a likewise from industries in the vicinity).

8.2. Modified and Abandoned Projects

Many announced CCS projects have been subsequently postponed or abandoned. This high attrition level has partially resulted from insufficient financing, subsidy withdrawal, or public rejection of CO_2 storage. In other instances, however, conceptual shortcomings have caused electrical power suppliers to retreat from the aspiration of clean fossil fuel generation. Numerous examples of project delays and cancellations prevail in countries once highly dedicated to CCS.

Norway. In June 2007, the Norwegian Ministry of Petroleum and Energy signed an agreement to establish the "European CO_2 Test Centre Mongstad" at Norway's largest refinery north of Bergen. The project was intended to develop "the world's largest CO_2 capture facility with subsequent compression and storage".[241]

According to initial planning, a new gas-fired combined heat and power plant (CHP) would have been commissioned in 2010, with full CO_2 capture added by 2014. The plant had been designed for generating 280 MW of electricity with 350 MW of thermal capacity. Part of the electrical power would have been used for capturing 0.35 Mt/a of CO_2 emissions, about 20% of the 1.8 Mt of carbon dioxide emitted each year. Another 1.1 Mt/a was to be captured by flue gas absorption. Subsequently, however, two of the industrial partners, Vattenfall and DONG Energy, withdrew from the project. Realisation has now been delayed until 2018.[242] Carbon capture capabilities would be far more expensive than initial estimates and could cost more than the gas plant itself

Denmark. At Nordjyllandsværket, the world's most efficient coal-fired

240 Department of Energy, Resources, and Tourism (January 10, 2010): "A Roadmap for CCS in Australia". Australian Government: Canberra.

241 Vattenfall (September 9, 2010): "Demonstration plant in Mongstad". Vattenfall AS: Stockholm.

242 Schjolberg, Beate (May 7, 2010): "Norway puts brake on Mongstad CCS". Upstream: Oslo.

power plant with 91% fuel utilisation, Vattenfall announced plans to build a full-scale CCS demonstration installation in February 2008.[243] The close proximity of the Vedsted CO_2 storage location in North Jutland constitutes a geographic advantage not available to most power stations. The plant would be capable of providing negative ETS offsets, since biomass firing is being substituted for one third of regular coal combustion. Vattenfall decided in 2009 to postpone the project, while submitting a revised application to the Danish Energy Agency for permission to store CO_2 in the Vedsted formation. A second CCS facility at the North Jutland Power Plant has likewise been delayed, with commissioning currently planned for around 2020. This revised schedule is necessary for conducting geological and geophysical studies on the suitability of Vedsted for storage uses.

United Kingdom. In 2007, BP had already discarded its intention to build a carbon capture centre in Scotland after the British government postponed an essential funding decision.[244] In 2008, however, DONG Energy announced its participation together with Peel Energy and RWE Power in constructing a 1,600 MW CCS power plant at the Scottish coastal town of Hunterston.[245] The advanced design would have been capable of firing biomass as well as imported coal while being availed of nearby offshore CO_2 storage formations. After evaluating initial performance data in 2009, however, DONG announced the abandonment of its CCS projects in Denmark and the United Kingdom while commencing a 30-year coal phase-out programme.[246] RWE likewise withdrew from the Hunterston project.

A revised CCS concept for the Hunterston power plant was announced in December 2010 by a new Peel Energy consortium including Doosan Power Systems, the engineering and construction company Fluor, and Petrofac, an international oil and gas facilities service provider.[247] The power plant would likewise be suitable for multiple fuels, including wood pellets, promising alleviation of ETS burdens by CCS and additional offsetting revenues from the sequestration of CO_2 from biomass. In contrast with earlier project objectives, however, only 300 MW of CCS generation capacity will now be initially deployed.[248]

243 Vattenfall (September 9, 2010): "Vattenfall´s CCS plant in northern Denmark". Vattenfall AS: Stockholm.

244 Moore, James (May 24, 2007): "BP scraps its carbon capture venture". The Independent: London.

245 Largs & Millport (November 26, 2008): "£2 billion clean coal power plant for Hunterston". Largs & Millport Weekly News: Androssen; POWERnews (December 17, 2008): "RWE, DONG Energy, and Peel Energyto Collaborate on UK CCS Project". TradeFair Group; Houston.

246 Ringstrom, Anna and John Acher (May 26, 2010): "DONG Energy's coal phase-out progressing: CEO". Reuters.

247 Bain, Simon (December 16, 2010): "Ayrshire Power consortium set to develop CCS plant". The Herald: Glasgow.

248 Riddell, John (December 15, 2010): "Coal plant plan is very much a threat". Largs & Millport Weekly News: Androssen.

In October 2011, the British government denied anticipated subsidies of £1.5 billion for a CCS demonstration project at the 2,400 MW coal-fired plant operated by Scottish Power at Longannet due to inordinately high technology costs.[249] However, funding of up to £1 billion for CCS projects granted by a new bidding process in England and Scotland was simultaneously announced.

The Scottish government intends to conduct "rolling reviews" of CCS until 2018, stating that "if CCS is not seen as technically or financially viable at some stage in the future then alternatives will be considered based around the Emissions Trading Scheme, including the possibility of an Emissions Performance Standard".[250] Coal-powered plants would thereupon be permitted to curtail unprofitable CO_2 capture operations and revert to buying emissions credits. This policy could significantly increase the forward risks of pipelines and infrastructure dependent on CO_2 transport revenues.

