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CARBON CAPTURE AND STORAGE: AN OPTION FOR HELPING TO MEET GROWING GLOBAL ENERGY DEMAND WHILE COUNTERING CLIMATE CHANGE

Victor K. Der *

I. INTRODUCTION

The global community is facing an energy and environmental paradox that could have profound implications for the worldwide economy. Fossil fuels—coal, oil, and natural gas—provide the vast majority of energy, particularly electricity, needed daily to power the world.[1] From 1971 to 2006, fossil fuels generated on average two-thirds of the world's total electricity, according to the Organization for Economic Cooperation and Development ("OECD").[2] But fossil fuels, especially coal, are also the most car-

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1. According to the International Energy Agency, fossil fuels accounted for more than 80% of world energy consumption in 2008. *See* INT'L ENERGY AGENCY, WORLD ENERGY OUTLOOK 2008: EXECUTIVE SUMMARY 4 (2008), *available at* http://www.worldenergyoutlook.org/docs/weo2008/WEO2008_es_english.pdf.

2. *See* ORG. FOR ECON. COOPERATION & DEV., OECD FACTBOOK 2009: ECONOMIC, ENVIRONMENTAL AND SOCIAL STATISTICS 120 (2009), *available at* http://puck.Sourceoecd.

bon-intensive energy sources: in 2008 fossil fuels accounted for nearly all of the six billion tons of U.S. carbon dioxide ("CO_2") emissions from energy consumption,[3] while coal contributed 36% of domestic CO_2 emissions.[4] The paradox is this: historically, energy from generally plentiful and affordable supplies of fossil fuels, even with their potentially disruptive impact, has been considered one of the important enablers of domestic economic growth.[5] At the same time, the use of these resources has released gigatons[6] of CO_2, a major greenhouse gas ("GHG"), into the atmosphere.[7] Many respected scientists agree with the idea that excessive atmospheric GHG emissions are statistically linked to the challenge of global climate change.[8] Even in entertainment,[9] political,[10] and religious[11] circles, prominent leaders who might disagree on other issues often find consensus with the need to act with respect to climate change.

Top coal producing nations, including the United States, China, and India, hold domestic coal reserves so abundant that exploration for the resource appears neglected.[12] These nations are also

org/pdf/factbook2009/302009011e-05-01-04.pdf. The OECD noted that some non-OECD countries may have difficulty reporting electricity from combustible renewables or waste biomass. *Id.* The minimum percentage of worldwide electricity attributed to fossil fuel in OECD's dataset was 62.2%, and the maximum percentage was 75.1%. *See* ORG. FOR ECON. COOPERATION & DEV., OECD FACTBOOK 2009: ECONOMIC, ENVIRONMENTAL AND SOCIAL STATISTICS, World Electricity Generation by Source-Energy, *available at* http://dx.doi.org/10.1787/536312870056.

3. *See* ENERGY INFO. ADMIN., U.S. DEP'T OF ENERGY, ANNUAL ENERGY OUTLOOK 2010, at 36 tbl.A18, *available at* http://www.eia.doe.gov/oiaf/aeo/pdf/appa.pdf.

4. *See id.*

5. *See The Oilshock: Pistol Pointed at the Heart*, ECONOMIST, May 31, 2008, at 58 ("[A]t the end of the 1970s, two successive oil shocks triggered long and deep recessions . . . . [O]il retains the power to disrupt."); *see also* Alfred J. Cavallo, *Hubbert's Model: Uses, Meanings, and Limits—1*, OIL & GAS J., June 6, 2005, at 22.

6. A gigaton is the equivalent of 1 billion tons.

7. *See* ENERGY INFO. ADMIN., *supra* note 3.

8. *See, e.g.*, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2007: SYNTHESIS REPORT 36 fig.2.1 (2007), *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf; Dr. Steven Chu, Energy@Berkeley: Solutions for Global Warming (Nov. 13, 2007), *available at* http://www.youtube.com/watch?v=HbjJxXgyxGE.

9. *See, e.g.*, Repower America, David Letterman and Billy Crystal, We Can Solve It (June 19, 2008), *available at* http://www.youtube.com/watch?v=7ZsURv-GR1Y.

10. *See, e.g.*, Repower America, Nancy Pelosi and Newt Gingrich Agree on Climate Change (July 11, 2008), *available at* http://www.youtube.com/watch?v=C-NIbZXNRns.

11. *See, e.g.*, Repower America, Al Sharpton & Pat Robertson Together on Climate Change (July 11, 2008), *available at* http://www.youtube.com/watch?v=gZ49e8YKycs&feature=channel.

12. Dr. Steven Chu, The Energy Problem: What the Helios Project Can Do About It (Apr. 23, 2007), *available at* http://www.youtube.com/watch?v=pLr4YbStc0M.

vested in an often extensive, dependent infrastructure.[13] Included in this infrastructure are coal-based generating plants with useful lives measured in decades, for which large investments have been made in response to long-term market signals.[14] A combination of considerations, including the length of plant service, investment requirements, significant lead-times needed to build energy infrastructure and gain cost improvements, and coal's relative abundance as an energy resource, make it unlikely that any country currently depending on this default fuel option[15] will completely replace its reliance in the short and intermediate term.[16] Even nations earnestly striving to move to more efficient or greener technologies in response to long-range market trends will need time to do so. Additionally, an estimated 1.5 billion people or more currently live without electricity.[17] If those nations create and utilize a fossil-fuel-powered grid[18] without the prospect of a scalable means for capturing CO_2, the global atmospheric buildup of this GHG would be direly exacerbated.

For the past several decades, the international research community, of which the U.S. Department of Energy's ("DOE") Office of Fossil Energy is an important part, has traveled a road of growing discovery regarding global climate change. During this period, policy and scientific debates about the role played by anthropogenic (i.e., human-induced) GHG emissions in warming the Earth's climate have continued.[19] Meanwhile, researchers

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13. *See* WORLD COAL INST., THE COAL RESOURCE: A COMPREHENSIVE OVERVIEW OF COAL 19–25 (2005), *available at* http://www.worldcoal.org/bin/pdf/original_pdf_file/coal_resource_overview_of_coal_report(03_06_2009).pdf; World Coal Inst., Coal Statistics, http://www.worldcoal.org/resources/coal-statistics/ (last visited Feb. 25, 2010).

14. *Newsmakers: Energy Sec. Steven Chu* (C-SPAN television broadcast Nov. 29, 2009), *available at* http://www.c-span.org/Watch/Media/2009/11/29/HP/A/26458/Energy+Sec+Steven+Chu.aspx.

15. *See* Chu, *supra* note 12.

16. *See* Chu, *supra* note 14.

17. United Nations Dev. Programme, World Health Org., *New Climate Deal Must Tackle Energy Poverty, Says UN* (Nov. 2009), http://content.undp.org/go/newsroom/2009/november/new-climate-deal-must-tackle-energy-poverty-says-un.en. According to Greenpeace, this number could be more than two billion people. *See* GREENPEACE BRIEFING, SOLAR GENERATION: ELECTRICITY FOR OVER 1 BILLION PEOPLE AND 2 MILLION JOBS BY 2020, at 3 (2010), *available at* http://www.greenpeace.org.br/energia/pdf/solargenback.pdf.

18. Michelle Nijhuis, *The Price of Power*, NAT'L GEOGRAPHIC: ENERGY FOR TOMORROW (COLLECTOR'S ED.), Mar. 2009, at 67, *available at* http://ngm.nationalgeographic.com/2009/03/price-of-power/nijhuis-text.

19. *See, e.g.*, The Pew Research Center for the People & the Press, Little Consensus on Global Warming (July 12, 2006), http://people-press.org/report/280/little-consensus-on-

have progressively built a body of knowledge based on experiments, observations, modeling, theory testing, the study of ancient ice cores, and examination of historical and current weather data.[20] The consensus among the scientific community emanating from this gradual accumulation of evidence and analysis is that rising fossil fuel CO_2 emissions are contributing significantly to more extreme temperature swings and could permanently and adversely impact the Earth's climate.[21]

Complicating matters, the formidable challenge of reducing GHG emissions is coming at a time when significantly more energy will be needed to meet expected future demand, much of which will come from developing countries.[22] While alternative sources of energy exist, short- and intermediate-term forecasts demonstrate there are barriers to global substitution, including expense, intermittency, adjustability, geographic concentration, and long development lead-times.[23] The practical challenge facing the United States and other developed nations is how to continue to depend on coal as a primary electricity source while assuring this reliance is both economically and environmentally sustainable. Of equal importance in resolving this issue, however, is an associated philosophical challenge: in an increasingly carbon-constrained world, what workable solution can we provide for coal-producing and consuming nations, whose participation in the effort to resolve atmospheric CO_2 buildup is critical to success?

Underlying all of these issues is the fact that climate change is a complex and challenging problem with many variables and no all-encompassing answer. As a result, many think developing a portfolio or range of options is the most suitable, potentially effective, and sustainable response.[24] While energy efficiency improvements, increased use of renewables, and greater utilization

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global-warming.

20. *See, e.g.*, Richard Alley et al., *Summary for Policymakers*, *in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE IPCC 2–18 figs.SPM 1, 2, 3, 4, 5, 6 & 7 & tbls.SPM 1, 2 & 3 (S. Solomon et al. eds., 2007), *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf.

21. *See, e.g.*, Peter T. Doran & Maggie Kendall Zimmerman, *Examining the Scientific Consensus on Climate Change*, EOS, Jan. 20, 2009, at 22.

22. *See* INT'L ENERGY AGENCY, WORLD ENERGY OUTLOOK 2009: EXECUTIVE SUMMARY 4 (2009), *available at* http://www.iea.org/Textbase/npsum/weo2009/sum.pdf.

23. INT'L ENERGY AGENCY, *supra* note 1, at 4–5.

24. *See, e.g.*, *id.* at 13–15.

of nuclear power are important components of this portfolio, among the most promising potential solutions for countries reliant on large fossil fuel reserves is CO_2 capture and storage ("CCS"), also known as sequestration.[25] This procedure can reduce CO_2 output from present stationary emitting sources and help avoid future atmospheric emissions.[26]

For a number of years, DOE has been at the forefront of domestic and international research and development ("R&D") efforts to actively pursue the capture and storage of CO_2 emissions from fossil fuel power and industrial plants.[27] For example, over thirty years ago, DOE improved enhanced oil recovery ("EOR") with low temperature CO_2 flooding, as disclosed in the Comberiati patent application from 1979.[28] Because of CCS research and other worldwide R&D initiatives,[29] if there is a sufficient price placed on emitting CO_2 within the decade, CCS could transition from experimental and demonstration levels to global commercial deployment. While substantial progress has been made, CCS is at a critical stage of development: there are still several significant technical and non-technical hurdles[30] that must be overcome before this transition can occur and the technology is firmly established as an effective option for reducing CO_2 emissions. Many of these challenges are being addressed directly and indirectly through both the DOE R&D program and international partnerships. Although significant and complex, none of these hurdles

25. *See* Steven Chu, Editorial, *Carbon Capture and Sequestration*, 325 SCIENCE 1599, 1599 (2009).

26. In addition to the geological approach, other sequestration ideas are also being researched. *See id.*

27. Nat'l Energy Tech. Lab., U.S. Dep't of Energy, Carbon Sequestration: Carbon Capture and Storage Database (2009), http://www.netl.doe.gov/technologies/carbon_seq/database/index.html; *see, e.g.*, U.S. Dep't of Energy, Carbon Capture 2020 Workshop (Oct. 5–6, 2009), http://www.netl.doe.gov/publications/proceedings/09/CC2020/index.html.

28. Method for Enhanced Oil Recovery, U.S. Patent No. 4,224,992 (filed Apr. 30, 1979) (assigning the patent to DOE).

29. *E.g.*, System for Small Particle and CO_2 Removal from Flue Gas Using an Improved Chimney or Stack, U.S. Patent No. 6,648,949 (filed Nov. 18, 2003) (assigning the patent to DOE).

30. *See, e.g.*, ORG. FOR ECON. COOPERATION & DEV. & INT'L ENERGY AGENCY, CARBON CAPTURE AND STORAGE 3 (2009), *available at* http://www.iea.org/G8/docs/ccs_g8july09.pdf; *see also* EXXONMOBIL, OUTLOOK FOR ENERGY: A VIEW TO 2030, at 24 (2009), *available at* http://www.exxonmobil.com/corporate/files/news_pub_eo_2009.pdf. The ExxonMobil outlook hinted that CO_2 should be above $60 per ton if CCS is going to become popular with today's technology. EXXONMOBIL, *supra*. The outlook predicted that below $30 per ton it would be cheaper to buy a CO_2 offset. *Id.*

appear insurmountable,[31] yet failure to deal with them in a timely and effective fashion could delay—or even prevent—expedited and comprehensive CCS deployment.

The atmosphere of international urgency for dealing with the climate change issue is further driving an accelerated deployment of CCS. Some experts suggest cost-competitive CCS must be deployed in a majority of countries and situations by 2020.[32] Many also believe this action is necessary to reduce energy-related CO_2 emissions enough to begin the process of stabilizing atmospheric GHG concentrations to help avoid possibly catastrophic warming later in the century.[33] The crux of the matter is this: the manner in which these issues are resolved will likely impact not only the effectiveness of CCS as part of a portfolio solution, but also global energy supply, use, and cost, as well as the growth of economies primarily dependent on coal for electricity. Cumulatively, these issues add up to a daunting challenge that the international community recognizes it must address with alacrity.

Consequently, this discussion focuses on the potential of CCS for meeting the world's CO_2 reduction goal, the nature of the challenges facing commercial deployment of the technology and how they might be overcome, the current status of R&D and the role played by the DOE program, and how international cooperation is the key to progress in mitigating climate change.

II. HOW CARBON CAPTURE AND STORAGE CAN HELP MEET CO_2 REDUCTION GOALS

An abundance of coal and natural gas in North America has, to a large degree, historically powered the economy of the United States, and this remains true today. In 2008, 51% of U.S. electricity came from coal while 17% came from natural gas.[34] A recent Congressional Research Service analysis of total fossil fuel reserves of selected nations indicated that coal represents 93% of the United States' total fossil fuel reserves and over half of the

31. Chu, *supra* note 12.

32. *See, e.g.*, Chu, *supra* note 25.

33. *See, e.g.*, INT'L ENERGY AGENCY, TECHNOLOGY ROADMAP: CARBON CAPTURE AND STORAGE 4–5 (2009), *available at* http://www.iea.org/papers/2009/CCS_Roadmap.pdf.

34. ENERGY INFO. ADMIN., U.S. DEP'T OF ENERGY, ANNUAL ENERGY REVIEW 2008, at 37 fig.2.0 (2009), *available at* http://www.eia.doe.gov/aer/pdf/aer.pdf.

world's fossil fuel reserves when expressed in barrels of oil equivalent ("BOE").[35] In 2005 the Energy Information Administration ("EIA") reported 263 billion short tons of recoverable coal[36] in the United States and recent rates of consumption of about 1.13 billion tons per year,[37] which indicates the United States has sufficient coal to meet its needs for at least the next two centuries. In 2008, 91% of coal consumed in the United States was for electricity generation,[38] the source of the majority of the nation's GHG emissions.[39] Although EIA predicts coal's share of total U.S. electricity generation may decline from 48.5% to 43.8% between now and 2035,[40] coal would still represent the largest single share by fuel type.[41]

The cumulative amount of CO_2 emitted into the atmosphere, in combination with CO_2's radiative forcing function, has been shown to add significantly to the greenhouse effect.[42] Radiative forcing refers to an imbalance between incoming solar radiation and outgoing infrared radiation that causes the Earth's radiative balance to absorb more heat.[43] This imbalance is thought to contribute to greater temperature variation in regions with polar ice, elevated sea levels from ice melt, and changes in precipitation

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35. GENE WHITNEY ET AL., CONG. RESEARCH SERV., U.S. FOSSIL FUEL RESOURCES: TERMINOLOGY, REPORTING, AND SUMMARY 17 tbl.5 (2009).

36. ENERGY INFO. ADMIN., *supra* note 34, at 331 tbl.11.13.

37. *Id.* at xxix fig.38.

38. *Id.* at 37 fig.2.0.

39. U.S. Envtl. Prot. Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2006 (2008), http://epa.gov/climatechange/emissions/downloads/2008_GHG_Fast_Facts.pdf.