An investigation commissioned by Friends of the Earth, WWF, and the Royal Society for the Protection of Birds (RSPB) has concluded: "Even relatively cautious estimates of generation from renewables in Scotland, based on known projects and current rates of development, show very high levels of renewables production by 2020, and potentially higher levels thereafter, sufficient to effectively decarbonise electricity consumption in Scotland before 2030."[251] Among the benefits of "a high proportion of renewable generation, consumers are better insulated from fuel price variations or future fuel scarcity". Regarding fossil fuel power production, "new coal and gas-fired generation is expected at some point before 2020 to be more expensive than onshore wind. Given sufficient interconnection capacity to the rest of the GB system, it is not essential for there to be any coal, gas or nuclear generation in Scotland."

Despite sufficient harbour capacities for coal imports and the near proximity of North Sea gas fields both for energy supplies and CO_2 storage, the Government of Scotland has adopted a visibly reserved position regarding CCS that may be instructive for other countries with less favourable prerequisites for this technology.

Poland. Of the six EU-funded projects, the 250 MW demonstration plant at Belchatow was among the most promising. Feasible geological conditions for CO_2 storage in Poland have been determined in saline aquifers, gas fields, and coal beds. The 5,053 MW Belchatow lignite power station is Europe's largest single source of greenhouse gas emissions. In April 2013, however, the utility corporation PGE Elektrownia Belchatów S.A. confirmed the decision to "terminate" the CCS venture.[252] Despite relatively modest costs of €600

249 Schaps, Karolin et al. (October 19): "UK scraps Longannet carbon project funding". Reuters.

250 Riddell, John (December 15, 2010), op. cit.

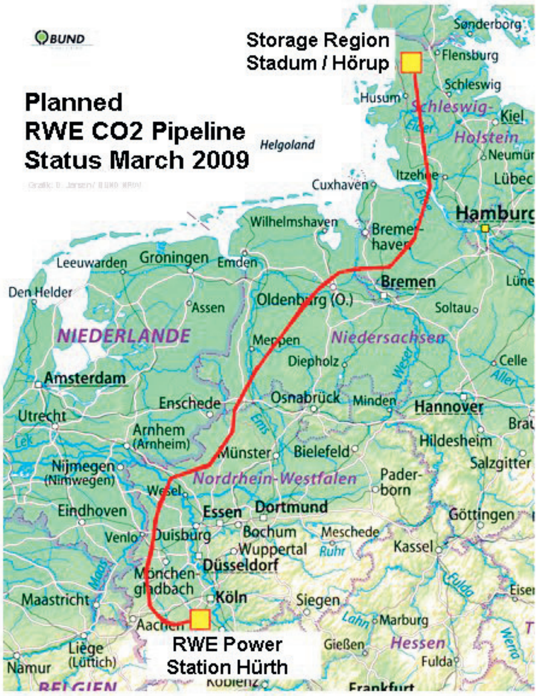
251 Gardner, Paul (September 30, 2010): Options for Coping with High Renewables Penetration in Scotland. Garrad Hassan & Partners Ltd., pp. 41 - 42: Bristol; Stratford, Beth (December 2010): The Power of Scotland Secured. FoE, WWF, RSPB.

252 Hallerman, Tamar (April 12, 2013): "PGE Ends Polish CCS Project; 'Green Hydrogen'

million, technical, legal and social risks had become a "material hazard for project continuation". Initially, 100,000 tonnes of CO_2 were to be captured from the retrofitted 250 MW plant. In a second phase, 1.8 Mt would have been drawn from 858 MW of cumulative generation using an advanced amine post-combustion capture system provided by Alstom.

The project was ranked second by the European Commission among preferred CCS projects in the summer of 2012, having already received additional funding commitments of €317 million from the Norwegian government and the European Energy Programme for Recovery in 2009.

Germany. The inadequacy of preparatory planning was illustrated in November 2009 by the denial of a 1 billion euro EU subsidy to RWE for a 400 MW IGCC lignite power plant at Hürth near Cologne. The intended CO_2 storage in northern Germany near the Danish border would have required a 530-kilometre, 24-inch pipeline routed at a depth of 1.5 metres[253] through densely populated regions potentially hostile to the project. The cost of the pipeline was estimated at €505 million in the year 2007. The use of domestic lignite for power generation by RWE contributes around 85 Mt of carbon dioxide to the emissions budget of western Germany, while lignite plants in the eastern states produce 70 Mt of CO_2/a. Additional hard coal and gas generation nearly doubles total emissions at RWE, making its German operations collectively Europe's largest source of greenhouse gases.[254] At 2.6 Mt per year, the planned pipeline would have transported less than 2% of the company's annual CO_2 emissions of about 150 Mt.[255]



BUND - Friends of the Earth Germany

The largest greenhouse gas point sources in Germany and adjacent mining regions in the Czech Republic, Poland, and Hungary are lignite power stations. Even after extensive plant modernisation had been completed in 1995 - 2001, this low-grade coal accounted for 22% of Germany's carbon dioxide emissions but only 11% of total energy consumption. The termination of lignite power generation therefore could appear to be an effective way of reducing emissions. However, the environmental detriments of lignite are overshadowed by an average thermal price of only €1.4/GJ,[256] considerably less than imported

also Appears Done". Exchange Monitor Publications: Washington.

253 Der Klimaschutz-Pipeline. RWE Dea AG: Hamburg.

254 Teske, Sven (April 2005): Gegen den Strom. Greenpeace International: Hamburg, p. 19.

255 Scheper, Alexandra (April 2007): Investition in Ineffizienz und Wahnwitz. Die Geschäfte von RWE. urgewald e. V.: Berlin, p. 13.

256 A Joule is 1 Watt-second; one megawatt-hour is 3.6 billion Joules, or 3.6 GJ. 1 GJ is

coal or natural gas. Domestic lignite mining costs also remain impervious to international energy market volatility.

Lignite relinquishes its economic advantage when the extraneous costs of landscape destruction, hydrological imbalances, and the demographic impoverishment of mining districts are considered. These impairments revoke the benefits of carbon capture in precluding ETS obligations. The additional energy requirements of CCS translate in Germany to increased lignite usage and total emissions exceeding more than 200 Mt of CO_2/a for one-fourth of electricity generation.

Since experimental CCS projects could not contribute to meeting greenhouse gas reduction targets, prolonging nuclear generation from Germany's 17 remaining reactors was originally intended as a temporary CO_2-free substitute. A reversal to nuclear phase-out in the aftermath of the March 2011 Fukushima disaster in Japan has since eliminated that perspective, expected in initial analyses to add 40 Mt of CO_2 per year to the country's emissions budget.[257] In an energy programme presented in September 2010,[258] however, the German federal government had already identified energy efficiency and renewable energies as "central approaches" for reducing greenhouse gas emissions by at least 80% in 2050. By contrast, CO_2 capture and storage was only termed an "option" directed particularly toward "energy intensive industries with high process-related CO_2 emissions such as steel, lime, cement, chemical production, and refineries". Such projects have not materialised.

Carbon dioxide repository planning for depleted gas fields in the state of Saxony-Anhalt was immediately confronted by unresolved issues of geological and well-hole integrity under CO_2 storage pressure.[259] The research phase intended from 2008 to 2011 included EGR testing under the designation "CO_2 Large-Scale Enhanced Gas Recovery in the Altmark Natural Gas Field (CLEAN)", a coordinated effort of Gaz de France (GdF), Suez E&P Deutschland, the German Research Center for Geosciences (GFZ Potsdam), and Vattenfall Europe. Local doctors petitioned to have the project abandoned due to their inability to respond in a timely manner to CO_2-related accidents. Extensive mercury deposits lodging in the gas formations would also present a latent health hazard. The project was terminated on June 30, 2011.

United States. The FutureGen project was announced by President George W. Bush in 2003 for a near zero-emissions coal-fuelled power plant designed to produce hydrogen and electricity. In 2007, Mattoon, Illinois was selected as the site of the $1.8 billion project owing to the proximity of coal

equal to 0.948 million British Thermal Units (MBTU).

257 Chestney, Nina and Jackie Cowhig (June 1, 2011): "German Nuclear Cull To Add 40 Million Tonnes CO_2 Per Year". World Environment News: Sydney.

258 Federal Ministry for Economics and Technology (September 28, 2010): Energiekonzept für eine umweltschonende,zuverlässige und bezahlbare Energieversorgung. BMWi: Berlin, p. 16.

259 Die Linke (November 10, 2010): "CCS-Forschungsprojekt CLEAN in der Altmark". Deutscher Bundestag, Drucksache 17/3726: Berlin.

resources and suitable geological storage formations. Subsequent technological simplifications were necessary to prevent project cancellation due to cost overruns.[260] The DOE then announced in August 2010 that new power plant construction had been abandoned. Instead of the IGCC design originally intended, only the storage site would be used for sequestering CO_2 from an existing power plant retrofitted with oxyfuel capture technology. A 175-mile (280-km) pipeline is to be constructed between the plant and the FutureGen storage location. Since property owners will receive royalty income for the subsurface land use, several communities are eager to be zoned as CO_2 storage tracts.[261] A $1.13 billion American Recovery subsidy is being provided to the FutureGen consortium, covering most of the $1.2 billion project expenditures.

The uncertain economic viability of IGCC designs employed for pre-combustion CO_2 capture has been illustrated by a 618 MW power plant under construction near Edwardsport, Illinois.[262] The original cost projection of $1.2 billion that included CCS in 2006 was raised in subsequent steps to nearly $3 billion without CO_2 capture.[263] The operator, Duke Energy, has noted that the plant is the first in the nation to use coal gasification on such a large scale. Even though the venture is benefiting from $460 million in tax incentives, Duke customers have been confronted with rate hikes totalling 34% to cover remaining project costs. The final cost had risen to $3.5 billion when the plant was dedicated in the spring of 2013.[264]

In July 2011, AEP prematurely terminated CCS operations at its Mountaineer coal power plant in New Haven, West Virginia, after completion of the engineering design and evaluation phase.[265] Continuation of the venture was not deemed prudent under the prevailing uncertainty of US climate policy.

In 2010, the 582 MW IGCC plant in Kemper County, Mississippi had been projected to cost $2.4 billion by completion in 2014.[266] A precautionary cap of $3.2 billion was imposed to preclude excessive cost overruns. In 2013, the cost estimate was raised to $2.88 billion, with associated lignite mines and pipelines priced at an additional $377 million.[267]

A further IGCC project in Rockville, Indiana, was approved in December,

260 Mercer, David (August 5, 2010): “DOE alters FutureGen plans in Illinois”. AP News.

261 Thoele, Cathy (November 18, 2010), op. cit.

262 Wilson, Charles (November 27, 2009): “Cost of coal-gasification plant reaches $2.5 billion”. Associated Press.

263 Blair, John (December 19, 2010): “History repeats in Duke ethics controversy”. Courier & Press: Evansville.

264 Silverstein, Ken (April 21, 2013): “Coal Gasification Could Unlock Coal’s Future”. Energybiz: Aurora.

265 Carbon Capture Journal (July 17, 2011): “AEP cancels CCS demo plans at Mountaineer plant”. Global CCS Institute: Canberra.