40. Richard Newell, Adm'r, Energy Info. Admin., U.S. Dep't of Energy, Annual Energy Outlook 2010: Reference Case, Presentation at the Paul H. Nitze School of Advanced International Studies (Dec. 14, 2009).

41. *Id.*

42. ENERGY INFO. ADMIN., *supra* note 34, at 346 fig.12.1; *see* Piers Forster et al., *Changes in Atmospheric Constituents and in Radiative Forcing*, *in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, *supra* note 20, at 141 tbl.2.1; ROBERT HENSON, THE ROUGH GUIDE TO CLIMATE CHANGE 25 (2008). It should be noted that standard estimates indicate methane is twenty-five times more potent than CO_2 as a GHG, but there is far less methane in the atmosphere. *See* Nat'l Oceanic & Atmospheric Admin. Greenhouse Gases Continue to Climb Despite Economic Slump (Apr. 21, 2009), http://www.noaanews.noaa.gov/stories2009/20090421_carbon.html. A recent study by NASA's Goddard Institute for Space Studies, however, suggests that methane's contribution could be greater than earlier estimates due to its persistent effect. *See* Krishna Ramanujan, Methane's Impacts on Climate Change May Be Twice Previous Estimates (July 18, 2005), http://www.nasa.gov/vision/earth/lookingatearth/methane.html.

43. Forster et al., *supra* note 42, at 136.

that could exhibit extremes, such as droughts and flooding.[44] Radiative forcing also measures the relative contribution and influence of different GHGs on climate change.[45]

Essentially, we can discern from these numbers that (1) coal use as a source of electricity generation has traditionally been important to the U.S. economy; (2) coal represents the vast majority of the United States' traditional domestic energy reserves; (3) because of coal's abundance and existing infrastructure, we are likely to continue to use coal as a major source of electricity for the foreseeable future; and (4) coal-based CO_2 emissions, both from a quantity and radiative perspective, are an important consideration when looking at the potential impact on global climate. Consequently, we need to substantially reduce the atmospheric CO_2 emissions associated with the use of coal.

Analogous calculations apply when looking at the abundance and probable longevity of coal from an international perspective. According to OECD, fossil fuels provided nearly two-thirds of total world electricity production in 2005, with coal and its earlier formative stage, peat, accounting for 40%.[46] This is a scenario many forecasts do not expect to change appreciably over the near and intermediate term. In one scenario, EIA expects a world coal consumption growth trend of 1.7% annually through 2030.[47] The International Energy Agency ("IEA") predicts a similar trend, forecasting that fossil fuels will remain the dominant sources of primary energy worldwide through 2030, and coal's share of the global power sector will rise 3% to a total of 44% by 2030.[48] Both forecasts agree much of the increase in coal use will come from developing countries, particularly China and India.[49]

There are several reasons to expect continued worldwide reliance on coal for electricity generation. Coal has shown itself to be among the most affordable and reliable fuel options for large-scale electricity generation in the United States, where the power

44. *See* Hervé Le Treut et al., *Historical Overview of Climate Change Science*, *in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, *supra* note 20, at 101, 109, 116, 122.

45. Forster et al., *supra* note 42, at 136.

46. ENERGY INFO. ADMIN., *supra* note 34, at 307 tbl.11.1.

47. ENERGY INFO. ADMIN, U.S. DEP'T OF ENERGY, INTERNATIONAL ENERGY OUTLOOK 2009, at 9 (2009), *available at* http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2009).pdf.

48. INT'L ENERGY AGENCY, *supra* note 22, at 4.

49. *Id.*; ENERGY INFO. ADMIN., *supra* note 47, at ix, 51.

generation market seeks reliability and affordability.[50] Elementary economic laws of supply and demand anticipate coal's affordability in view of the abundant resources available in the United States (China, India, Russia, and several other countries also have large reserves).[51] This affordability provides a cushion for absorbing the added costs of new technologies and pollution control innovations, such as CCS, while keeping coal competitive as an energy option.[52] These qualities cumulatively make coal-based power plants important electricity price stabilizers and reliable electricity producers.[53]

But hydrocarbon fuel use does not come without significant challenges in terms of climate change. The same carbon bonding that allows coal to release energy upon combustion also results in it being a major source of human-generated CO_2 emissions.[54] In 2006 coal delivered a little over one-quarter of world energy to end users and over 40% of global CO_2 emissions.[55] EIA statistics suggest the roughly 6.7 billion short tons of coal used worldwide in 2006[56] may have produced 13.3 billion short tons of CO_2 emissions,[57] though this depends on the composition of the coal and means of combustion. The United Nations Intergovernmental Panel on Climate Change ("IPCC") comprised of noted climate scientists from around the world, believes warming of the climate is underway and "[g]lobal atmospheric concentrations of [GHGs] have increased markedly as a result of human activities since

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50. *See* William L. Massey et al., *Reliability-Based Competition in Wholesale Electricity: Legal and Policy Perspectives*, 25 ENERGY L.J. 319, 319–21 (2004), *available at* http://www.felj.org/elj/Energy%20Journals/Vol25_No2_2004_Art_%Reliability-Based.pdf; U.S. Dep't of Energy, Clean Power Generation-Market and Policy Drivers, http://www.netl.doe.gov/KeyIssues/clean_power2.html (last visited Feb. 25, 2010).

51. *See* U.S. Dep't of Energy, *supra* note 50; World Coal Inst., *supra* note 13.

52. *See* MASS. INST. OF TECH., THE FUTURE OF COAL: OPTIONS FOR A CARBON-CONSTRAINED WORLD xi (2007), *available at* http://web.mit.edu/coal/The_Future_of_Coal.pdf.

53. *See supra* notes 50–52 and accompanying text.

54. *See* ENERGY INFO. ADMIN., *supra* note 47, at 109.

55. *Id.* at 49, 110.

56. Energy Info. Admin., U.S. Dep't of Energy, World Coal Data, http://www.eia.doe.gov/iea/coal.html (last visited Feb. 25, 2010).

57. ENERGY INFO. ADMIN., *supra* note 47, at 113. The EIA predicts that "[t]otal carbon dioxide emissions from the combustion of coal throughout the world [will] increase by 1.7% per year on average, from 12.1 billion metric tons in 2006 to 18.0 billion metric tons in 2030." *Id.*

1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years."[58]

Present affordability,[59] combined with the motivation by both developed and developing countries to minimize the cost of electricity, makes it unlikely any of the current large-scale coal consumers could abruptly abandon their prior economic investment in coal entirely. Additionally, the attraction of plentiful and relatively inexpensive electricity may be irresistible for nations that can barely afford to use the cheapest energy resource already in hand. During the past twenty years, about three-quarters of human-caused GHG emissions are attributable to burning fossil fuels,[60] and U.S. CO_2 emissions have increased about 20% over this period.[61] Taken as a whole, these factors suggest the scale of CO_2 reduction needed to address potential worldwide carbon emissions is staggering.

According to EIA, in 2006 the United States produced more than 21% of the global Gross Domestic Product ("GDP") of $59.9 trillion (expressed in purchasing power parity); the United States had the largest total GDP for any single nation.[62] That same year, the United States was the second largest contributor of CO_2 emissions after China.[63] But it is also important to keep in mind the global aggregate perspective of the GHG issue. There is an obvious need to reduce global carbon intensity per unit of industrial production in terms of the major components of the industrial sector, such as chemicals, petroleum and coal products, primary metals, nonmetallic mineral products, plastics and rubber products, and other key groups.[64] Many simple technical and policy options could yield localized reductions of CO_2 emissions at the expense of increasing the difficulty of meeting national and global emission benchmarks. This would occur, for example, if top CO_2

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58. IPCC, *supra* note 8, at 30, 37.

59. *See* World Coal Inst., Coal Price, http://www.worldcoal.org/coal/market-amp-transportation/coal-price (last visited Feb. 25, 2010).

60. *See* Energy Info. Admin., U.S. Dep't of Energy, Energy and the Environment Explained: Greenhouse Gases' Effect on the Climate (2009), http://tonto.eia.doe.gov/energy explained/index.cfm?page=environment_how_ghg_affect_climate.

61. *See* ENERGY INFO. ADMIN., U.S. DEP'T OF ENERGY, U.S. CARBON DIOXIDE EMISSIONS FROM ENERGY SOURCES: 2008 *FLASH* ESTIMATE 15 (2009), *available at* http:// www.eia.doe.gov/oiaf/1605/flash/pdf/flash.pdf.