266 PowerGen Worldwide (December 17, 2010): “582 MW coal-fired power plant breaks ground”. PennWell Corporation: Tulsa.

267 IEA Clean Coal Centre (April 5, 2013): “USA: IGCC Power Plant Will Not Seek DOE Loan Help”. IEA: London.

2010, by the state finance authority.[268] The realisation cost of $2.65 billion includes 90% CO_2 emissions capture and the production of synthetic natural gas in quantities sufficient to cover 17% of the state's gas supply needs. However, profitable operation by the Indiana Gasification Corporation is predicated on twice current gas prices and connection to a long-distance CO_2 pipeline for EOR, leaving adequate project financing in doubt.

The prospects for a CO_2 pipeline network have since declined. In the beginning of 2011, the state senate of neighbouring Illinois failed to approve the Taylorville Energy Center coal gasification plant with 716 MW generation capacity and 602 MW net output, designated by the Tenaska Corporation as the most advanced clean coal installation in the world.[269] The rejected legislation would have allowed above-market electricity prices to complement a $417 million tax credit from stimulus funds and a $2.58 billion federal loan guarantee.

Canada. In February 2013, the government of Alberta cancelled a C$285 million 15-year funding commitment for carbon capture operations at the Swan Hills Synfuels plant due the high expense of producing coal-to-gas fuel in comparison with natural gas.[270] While the venture may be resumed at a later date, the TransAlta Corporation had already abandoned another of Alberta's prime CCS projects the previous year. Deficient markets for CO_2 and for emission reduction allocations compelled the termination of a C$1.4 billion carbon capture facility originally intended for a coal-fired power plant.

Australia. In December 2010, the $4.3 billion coal-fired ZeroGen Flagship project in Queensland was abandoned.[271] Initial research had demonstrated that planned commercial operation by 2015 would be impossible to achieve. The IGCC plant was designed for 65% CO_2 emissions capture with a potential of 90%, providing up to 2 Mt/a for storage in underground sandstone formations. Despite this setback, Queensland Premier Anna Bligh confirmed that greater expenditures on CCS technology were intended "over the next three to four years" in cooperation with the coal industry.

9. Commercial Prospects for CCS

In order to prevent stationary fossil fuel combustion from affecting the global climate, a comprehensive CO_2 storage infrastructure comparable in scale

268 Chadwick, John (December 29, 2010): "Coal gasification and power plant projects gain approvals in U.S.". Mine Web: London.

269 Tomic, Jeffrey (January 9, 2011): "Clean coal plant plans imperiled by Illinois Senate bill's failure". Star-Dispatch: St. Louis.

270 Jones, Jeffrey (February 26, 2013): "Alberta pulls funding from carbon-capture project". World Environment News: Sydney.

271 United Press International (December 20, 2010): "Australia scraps coal-fired CCS plant". UPI.

to current oil and gas extraction would be required.[272] Implementing such a strategy would require the parasitic losses of CCS process chains to be compensated by increased equipment investments and ongoing fuel purchases.

9.1. Impediments to Global CCS Strategies

In the year 2010, 68% of the world's recoverable coal reserves were concentrated in four regions: the United States (29%), Russia (19%), other non-OECD Europe and Eurasia (10%), and Australia/New Zealand (9%).[273] Although China (14%) and India (7%) together account for more than a fifth of statistical coal reserves, rising demand has made these economies increasingly dependent on foreign fuel supplies. A Chinese industry study released in 2003 forecast a domestic coal consumption of 1,720 Mt in the year 2010 and 1,950 - 2,100 Mt in 2020.[274] The actual demand trajectory has since exceeded twice these levels. Coal production in China is now expected to attain four billion tonnes by 2015,[275] while imports increased to 145 Mt in 2012.[276] India will likely become the world's largest coal importer by 2017.[277]

The long-term dedication of coal production capacities to fulfilling growing conventional demand effectively precludes the additional energy requirements of CCS implementation. Certain producers such as Indonesia and South Africa have occasionally restricted exports to maintain domestic priorities.

CO_2-reduced power plants require separate on-site capture and compression equipment, cross-country pipeline networks, and adequate geological repositories. The sequestration regions must be monitored for many centuries after plant decommissioning at incalculable expense. The responsibility for maintaining storage integrity ultimately passes from commercial operators to national authorities. A perpetual burden is therefore imposed on state treasuries, because indefinite monitoring, data evaluation, and leak investigation cannot otherwise be ensured. Any detected seismic disturbance will entail intensified supervision, analysis, and hazard control procedures at costs borne by future generations.

9.2. Enhanced Hydrocarbon Recovery

While carbon storage for purposes of climate protection fulfils no near-term commercial purpose, CO_2 enhancement of oil and gas production is

272 Meyer, James P., op. cit., p. iv.

273 Energy Information Administration (May 25, 2010), op. cit.

274 Youguo, He (2003): "China's Coal Demand Outlook for 2020 and Analysis of Coal Supply Capacity". China Coal Industry Development Research and Consulting Co. Ltd.: Beijing, p. 4.