62. *See* ENERGY INFO. ADMIN., *supra* note 47, at 124 tbl.A3.

63. *Id.* at 131 tbl.A10.

64. *See* ENERGY INFO. ADMIN., *supra* note 34, at 353 tbl.12.4.

producing industries shifted activities across a state or national boundary, or if a CO_2 offsetting activity simply moved inside these boundaries.[65] Absent a reduction in demand for carbon-intensive products or services, some combination of efficiency improvements[66] and deployment of CCS appears necessary to offset or fulfill global CO_2 emissions goals within top industry emitting sectors.[67]

Developing countries exceeded the CO_2 emissions of the OECD (consisting primarily of developed economies) by 14% in 2006.[68] In view of historical data collected between 1990 and 2006 (and without any policy change), EIA foresees at least one scenario where world energy-related CO_2 emissions could grow 25% by 2030,[69] and coal's share of the total increasing from 42% to 45%.[70] Due to a heavy reliance on coal for economic growth, EIA predicts India and China's combined share of world CO_2 emissions will grow from 25% in 2006 to 34% by 2030, and China itself could contribute 29% of the global total if historical trends persist.[71] Meanwhile, IEA foresees a 40% increase in world primary energy demand by 2030, with India and China accounting for 53% of the increase.[72] IEA also foresees an unsustainable energy trend heading towards a 40% rise in global CO_2 emissions, with non-OECD countries contributing 90% of the projected rise.[73]

What might the consequences be if present trends continue unabated? "In computer-based models, rising concentrations of

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65. *See* CONG. BUDGET OFFICE, EVALUATING THE ROLE OF PRICES AND R&D IN REDUCING CARBON DIOXIDE EMISSIONS 18–19 (2006), *available at* http://www.cbo.gov/ftp docs/75xx/doc7567/09-18-CarbonEmissions.pdf.

66. INT'L ENERGY AGENCY, TRACKING INDUSTRIAL ENERGY EFFICIENCY AND CO_2 EMISSIONS 21, 22 tbl.1, 23 (2007), *available at* http://www.iea.org/textbase/nppdf/free/2007/tracking_emissions.pdf.

67. *See* ENERGY INFO. ADMIN., U.S. DEP'T OF ENERGY, ENERGY MARKET AND ECONOMIC IMPACTS OF H.R. 2454, THE AMERICAN CLEAN ENERGY AND SECURITY ACT OF 2009 ix–x (2009), *available at* http://www.eia.doe.gov/oiaf/servicerpt/hr2454/pdf/sroiaf(2009)05.pdf.

68. ENERGY INFO. ADMIN., *supra* note 47, at 109.

69. ENERGY INFO. ADMIN., U.S. DEP'T OF ENERGY, ANNUAL ENERGY OUTLOOK 2008 WITH PROJECTIONS TO 2030, at 86 (2008), *available at* http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2008).pdf.

70. ENERGY INFO. ADMIN., *supra* note 47, at 110.

71. *Id.*

72. Int'l Energy Agency, World Energy Outlook 2009 Fact Sheet: Why is Our Current Energy Pathway Unsustainable? 1 (2009), http://www.iea.org/weo/docs/weo2009/fact_sheets_weo_2009.pdf.

73. *Id.*

greenhouse gases" contribute to "an increase in the average surface temperature of the Earth over time. Rising temperatures may, in turn, produce changes in precipitation patterns, storm severity, and sea level commonly referred to as 'climate change.'"[74] The qualification "average" is central to this analysis since extreme temperature declines in one area are not necessarily adequate to offset any combination of more severe temperature increases in another area or smaller temperature rises spread over a wider area. Assessments from the IPCC suggest the Earth's climate has already warmed over the past century and that human activity has "become a dominant force."[75] Looking ahead to the future, the United Nations ("UN") Environment Program recently noted, "[t]he observed increase in GHG concentration since 1750 has most likely committed the world to a warming of 1.4–4.3 degrees Celsius [i.e., 2.5–7.7 degrees Fahrenheit] above pre-industrial surface temperatures" throughout the twenty-first century.[76] IEA's World Energy Outlook 2009 indicates that "[w]ithout a change in policy, the world is on a path for a rise in global temperature of up to 6 [degrees] Celsius, with catastrophic consequences for our climate" by the end of the 21st century.[77]

Given the nature of the problem, and the potential consequences, every nation—rich or poor, large or small, developed or developing—has an undeniable stake in successfully confronting the CO_2 challenge. The question facing the world community is not whether emissions need to be reduced, but how much of a reduction is required, and what is the most effective way to achieve that reduction. In response to these and other similar questions, several different CO_2 targets, timetables, and rationales have been proposed and discussed by the international community. For example, the European Union has called for developed nations to reduce emissions by 20% from 1990 levels by 2020, and the G8 has an 80% reduction goal for rich nations by 2050.[78] The IPCC

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74. Energy Info. Admin., *supra* note 60.

75. Hervé Le Treut et al., *supra* note 44, at 105.

76. UNITED NATIONS ENV'T PROGRAM, CLIMATE CHANGE SCIENCE COMPENDIUM 2009, at 11 (Catherine P. McMullen et al. eds., 2009), *available at* http://www.unep.org/pdf/ccScienceCompendium2009/cc_ScienceCompendium2009_full_en.pdf.

77. Int'l Energy Agency, World Energy Outlook 2009 Fact Sheet: What Might a Low-Carbon Energy Future Look Like? (2009), http://www.iea.org/weo/docs/weo2009/fact_sheets_weo_2009.pdf.

78. Meagan Rowling, *G8 Signals on Climate Change Fall Short—Experts,* REUTERS, ALERTNET, July 7, 2009, http://www.alertnet.org/db/an_art/20316/2009/06/7-164638-1.htm.

has said the key to preventing global warming is keeping CO_2 emissions below 450 parts per million.[79] This would require developed countries to cut their emissions at least 25% below 1990 levels by 2020.[80] The IEA says this "450 scenario is achievable—but very challenging."[81] Although the results of the Conference of Parties 15 meeting in Copenhagen last December are still being analyzed and discussed, the accord resulting from those deliberations recognized that the increase in global temperature should "be below 2 degrees Celsius."[82] Among other things, the accord also noted that "deep cuts in global emissions are required according to science, and as documented by the IPCC Fourth Assessment Report" and recognized the "crucial role of reducing emission[s] from deforestation and forest degradation."[83] The accord also called for "[s]caled up, new and additional, predictable and adequate funding as well as improved access" for developing countries, the commitment of $30 billion by developed countries between 2010 and 2012 with "balanced allocation between adaptation and mitigation," and $100 billion annually by 2020 to address mitigation and other needs of developing countries.[84]

The sense of urgency created by these and other climate-related reports, meetings, and forums have led to thoughtful discussion about what might be the best approach for dealing with this significant challenge. As deeper cuts in CO_2 emissions continue to be suggested, many scientists have increasingly argued for the use of a portfolio approach as the best strategy for reducing risk, with advanced coal power generation including CCS as a key component.[85] This thinking was reflected in a recent National Academy of Sciences report, which noted, "substantial reductions in greenhouse gas emissions from the electricity sector are

79. *See* Brian Fisher et al., *Issues Related to Mitigation in the Long-Term Context*, *in* CLIMATE CHANGE 2007: MITIGATION, CONTRIBUTION OF WORKING GROUP III TO THE FOURTH ASSESSMENT REPORT OF THE IPCC 227, 231 (Bert Metz et al. eds., 2007), *available at* http://www.ipcc.ch/ipccreports/ar4-wg3.htm.

80. *Id.*

81. Int'l Energy Agency, *supra* note 77.

82. United Nations Climate Change Conference, Dec. 7–18, 2009, *Copenhagen Accord*, ¶ 1, Decision -/CP.15, *available at* http://unfccc.int/files/meetings/cop_15/application/pdf/cop15_cph_auv.pdf [hereinafter *Copenhagen Accord*].

83. *Id.* at ¶¶ 2, 6.

84. *Id.* at ¶¶ 2, 6, 8.