275 Reuters (March 4, 2011): "China coal output could reach 4 bln T by 2015 - Datong Coal".

276 Kever, Jeannie (February 10, 2013): "Study: Coal train to China slowing". Houston Chronicle: Houston.

277 Overdorf, Jason (December 19, 2012): "India to be world's largest coal importer by 2017". Global Post: Boston.

sustained by the ongoing demand for fossil fuels. Carbon dioxide used for hydrocarbon extraction alleviates the perceived need for its passive disposal.

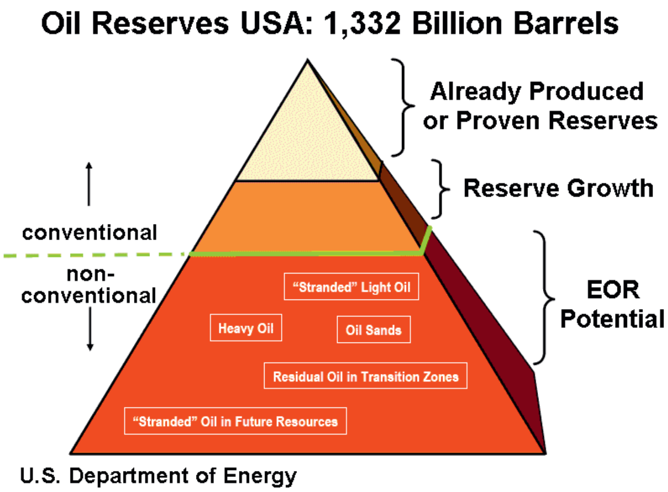
In addition to standard EOR and EGR applications, supercritical CO_2 is being employed as a hydraulic fracture fluid for shale gas extraction in the United States. Common regulations apply both to natural gas and shale gas extraction, both of which employ "Class II wells" that allow "brines and other fluids" to be injected.[278]

In Germany, CO_2 procured from the chemical industry has been injected to break open particularly dense natural gas formations in Lower Saxony.[279] Several thousand tonnes of carbon dioxide were injected by ExxonMobil in 26 instances between 2007 and 2010, with CO_2 comprising 30% - 70% of the fracture fluid. In relation to roughly one million tonnes of carbon dioxide emitted per day by German coal power plants, however, improved gas extraction using hydraulic fracturing provides no comparable CO_2 offset opportunities. Coal and lignite usage might be diminished in favour of local natural gas to facilitate emission reductions, but the routine injection of carbon dioxide for that purpose could widen the concerns already harboured against geological sequestration.

In the United States, some two hundred billion barrels of oil have been discovered but only partially exploited due to the geographical and geological inaccessibility of many deposits as well as technological limitations. Tom Sarkus of the US Clean Coal Initiative has stated: "We have all this talk about carbon caps and the oil industry can't get their hands on enough CO_2."[280]

According to assessments released in 2006, enhanced oil recovery, the development of oil sands, and residual oil in transition zones could theoretically represent a "total undeveloped remaining domestic oil resource" of 400 billion barrels, "nearly twenty times current proved crude oil reserves of 21.9 billion barrels, and two hundred times annual crude oil production of 1.88 billion barrels (in 2003)".[281]

The subsequent combustion of crude oil emits CO_2. Although in practice some of the carbon extracted by EOR remains embedded in chemical products such as plastics and paraffin, the average incremental



278 Ground Water Protection Council, ALL Consulting (April 2009): Modern Shale Gas Development in the United States. A Primer. Department of Energy: Washington, p. 32.

279 Hanke, Steven (February 2011): "Mit CCS zum Gasboom". Energlobe.de: Berlin.

280 Newkirk, Margaret (July 31, 2010): "Southern Co. moves ahead on 'clean coal'". The Atlanta Journal-Constitution: Atlanta.

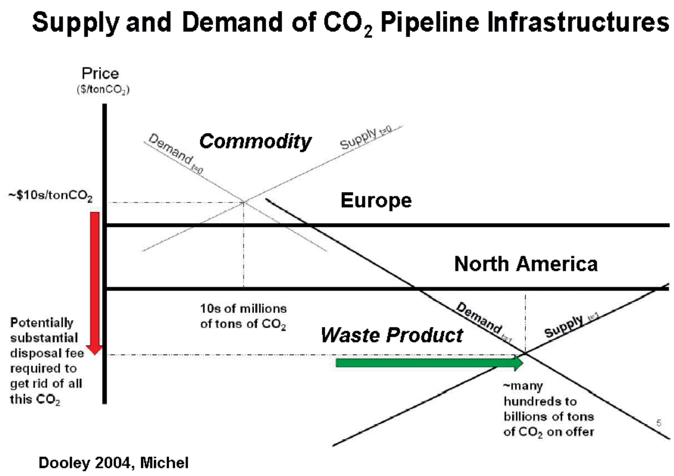
281 Advanced Resources International (February 2006): Undeveloped Domestic Oil Resources: The Foundation for Increasing Oil Production and a Viable Domestic Oil Industry. Department of Energy: Washington, p. A-9.

production of 3.6 barrels of crude oil per ton of CO_2 in the United States ultimately releases at least as much carbon dioxide into the atmosphere.