85. *See, e.g.*, EDWARD S. RUBIN, A PERFORMANCE STANDARDS APPROACH TO REDUCING CO_2 EMISSIONS FROM ELECTRIC POWER PLANTS (2009), *available at* http://www.pewclimate.org/docUploads/Coal-Initiative-Series-Rubin.pdf.

achievable over the next two to three decades through a portfolio approach involving the widespread deployment of energy efficient technologies; renewable energy; coal, natural gas, and biomass with carbon capture and storage; and nuclear technologies."[86] While future emissions of CO_2 can be avoided in electric power by some combination of the above options, emissions from pre-existing sources can be reduced and future emissions avoided by using CCS.

The IPCC has predicted that CCS can achieve up to 55% of the reductions required to stabilize atmospheric levels of CO_2 in this century.[87] The IPCC has also said technology development, improvements from industry, and research initiatives, such as DOE's Carbon Sequestration Program, could help reduce the current costs of capturing and storing CO_2 from power plants by 30% or more.[88] IEA has concluded that CCS will need to contribute one-fifth of the necessary emissions reductions to achieve GHG stabilization in the most efficient manner.[89] In a 2007 interdisciplinary study, the Massachusetts Institute of Technology identified CCS as the "critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs."[90] The consensus points in the direction of CCS technologies offering a promising option for helping retain coal and other fossil fuels as viable contributors to the energy supply needed to sustain a globally competitive economy in a carbon-constrained world. It should be noted that global stabilization of GHG will require CCS not only for coal plants, but also for natural gas and biomass utilization as well.

So how does CCS work? CO_2 is a byproduct that results when the energy of a fossil fuel is released during oxidation or combustion.[91] CO_2 is far more difficult to control than other air emissions

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86. NAT'L ACAD. OF SCI. ET AL., AMERICA'S ENERGY FUTURE: TECHNOLOGY AND TRANSFORMATION 4 (2009).

87. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *Summary for Policymakers*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE 12 (Bert Metz et al. eds., 2005), *available at* http://www.ipcc.ch/publications_and_data/publications_and_data_reports_carbon_dioxide.htm.

88. *Id.* at 11.

89. Int'l Energy Agency, CCS for Power Generation and Industry, http://www.iea.org/roadmaps/ccs_power.asp (last visited Feb. 25, 2010).

90. MASS. INST. OF TECH., *supra* note 52, at x.

91. U.S. ENVTL. PROT. AGENCY, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990–2007, at 1-3 to 1-6 (2009), *available at* http://www.epa.gov/climatechange/

because as a primary product of oxidation or combustion, the "quantities of CO_2 [that must] be removed dwarf those of other" coal combustion reactants, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_X).[92]

Essentially, CCS is a group of technologies for (1) capturing CO_2, (2) compressing and transporting it, and (3) achieving geologic storage by injecting it into suitable permanent sites deep underground.[93] CO_2 is separated from the fuel either before or after it is burned to produce energy.[94] In pulverized coal systems, which make up the vast majority of the United States' existing fleet of coal-based power plants, the CO_2 must be separated at fairly diluted concentrations from the balance of the combustion flue gases; in other systems, such as coal gasification, CO_2 can be more easily separated.[95] After separation, the CO_2 is compressed to a liquid-like state (called "supercritical fluid"), transported (usually by pipeline) to an injection well, and then pumped underground into a secure geologic storage area.[96] The storage areas where injection occurs are at depths sufficient "to maintain critical pressures and temperatures."[97] The CO_2 seeps into the pore spaces in the surrounding rock, and its escape to the surface is blocked by overlaying impermeable cap rock.[98] In deep underground saline formations, carbon dioxide eventually dissolves over time into the salty water.[99] In many of these formations, the CO_2 also chemically reacts with surrounding rock, transforming the carbon dioxide into "mineral carbonates," that have been doc-

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emissions/downloads09/GHG2007entire_report-508.pdf.

92. ELEC. POWER RESEARCH INST., ADVANCED COAL POWER SYSTEMS WITH CO_2 CAPTURE: EPRI'S COAL FLEET FOR TOMORROW VISION 2-1 (2008), *available at* http://www.epri.com (search "1016877").

93. *Id.* at 1–2.

94. *See id.*

95. MASS. INST. OF TECH., *supra* note 52, at 24; *see* U.S. Dep't of Energy, Gasification Technology R&D, http://www.fossil.energy.gov/programs/powersystems/gasification/index.html (last visited Feb. 25, 2010).

96. ELEC. POWER RESEARCH INST., *supra* note 92, at 1-2, 5-1.

97. CARMEN DIFIGLIO, COAL WITH CARBON CAPTURE AND STORAGE: THE MAIN COMPETITOR 1 (2006), *available at* http://www.physics.harvard.edu/wilson/energypmp/2006_Difiglio.doc.

98. ELEC. POWER RESEARCH INST., *supra* note 92, at 5-6.

99. *Id.* at 5-5.

umented to be stable over geological time periods of millions of years.[100]

At present CO_2 pricing levels, research into the topics of air capture and beneficial reuses of CO_2 outside of geologic storage appear challenged by at least one of the following: energy requirements,[101] scalability costs,[102] or experiment sizing orders of a magnitude smaller than a gigaton.[103] Consequently, ongoing research and feasibility studies defer these topics to a separate paper. This discussion focuses primarily on reviewing the geologic storage option.

Geologic storage is possible in a number of ways, including in:

- depleted and declining oil fields, where geologic storage is presently used to enhance oil recovery;
- natural gas fields;
- unmineable coal seams, which may add to natural gas supply by displacing methane;
- very deep saline formations, which underlie much of the world; and
- other significant geologic formations, such as basalt.[104]

The IPCC estimates the world's potential storage capacity for CCS is around 2 trillion metric tons, although there could be "a much larger potential."[105] Other experts believe it may be as high as 11 trillion tons with future technology and more experience.[106] In any case, there is sufficient storage to hold emissions for sev-

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100. Daniel J. Fauth et al., *Carbon Dioxide Storage as Mineral Carbonates*, 45 ACS FUELS 708, 708 (2000), *available at* http://www.anl.gov/PCS/acsfuel/preprint%20archive/Files/45_4_WASHINGTON%20DC_08-00_0708.pdf.

101. KRISTINA WEYER ET AL., THEORETICAL MAXIMUM ALGAL OIL PRODUCTION 11, 17 fig.6, 19 (2009), *available at* http://comste.gov.ph/images/files/TheoreticalMaximum_for%20ALGOIL%206-11-09.pdf.

102. *Id.* at 11.

103. NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, DE-FOA-0000042, FINANCIAL ASSISTANCE FUNDING OPPORTUNITY ANNOUNCEMENT: RECOVERY ACT: CLEAN COAL POWER INITIATIVE-ROUND 3, at 7 (2009). http://www.netl.doe.gov/technologies/coalpower/cctc/ccpi/bibliography/program/solicitations/Read%20the%20FOA-DE-FOA-0000042.pdf.

104. MASS. INST. OF TECH., *supra* note 52, at 44.

105. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *supra* note 87, at 12.

106. JAMES DOOLEY ET AL., CCS: A KEY TO ADDRESSING CLIMATE CHANGE 2 (2008), *available at* http://www.pnl.gov/gtsp/publications/2008/papers/petroleum_economist_ccs.pdf.

eral centuries. Also, many potential storage formations are favorably matched with large-scale CO_2 sources.[107] For demonstration purposes, using present technology with stringent site characterization[108] and selection criteria,[109] it is likely that safety and environmental concerns will require a need to limit capacity in exchange for the most stable and predictable geologic characteristics, meaning the amount of CO_2 stored, although still impressive, would likely be reduced.

Ongoing and future research is directed toward improving the cost-effectiveness and inter-operability of technologies to capture CO_2 from both new and existing coal plants.[110] Additionally, an early version of CCS technology appears to be commercially exploited; it has long been used by the industry for EOR, removal of CO_2 from gas streams that would have previously been emitted into the atmosphere, or separation of CO_2 as a product gas.[111] These industrial-level experiences have been complemented by numerous research-scale CCS projects, such as those that are part of the DOE program, industry partnerships, and other initiatives.[112]

CCS has great potential for effectively countering atmospheric CO_2 build-up on a global scale. In theoretical, simulation, or laboratory bench settings, as well as small-scale industrial operations, the critical elements of CCS have been separately demonstrated.[113] Additionally, adequate storage sites and capacities

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107. *See, e.g.*, NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, CARBON SEQUESTRATION ATLAS OF THE UNITED STATES AND CANADA 26 (2007), *available at* http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlas/ATLAS.pdf.