In Europe, there are about 200 oilfields in the North Sea,[282] some of which could be employed for EOR. While at least six potential projects in the United Kingdom, the Netherlands, and Denmark were listed in 2010, production cannot be undertaken before a sufficient volume of anthropogenic carbon dioxide is available. High-purity industrial CO_2 sources such as ammonia/fertiliser plants, ethanol and ethylene oxide plants, hydrogen plants, and natural gas processing plants "have lower capture costs than power plants and, consequently, could adopt CCS before such technologies begin to deploy broadly within the electric power sector".[283] To the extent that such installations become preferred providers for EOR ventures, the marketing prospects for the electrical power industry would be proportionally reduced.

Enhanced oil recovery transforms carbon dioxide from power plant effluents to the status of a commodity. Initially, a small number of sellers will determine CO_2 market prices.[284] If CCS systems are deployed on a large scale, however, "the supply of pipeline quality CO_2 on offer significantly exceeds demand".

While existing EOR contracts may remain profitable, market prices for surplus greenhouse gases cannot offset the cost of CCS implementation. Captured CO_2 then becomes a waste product for which disposal costs must be paid. Under this condition, a plant operator might suspend the operation of a CO_2 separation installation. While the resulting expense of ETS allocations would then be incurred, the electricity no longer required for CO_2 capture and compression could be additionally sold to the power grid for potentially greater returns.



The Alberta Carbon Capture and Storage Development Council has estimated that with an oil price of $75 per barrel and a field-delivered CO_2 price of $20 per ton, "proven recovery techniques have the potential to add 1.4 billion barrels of incremental oil and sequester 450 Mt of CO_2".[285] However, the combustion of all mineral oil products derived from this quantity of petroleum could emit up to 600 Mt of CO_2. Oil price increases provide an incentive for intensified CO_2 injection and EOR network

282 Carbon Capture & Storage Association (2010): "Technical background on Enhanced Hydrocarbon Recovery using CO_2 accompanied by permanent CO_2 storage". CCSA: London, p. 3.

283 Advanced Resources International (March 10, 2010), op. cit., p. A-9.

284 Dooley, J.J. et al. (July 2010), op. cit, p. 18.

285 Alberta Carbon Capture and Storage Development Council (March 2009), op. cit., p. 8.

expansion.

9.3. CCS vs. Climate Protection

CCS as a future corrective technology serves as a pretext to continue inherited coal usage. In addition, the CO_2 enhancement of oil and gas production contradicts emission reduction targets for greenhouse gases by introducing additional hydrocarbons into the biosphere that otherwise would have remained geologically inaccessible. In these respects, the EU-SET Plan reinforces fossil fuel infrastructures rather than superseding them.

Burning a barrel (159 litres) of crude oil weighing typically 135 kg produces around 430 kg of carbon dioxide. When all factors contributing to extraction, processing, and combustion are combined, the average life cycle emissions (excluding product transport) of North American petroleum are approximately 500 kg CO_2e per barrel.[286] In Alberta, the injection of one ton of CO_2 leads to 2.25 life cycle tons of greenhouse gas emissions. The current average for the United States is 1.8 tons, but with rising tendency. A net quantity of 0.8 tons of CO_2 (or 1.25 tons in Alberta) is therefore emitted into the atmosphere when a ton of carbon dioxide has been used to extract the corresponding amount of crude oil.

At the 2010 Convention on Climate Change in Cancún, Mexico, EOR was paradoxically included among Clean Development Mechanisms ostensibly intended to reduce carbon dioxide emissions by cost-effective means.[287] Such arrangements could induce semi-pressurised LNG tankers that normally return empty to transport CO_2 from China and Japan for sequestration in depleted gas basins in the Middle East, creating emissions credits for the natural gas industry.[288] The global carbon dioxide trade might encompass EOR applications while disregarding the life cycle emissions released from additionally retrieved hydrocarbons.

10. Public Action as Pathway to Sustainable Energy

The unsuitability of CCS as an adequate contribution to international climate protection strategies was not initially foreseeable. Enhanced Hydrocarbon Recovery constituted a demonstrated analogous approach to reconciling

286 Mangmeechai, Aweewan (August 2009): Life Cycle Greenhouse Gas Emissions, Consumptive Water Use and Levelized Costs of Unconventional Oil in North America. Carnegie Mellon University: Pittsburgh, p. 108.

287 Carbon Capture Journal (December 13, 2010): "UN accepts CCS in the Clean Development Mechanism". Global CCS Institute: Canberra; Hanke, Steven (December 16, 2010): "Müll für die Dritte Welt. UN fördern CO_2-Speicher in Entwicklungsländern". Energlobe.de: Berlin.

288 Parkinson, Giles (December 6, 2010): "Cancun calling – rorts and all". Climate Spectator: Melbourne.

fossil fuel usage with CO_2 reduction goals. This option was pursued to sustain coal and gas power generation within the framework of "decarbonisation" foreseen by the EU "Energy Roadmap 2050".[289] Yet the removal of carbon from emissions incongruously requires greater quantities of carbon-based fuel for powering inefficient CCS processes. This contradiction has precluded the prospect of global implementation. Developing industrial countries such as China and India are dependent on rising coal imports for conventional power generation. Expanding these fuel supply chains cannot be justified for CO_2 elimination technologies unless commensurate economic incentives are provided.

The reduction of costs through plant efficiency improvements is therefore a necessary but insufficient prerequisite for international CCS implementation. The assurance of Vattenfall CEO Lars Göran Josefsson in 2007 that CO_2-free power stations could be mass-produced "beginning in 2015 if possible"[290] lacked appropriate commercial substantiation. By temporarily subduing political concerns over coal-powered generation, critical years were lost for mounting an effective global offensive against climate change.