108. For example, see site characterization presentations from the Recovery Act Site Characterization Projects Kick-Off Meeting held February 3–4, 2010. Nat'l Energy Tech. Lab., Recovery Act Site Characterization Projects Kick-Off Meeting, http://www.netl.doe.gov/publications/proceedings/10/rascp/index.html#pres (last visited Feb. 25, 2010).

109. *See* JOEL SMINCHAK ET AL., ISSUES RELATED TO SEISMIC ACTIVITY INDUCED BY THE INJECTION OF CO_2 IN DEEP-SALINE AQUIFERS 2 (2001), *available at* http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p37.pdf.

110. *See* Chu, *supra* note 25, at 1599.

111. *See* R. Stuart Haszeldine, *Carbon Capture and Storage: How Green Can Black Be*, 325 SCIENCE 1647, 1649 (2009).

112. Jared Ciferno, Existing Plants Tech. Manager, U.S. Dep't of Energy, DOE/NETLs Existing Plants CO_2 Capture R&D Program, Presentation at the NETL Carbon Capture 2020 Workshop, University of Maryland (Oct. 5–9, 2009), *available at* http://www.netl.doe.gov/publications/proceedings/09/cc2020/pdfs/ciferno_presentation.pdf.

113. *See* U.S. DEP'T OF ENERGY, CARBON SEQUESTRATION TECHNOLOGY ROADMAP AND PROGRAM PLAN 2007, at 6–8 (2007), *available at* http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf.

appear to exist around the globe with the caveat that these sites and their capacities need to be characterized and verified for storage suitability.[114] Further testing of preliminary results by operating larger-scale CCS plants and storage facilities in a variety of environments and settings, as well as improving cost-effectiveness, is essential for the technology to fully realize its promise.[115] And there are a number of existing challenges that ultimately must be resolved before CCS can be demonstrated and deployed at the commercial level.[116]

III. THE CHALLENGES FACING CCS

As important as timely technology development is to establishing CCS viability, having definitive standards, practices, and procedures, encouraging private-sector investment, and addressing liability and regulatory issues are also essential. Current barriers that could delay or—if not resolved—prevent the rapid deployment of CCS essentially fall into two categories: technical and non-technical. The key technical challenges to CCS include (1) addressing the cost and energy penalty of capture; (2) proving CO_2 storage permanence; (3) verifying that sufficient storage capacity exists; and (4) developing best practices for the lifecycle of a CCS project, from site selection to post-closure monitoring.[117] Non-technical challenges primarily consist of (1) the global need for significant financial investments to bring numerous commercial-scale demonstration projects on-line in the near future; (2) establishing an adequate legal and regulatory framework to support broad CCS deployment, including dealing with long-term liability; and (3) building public understanding, awareness, and acceptance.[118] As a group, these challenges have many com-

114. *See id.* at 13–14; Daniel P. Schrag, *Making Carbon Capture and Storage Work*, *in* ACTING IN TIME ON ENERGY POLICY 9 (Kelly Gallagher ed., 2009), *available at* http://belfercenter.ksg.harvard.edu/actingintimeonenergy/papers/schrag-ccs.pdf.

115. *See* Chu, *supra* note 25.

116. *See* U.S. DEP'T OF ENERGY, *supra* note 113, at 11–13.

117. *See id.*

118. *See, e.g.*, COAL RESEARCH FORUM & COAL UTILIZATION SUBJECT GROUP OF THE INST. OF CHEM. ENG'RS, COAL RESEARCH AND ENGINEERING NEEDS IN THE U.K. 11 (4th ed. 2005), *available at* http://coalresearchforum.org/crfneeds.pdf. The specific details of how future rules and/or legislation could be crafted in view of respective Safe Drinking Water Act and Clean Air Act requirements also present a deployment challenge.

plex nuances; what follows is a brief outline of the most significant issues.

A. *Technical Challenges*

1. Cost and Energy Penalty

CCS represents a significant financial investment; cost has been identified as perhaps the greatest single hurdle to CCS deployment.[119] A new coal-fired plant can be designed to incorporate CCS from the very beginning, or it can be built to include upfront investments that lower the cost of later adding the technology.[120] "Retrofitting existing plants for CCS is expected to be more expensive (in terms of dollars per metric ton of CO_2 avoided and the incremental impact on the levelized cost of electricity). . . ."[121] The incremental cost of CCS varies depending on parameters such as the choice of capture technology, the percentage of CO_2 captured, the type of coal used, and the distance to and type of geologic storage area.[122] The reality is that, absent a regulatory framework for carbon valuation, there is little incentive for plant operators to build carbon-capture-ready plants or retrofit existing facilities if there are significant up-front costs to do so.

Additionally, all capture systems currently require large amounts of energy for their operation, resulting in decreased plant efficiencies and reduced net power outputs when compared to the same plants without CCS.[123] These "penalties" mean commercially available CCS technologies add around 80% to the cost of electricity for a new pulverized coal plant and around 35% to the cost of electricity for a new advanced gasification plant.[124] This

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119. *See Future of Coal: Hearing Before the S. Comm. on Energy and Natural Resources*, 110th Cong. 5 (2007) (statement of Bryan Hannegan, Vice President, Electric Power Research Institute).

120. NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, DOE/NETL-402/102309, COAL-FIRED POWER PLANTS IN THE UNITED STATES: EXAMINATION OF THE COSTS OF RETROFITTING WITH CO_2 CAPTURE TECHNOLOGY AND THE POTENTIAL FOR IMPROVEMENTS IN EFFICIENCY 1 (2010), *available at* http://www.netl.doe.gov/energy-analyses/pubs/GIS_CCS_retrofit.pdf.

121. PEW CTR. ON GLOBAL CLIMATE CHANGE, CARBON CAPTURE AND STORAGE (CCS) 3 (2009), http://www.pewclimate.org/docUploads/CCS-Fact-Sheet1_0.pdf.

122. *Id.*

123. *See* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *supra* note 87, at 4.

124. *Range of Innovative, Non-Geologic Applications for the Beneficial Reuse of Carbon Dioxide from Coal and Other Fossil Fuel Facilities: Hearing Before the Subcomm. on Ener-*

cost of electricity is also measured as a parasitic load and opportunity cost.[125] Cost and energy penalty reduction is one of two focuses (along with safe, long-term geologic storage) of DOE initiatives to support CCS research development and demonstrations. "The program is aggressively pursuing developments to reduce these costs to less than a 10 percent increase in the cost of electricity for new gasification-based energy plants, and less than a 35 percent increase in the cost of electricity for [traditional] pulverized coal energy plants."[126]

2. Permanence

An examination of historic oil and natural gas reservoir production reveals the physical separation of naturally occurring CO_2 from what began as an oil or natural gas well.[127] This suggests geologic CO_2 storage can be connected to a naturally occurring phenomenon in very specific geologic circumstances, which would be consistent with the goal of permanent storage. CO_2 often appears as a naturally occurring impurity in combination with natural gas that has been stored underground, and CCS history can trace its origins to efforts to purify natural gas.[128] A predecessor of injection-like technology can actually be found as early as 1900, invented by John C. Minor of New York City; as advances occurred, the art of injecting CO_2 for EOR operations came to fruition, as disclosed in a 1954 patent application, demonstrating there is more than a half century of experience with this procedure.[129] Analogously, CO_2 injection has also been adapted to natural gas reservoir depletion utilizing Enhanced Gas Recovery

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gy and Water Development of the S. Comm. on Appropriations, 111th Cong. 2–4 (2009) (statement of Scott M. Klara, Director, Strategic Center for Coal, U.S. Dep't of Energy) [hereinafter Klara].

125. *See* M.R. Haines & J.E. Davison, *Designing Carbon Capture Power Plants to Assist in Meeting Peak Power Demand*, 1 ENERGY PROCEDIA 1457, 1458 (2009).

126. Klara, *supra* note 124, at 4. For more details, see *infra* Part IV.

127. *See* Process for Separating Natural Gas and Carbon Dioxide, U.S. Patent No. 6,128,919 col.1, ll.21–30, 64–66, figs.1, 2 & 3 (filed Sept. 22, 1998).

128. *See Carbon Capture Has a Sparkling Future, New Findings Show*, SCI. DAILY, Apr. 2, 2009, http://www.sciencedaily.com/releases/2009/04/090401134602.htm; *see also* Soren Anderson & Richard Newell, *Prospects for Carbon Capture and Storage Technologies*, 29 ANN. REV. ENV'T & RESOURCES 109, 112 (2004).