During this interim period, governments and coal plant operators dedicated CCS funding and expertise to sustaining coal usage under the pretence of climate protection. Reputable scientists contributed misdirected momentum to this effort. Particularly renowned was the head of the Potsdam Institute for Climate Impact Research (Pik), Hans Joachim Schellnhuber, who advised the government of Brandenburg "not to take carbon storage off the table too early"[291] despite contrary scientific evidence submitted to national and state parliaments. Even more important would be an "aggressive and massive" entry into the technology of reusing separated carbon dioxide, enabling Germany to "play in the world league". If in fact the carbon dioxide emissions from German lignite power generation were converted to a common material like calcium carbonate, it would be necessary to market over ten times the volume of products sold by the domestic cement industry (approximately 25 Mt annually). For billions of tonnes of global CO_2, the chemical utilisation of carbon dioxide would be quickly suffocated by extreme output yields.

Josefsson and Schellnhuber were appointed in 2006 as German Chancellor Angela Merkel's personal climate advisors,[292] fostering optimistic expectations on the prospects for CCS. In a resolution on energy and climate policy of May 7, 2007, the Social Democratic Party (SPD) in Brandenburg called for all existing and newly built large-scale power plants to be equipped with CO_2 separation equipment "by 2020 at the very latest".[293]

289 Commission of the European Communities (March 27, 2013): Communication. Energy Roadmap 2050.COM(2011) 885/2. EC: Brussels, p. 3.

290 Deutsche Presseagentur (January 18, 2007): "Vattenfall setzt auf CO_2-freien Kohlestrom".

291 Braun, Rüdiger (August 31, 2011): "Forscher fordern Kreislaufwirtschaft". Märkische Allgemeine: Potsdam.

292 Presse- und Informationsamt der Bundesregierung (December 1, 2006): "Bundeskanzlerin Merkel benennt Klimaberater". Deutsche Bundesregierung: Berlin.

293 SPD Landesvorstand (May 7, 2007): "10-Punkte-Programm der Brandenburger SPD zur

After Vattenfall announced its intention to inject carbon dioxide below the Brandenburg city of Beeskow,[294] a public protest demonstration on September 4, 2010, drew 2,000 residents and sympathisers. The legality of the project was considered questionable, since a national law had not yet been passed to implement EU Directive 2009/31/EC.

Widespread popular opposition arose to proposed geological storage ventures in the German states of Saxony-Anhalt (with initially 100,000 tonnes of CO_2 at Maxdorf) and Schleswig-Holstein (2.6 Mt/a delivered by RWE), as well as at other potential sites indicated by Vattenfall planning and correlated geological evaluations. Meetings by citizens' groups from various regions corroborated practices of collusion between commercial enterprises, ministries, and planning officials to the exclusion of the general public, but with the participation of mining authorities and geological institutes. The circumvention of democratic participation necessitated a countervailing approach to maintain the integrity of regions potentially affected by CO_2 storage, some of which anticipated impairments of water supplies and property values.

Local and regional groups were coordinated at the website www.kein-co2-endlager.de to exchange information and organise collaborative efforts. In 2009, the northern German initiative collected 100,000 signatures for a petition to the federal government on legislation for CO_2 storage ventures. The international ramifications of CO_2 storage made it essential to exchange information with other countries. Denmark (www.nejtilco2lagring.dk) constituted a compelling priority due to the common border with Schleswig-Holstein and shale gas formations in the same region. Carbon dioxide utilisation in the Netherlands prevails in symbiosis with the natural gas industry, greenhouse agriculture, planning for a CO_2 hub in Rotterdam, and the policy-neutral CATO research programme (www.co2-cato.org). In western Poland, public opposition has arisen against the Gubin-Brody lignite mine planned by Polska Grupa Energetyczna (PGE). Trans-border information is exchanged with the Green League in Brandenburg (www.lausitzer-braunkohle.de).[295]

In regional planning documents from the year 2008, Vattenfall had justified a new opencast lignite mine at Jänschwalde North with two planned commercial 1,000 MW CCS power plants.[296] In 2013, the intention of erecting a CCS power plant at Jänschwalde was confirmed on the company website (www.vattenfall.de) after 2020 if industrial scaling is achieved by that time. In view of widespread public protest against CO_2 storage in Germany, however, the possibility of a transport pipeline either to neighbouring Poland or to the North Sea has been studied by the government of Brandenburg. Vat-

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Energiepolitik und zum Klimaschutz". SPD Brandenburg: Potsdam.

294 Donath, Jessica (August 20, 2010): "One German Town's Fight against CO_2 Capture Technology". Spiegel Online: Hamburg.

295 Hennig, Irmela (February 10, 2012): "Polen erkundet Lagerstätten für CO_2". Sächsische Zeitung: Dresden.

296 Schuster, René (May 28, 2011): "Das Braunkohlenplanverfahren Jänschwalde-Nord aus der Sicht eines Umweltverbandes - ausgewählte Aspekte". Grüne Liga: Cottbus.

tenfall has discounted the use of Polish geological repositories,[297] leaving its ultimate intentions for CCS and lignite mining expansion unclear.

Popular opposition against the economic and health detriments of geological CO_2 sequestration in Europe has coalesced around Article 19 of EU Directive 2009/31/EC that allows Member States to "retain the right to determine the areas within their territory from which storage sites may be selected".[298] This flexibility includes the option "not to allow any storage in parts or on the whole of their territory", thus recognising "any other use of the underground, such as exploration, production and storage of hydrocarbons or geothermal use of aquifers" that may involve "the development of renewable sources of energy". The variety of qualified alternatives makes the dedication of onshore regions to any one particular objective improbable.

A CO_2 storage law was passed by the lower house of German Parliament on July 7, 2011, rejected by the upper house the following September, but finally enacted on August 17, 2012 with significantly diluted provisions.[299] The legislation contains no references to global warming objectives. Only generalised requirements on safety and monitoring have been imposed. The federal states are authorised to allow or deny sequestration in individual "specific areas". With CO_2 storage limited to 1.3 Mt/a per site and 4 Mt/a totally, only research applications are feasible. Vattenfall has emphasised that any law allowing territorial exclusions "obstructs investments in Carbon Capture and Storage (CCS) and endangers the ambitious climate protection goals in Germany and Europe".[300]

Most German states have disallowed CO_2 storage, eliminating the prospect of strategic CCS implementation. Yet while public opposition has prevailed over political expediency and selective scientific reasoning, the ongoing inefficiency of democratic processes has likewise been demonstrated. The ultimate failure of CCS has been primarily due to local geography rather than rigorous methodology. While potential leakage from CO_2 storage sites has a bearing on local human health, property values, and tourism, the alleviation of such concerns has not resolved any overlying environmental issues.

CCS could never offer a global prospect for alleviating the detrimental effects of coal usage. Yet careful deliberations a decade earlier on the unsuitability of symbolic therapies could have provided greater lead times for reforming energy policy. As it is, the persistence of uncorrelated and poorly funded public initiatives has momentarily prevailed over political, scientific, and commercial negligence. This success cannot qualify as an enduring

297 Sim (August 1, 2012): "Vattenfall dementiert angebliche Pläne für eine CO_2-Verpressung in Polen". Lausitzer Rundschau: Cottbus.

298 Commission of the European Communities (April 23, 2009), op. cit.

299 Deutscher Bundestag (17.08.2012): Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (Kohlendioxid-Speicherungsgesetz – KSpG). Bundestag: Berlin.

300 Vattenfall Europe AG (July 8, 2011): "Abschließende Lesung des CCS-Gesetzes im Bundestag". Vattenfall: Cottbus.

victory, however, unless public resources are now rigorously appropriated to sustainable energy development. The future contribution of innovative disruptive technologies may be difficult to predict, yet their potential exceeds the routine suppression of ingenuity.

11. Conclusions

The global conditions of human existence may be irreversibly changing due to accelerated fossil fuel usage, which has become integral to the material needs of growing populations in developing nations. Increased emission reduction efforts are therefore necessary to reinforce the climate protection goals originally formulated under more modest energy scenarios.

The vision of eliminating carbon dioxide emissions from fossil fuel combustion using CCS is understandable for a number of reasons. The most prominent locations of energy consumption are large coal-fired power plants and industrial installations that appear suited for new designs and retrofits. The concentration of plant emissions at centralised locations would facilitate the transport of captured CO_2 by long-distance pipeline to geological storage formations.

However, CCS process chains are conditioned on multiplicative cost factors involving:

- additional capital expenses of the CCS process chain
- additional fuel procurement costs
- expanded water withdrawal requirements, both for equipment cooling and for mining
- CO_2 storage monitoring obligations enduring for centuries
- emergency hazard readiness over a wide area.

The growing global demand for fossil fuels would be further intensified by CCS deployment, raising operational costs above the level of alternative energy technologies. The price of renewable power is already predicted to drop below conventional sources by 2020, considerably before commercial deployment of CCS would be feasible. Under this circumstance, the development of CO_2 capture technologies remains potentially viable only under two particular circumstances.

The availability of carbon trading allocations could be reduced to limit the effects of smokestack emissions, thereby restricting the use of dwindling fossil fuel reserves. Appropriately scaled emission costs would allow CCS installations to be operated profitably. This prospect remains highly speculative even for European countries, however, while less affluent societies generally cannot submit to the diffuse necessity of dedicating capital to delaying the effects of climate change.

Marketing opportunities for carbon dioxide gas provide an alternative prospect for the commercial development of capture technologies. While only limited possibilities exist for chemical manufacturing, CO_2 is being deployed to increase the extraction of natural gas and crude oil. The ability of inexpensive carbon dioxide to coax additional quantities of petroleum from abandoned oilfields is helping to shift peak oil predictions into the future. However, the improvement of CO_2 capture technologies will add more carbon to the biosphere from the petroleum, natural gas, and shale gas industries. From this perspective, subsidies provided by the European Commission for CCS projects contradict its objectives of sustainable development.

The lack of capture-ready power plants, the deficiency of CCS projects in non-OECD countries as well as the ongoing expansion of EOR pipeline networks in North America indicate that most coal-fired plants in either current operation or planning will never contribute to a reduction of global CO_2 emissions. The vague promise of CCS as a remedial technology only makes alterations of the global climate and ocean chemistry more precarious by entrenching global dependence on coal.

The intensified consumption of fossil fuels is compressing the time frame during which atmospheric CO_2 concentrations will reach recognised critical levels. Although this accelerated usage may incrementally raise energy prices to reduce demand, the total amount of carbon in the biosphere is steadily increasing. Strategies for insuring the conditions of human existence must take this cumulative development into account. Myriad decentralised experiences and capabilities can be combined into a cohesive system of global energy services only after the incompatibility of coal and CCS with that aspiration is appreciated.

Air Pollution & Climate Secretariat

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