129. Art of Improving Mineral Wells, U.S. Patent No. 656,466 (filed Apr. 30, 1900); *see* Process of Recovering Oil from Oil Fields Involving the Use of Critically Carbonated Water, U.S. Patent No. 2,875,833 (filed Feb. 4, 1954).

("EGR").[130] As of 2008, about 48 million tons of mostly naturally produced CO_2 were injected annually for EOR operations in the United States.[131] Additionally, there are presently five "commercial-scale CCS projects in operation" in Norway, Algeria, the United States, and Canada, storing a total of approximately five million tons of CO_2 annually, according to the IEA.[132] There are also a number of other projects in various stages of planning throughout the world.[133] The scientific evidence emerging from existing operations and activities, such as DOE's CCS field test program, indicates that geologic storage has great potential for safely and permanently sequestering CO_2.[134] An IPCC Special Report on CCS noted that, for a well planned and operated project, the probability of leakage appeared low during simulations and limited testing and remains a topic for ongoing research.[135] Existing projects are helping scientists acquire the real-world experience and geology-specific data needed to more thoroughly validate the capability, potential, and impact of CCS.[136] Based on the evidence thus far, researchers expect to find that good site selection and characterization, proper injection rates, appropriate monitoring, and safe operational and remedial practices should increase confidence in CCS's long-term viability and permanence.[137] Scientific confirmation of long-term storage security and the diversity of geologic storage media is a precondition to large-scale commercial deployment.[138]

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130. *See* Applications of Waste Gas Injection into Natural Gas Reservoirs, U.S. Patent No. 7,172,030 fig.8 (filed Oct. 5, 2004).

131. NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, CARBON SEQUESTRATION THROUGH ENHANCED OIL RECOVERY 2 (2008), *available at* http://www.netl.doe.gov/publications/factsheets/program/Prog053.pdf.

132. INT'L ENERGY AGENCY, *supra* note 33, at 10.

133. *Id.*

134. Nat'l Energy Tech. Lab., Carbon Sequestration: NETL Carbon Capture and Storage Database, http://www.netl.doe.gov/technologies/carbon_seq/database/index.html (last visited Feb. 25, 2010).

135. Sally Benson et al., *Underground Geological Storage*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE, *supra* note 87, at 246.

136. *See* Nat'l Mining Ass'n, Carbon Capture and Storage: Clean Coal Technologies for Carbon Management, http://www.nma.org/ccs/ccsprojects.asp (last visited Feb. 25, 2010).

137. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *Summary for Policymakers*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE, *supra* note 87, at 14; Edward Rubin et al., *Technical Summary*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE, *supra* note 87, at 33.

138. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *Summary for Policymakers*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE, *supra* note 87, at 12; Edward Rubin et al., *Technical Summary*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE

3. Storage Capacity Verification

Implementation of CCS technology at the scale needed to achieve significant and meaningful reductions in CO_2 emissions requires knowledge of available geologic storage capacity. Previous assessment attempts used a wide variety of approaches and methodologies that considered various trapping mechanisms and data sets of variable size and quality.[139] The end result was widely varying estimates of inconsistent quality and reliability. Storage capacity estimates have been produced for Australia, Canada, northern Europe, Japan, and the United States, and projects are under way to assess the storage capacity in southern and eastern Europe.[140] This effort is distinguished from analogous efforts at establishing uniform international measures and methods for determining oil or natural gas reservoir capacity;[141] for CCS, it is necessary to generalize methodologies spanning a broader and more complex set of geologic formations. The Carbon Sequestration Leadership Forum ("CSLF"), a ministerial-level international climate change initiative of which DOE is a part, is seeking to develop a clear set of definitions and methodologies to facilitate consistent assessments of worldwide CO_2 storage capacity.[142] Through research and data gathering, DOE has identified potential capacity to store hundreds of years of CO_2 emissions, which is being proven through dozens of field tests.[143] The field test program is being implemented through the Regional Carbon Sequestration Partnerships ("RCSPs"),[144] "represent[ing] more than 350 unique

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CAPTURE AND STORAGE, *supra* note 87, at 35; *see* Klara, *supra* note 124, at 3.

139. Sally Benson et al., *Underground Geological Storage*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE, *supra* note 87, at 205–13, 225.

140. *Id.* at 33 tbl.TS.5.

141. *See* KATE ROBERTSON ET AL., NAT'L ENERGY TECH. LAB., DOE/NETL-2006/1236, INTERNATIONAL CARBON CAPTURE AND STORAGE PROJECTS: OVERCOMING LEGAL BARRIERS 5–6, 9 (2006), *available at* http://www.netl.doe.gov/energy-analyses/pubs/CCSregulatorypaperFinalReport.pdf; Nat'l Energy Tech. Lab., Carbon Sequestration: World Projects, http://www.netl.doe.gov/technologies/carbon_seq/core_rd/world_projects.html (last visited Feb. 25, 2010); *see also* IED Greenhouse Gas R&D Programme, R, D, & D Database, http://www.co2captureandstorage.info/search.php (last visited Feb. 25, 2010) (providing a database of CO_2 storage levels by region).

142. *See* Carbon Sequestration Leadership Forum, About the CSLF, http://www.cslforum.org/aboutus/ (last visited Feb. 25, 2010).

143. *See* Nat'l Energy Tech. Lab., Technologies: Carbon Sequestration, http://www.netl.doe.gov/technologies/carbon_seq/ (last visited Feb. 25, 2010).

144. *See infra* Part IV.

organizations in 42 [s]tates, three Native American Organizations, and four Canadian [p]rovinces."[145]

4. Best Practices

"Certainty" is a key term in relation to CCS. It applies not only to public expectation for safe and environmentally conscious operation, but also to those industries that will incorporate the added cost of CCS into the operation of existing and new facilities. Reliable and consistent demonstration of CCS operational characteristics will help provide the basis for a legal and regulatory framework that will help establish certainty.

At present, practices vary among regions; there is a need to amalgamate a more comprehensive set of "best practices" that researchers and technology users believe will allow consistently safe and effective long-term CO_2 collection, injection, and storage. This need is well-recognized, and there is a developing body of knowledge represented by a global database.[146] In the United States, DOE is developing "Best Practice Manuals" on topics such as site characterization, construction, operations, monitoring, mitigation, closure, and long-term stewardship.[147] These manuals will serve as guidelines for a future geologic sequestration industry, and help transfer the lessons learned to all RCSP stakeholders.[148]

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145. Klara, *supra* note 124, at 5; John Litynski et al., *U.S. Department of Energy's Regional Carbon Sequestration Partnership Program: Overview*, 1 ENERGY PROCEDIA 3959, 3959 (2009), *available at* http://www.sciencedirect.com (click "Search," type "U.S. Department of Energy's Regional Carbon Sequestration Partnership Program: Overview," and select first result).

146. Nat'l Energy Tech. Lab., Carbon Sequestration, NETL Carbon Capture and Storage Database, http://www.netl.doe.gov/technologies/carbon_seq/database/index.html (last visited Feb. 25, 2010).

147. *See, e.g.*, GEO-SEQ PROJECT TEAM, GEO-SEQ BEST PRACTICES MANUAL: GEOLOGIC CARBON DIOXIDE SEQUESTRATION: SITE EVALUATION TO IMPLEMENTATION (2009), *available at* http://osti.gov/bridge/servlets/purl/842996-Bodt8y/native/842996.pdf; NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, DOE/NETL-311/081508, BEST PRACTICES FOR MONITORING, VERIFICATION, AND ACCOUNTING OF CO_2 STORED IN DEEP GEOLOGIC FORMATIONS (2009), *available at* http://www.netl.doe.gov/technologies/carbon_seq/refshelf/MVA_Document.pdf.

148. *See* Dawn Deel, Project Manager, Sequestration Division, Nat'l Energy Tech. Lab., U.S. Dep't of Energy, DOE's Regional Carbon Sequestration Partnerships, Presentation During Regional Carbon Sequestration Partnerships-Monitoring, Verification, and Accounting (MVA) Webinar with the American Waterworks Association (Dec. 8, 2008), *available at* http://www.netl.doe.gov/publications/proceedings/08/rcspmva/1Brief%20Overview%20of%20DOE%20RCSP%20Program%20(Deel).pdf.

B. *Non-Technical Challenges*

1. Financing

Despite the promise of CCS technology, the current regulatory and fiscal climate makes it unlikely commercial power plants and industrial facilities will risk investments, due, in large part, to the previously mentioned cost and energy penalties and various uncertainties. To move the technology closer to deployment, governments must partner with industry to support near-term demonstration projects to help bridge the gap to commercialization. The first commercial-scale CCS projects integrated with power plants will generate valuable information on actual cost and performance, as well as the optimal configuration of the technologies involved. Large-scale, real-world projects also will provide much-needed data to guide investments in CCS and lead to cost reductions via technology improvements. Both domestically and internationally, there has been a strong increase in announcements of funding for projects of this type in the past year. In the United States, the American Recovery and Reinvestment Act ("ARRA") of 2009 provided $3.4 billion in funding for various levels of DOE clean coal and CCS technology development and demonstration; added to other agency program funding, the total reached nearly $4 billion.[149] The European Union, Australia, Canada, Japan, Norway, and the United Kingdom are among others funding CCS research and demonstrations.[150] Collectively, these represent a beginning for needed global CCS investments; but many fossil fuel-based economies will require substantial additional funding if they are to achieve the levels needed for commercial-scale CCS integration.[151] In the future, establishing predictable market signals[152] for CCS financing will encourage commercialization, at-

149. Press Release, U.S. Dep't of Energy, President Obama Announces $3.4 Billion Investment to Spur Transition to Smart Energy Grid (Oct. 27, 2009), *available at* http://www.energy.gov/8216.htm.

150. *See* Sally Benson et al., *Underground Storage*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE, *supra* note 87, at 260, 264; Ken Caldeira et al., *Ocean Storage*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE, *supra* note 87, at 285.

151. *See* Paul Freund et al., *Introduction*, *in* IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE, *supra* note 87, at 68–69; INT'L ENERGY AGENCY, *supra* note 33, at 4.

152. *See Newsmakers: Energy Sec. Steven Chu*, *supra* note 14.

tract substantial private sector investment,[153] and ultimately enable CCS to competitively mature within a portfolio of other low-carbon options.

2. Legal and Regulatory Framework

In some countries, CCS deployment will involve legal and regulatory issues, including managing public expectations; protecting public health; insuring safety for workers and populations living near underground storage areas, addressing environmental concerns; and fostering stewardship for permanent geologic CO_2 storage. Meanwhile, a flexible, adaptive framework is needed for the first wave of demonstration projects. A solid legal and regulatory system that provides structure and oversight and contributes to the certainty for CCS activities mentioned previously is essential for encouraging commercial development and ensuring safe, long-lasting operations. Addressing liability provides for long-term stewardship and is vital for both achieving a consistent regulatory climate and securing public confidence and acceptance of CCS projects. An established set of liability rules will offer reassurance that risks are predictably quantified and contained; without these rules, investors may be reluctant to risk capital on CCS projects.

Currently, a regulatory framework can be found in EPA's Underground Injection Control Code ("UIC").[154] EPA has also proposed rules for Class VI geologic sequestration wells.[155] Proposed Class VI well rules are distinguished from existing EPA Classes

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153. *Cf.* UNITED NATIONS ENVIRONMENT PROGRAMME, GLOBAL TRENDS IN SUSTAINABLE ENERGY INVESTMENT 2009: ANALYSIS OF TRENDS AND ISSUES IN THE FINANCING OF RENEWABLE ENERGY AND ENERGY EFFICIENCY 14 (2009), *available at* http://www.unep.org/pdf/Global_trends_report_2009.pdf. The transition to private sector investment is also seen when research cost-sharing formulas are used as an R&D initiative evolves into a commercial opportunity. *See, e.g.*, Press Release, U.S. Dep't of Energy, Secretary Chu Announces $ 2.4 Billion in Funding for Carbon Capture and Storage Projects (May 15, 2009), *available at* http://www.energy.gov/news2009/7405.htm.

154. *See generally* 40 C.F.R. pts. 144–49 (2009).

155. Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO_2) Geologic Sequestration (GS) Wells, 73 Fed. Reg. 43,492 (proposed July 25, 2008) (to be codified at 40 C.F.R. pts. 144, 146) (proposing rules for Class VI injection wells); Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO_2) Geologic Sequestration (GS) Wells, 74 Fed. Reg. 44,802 (proposed Aug. 31, 2009) (to be codified at 40 C.F.R. pt. 146) (providing notice of data availability and presenting an alternative related to the proposed injection depth requirements for Class VI wells).

I–V and state rules[156] in that the proposed requirements respond to previous questions regarding post-injection site care, large volumes, buoyancy, mobility, and corrosivity attributes associated with geologic sequestration of carbon dioxide.[157] Note that many CCS issues—such as drilling-induced seismicity,[158] retention after a seismic event,[159] EOR injection operations,[160] EGR injection operations,[161] and gas pipeline transportation and storage[162]—have been discussed elsewhere with existing rules, precedents, or proposed variations. Future innovations, experience with CCS demonstrations, or distinctions involving further speciation of impurities may guide additional regulatory amendments as CCS technologies continue to evolve. Globally, CCS advocates recognize the need for a legal and regulatory process that considers the broader set of questions and perspectives related to the technology, such as ownership rights, risk management, and adequate insurance, rather than simply focusing narrowly on technical issues.[163] They also realize the supporting policy development process should include public comment, notification and/or consultation. In this regard, the goals of the process should include:

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156. *See* Melisa F. Pollak & Elizabeth J. Wilson, *Regulating Geologic Sequestration in the United States: Early Rules Take Divergent Approaches*, 43 ENVTL. SCI. & TECH. 3035, 3037–38 tbl.2 (2009).

157. *See, e.g.*, Brian Graves, Region 6 UIC Land Ban Coordinator, EPA, Geologic Sequestration of Carbon Dioxide: EPA Proposed Rulemaking, Presentation at EPA Region 6 Ground Water Summit (Feb. 5, 2009), *available at* http://www.epa.gov/region6/water/swp/groundwater/2009-gws-presentations/10-geologic-sequestration-of-co2_graves.pdf.

158. *See* SMINCHAK ET AL., *supra* note 109, at figs.1, 2 & 3.

159. *See, e.g.*, Sohei Shimada, Dep't of Environment Systems, Univ. of Tokyo, Current State of Japanese Researches [sic] on Geological CO_2 Storage, Presentation at the Japan Society for the Promotion of Science London Symposium on Energy and Greenhouse Gas Mitigation Technology (Sept. 29, 2006), *available at* http://www.jsps.org/event/pdf/symposium/06_0929_7.pdf.

160. *See, e.g.*, Oil Recovery Process, U.S. Patent No. 5,297,626 (filed June 12, 1992).

161. *See, e.g.*, Applications of Waste Gas Injection into Natural Gas Reservoirs, U.S. Patent No. 7,172,030 fig.8 (filed Oct. 5, 2004).

162. *See, e.g.*, *Regulatory Aspects of Carbon Capture, Transportation, and Sequestration: Hearing on S. 2323 and S. 2144 Before the S. Comm. on Energy and Natural Resources*, 110th Cong. 15–19 (2008) (statement of Krista L. Edwards, Deputy Administrator, Pipeline and Hazardous Materials Safety Administration, Department of Transportation), *available at* http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Testimony/SENATE%20ENERGY%20-%20Edwards%201-31-08%20Written%20testimony.pdf; Robert R. Nordhaus & Emily Pitlick, *Carbon Dioxide Pipeline Regulation*, 30 ENERGY L.J. 85, 86 (2009).

163. *See, e.g.*, GLOBAL CCS INST., STRATEGIC ANALYSIS OF THE GLOBAL STATUS OF CARBON CAPTURE AND STORAGE: REPORT 3: POLICIES AND LEGISLATION FRAMING CARBON CAPTURE AND STORAGE GLOBALLY 2–3 (2009), *available at* http://www.globalccsinstitute.com/downloads/Reports/2009/worley/Foundation-Report-3-rev0.pdf.

- Implementing "best practices"[164] that will allow CCS to be deployed safely and effectively. This will serve as the basis to develop well-founded regulatory standards, help to continually increase project quality, and improve public confidence in the projects themselves.

- Devising adequate provisions to assign the long-term liability of storage sites. This forms the basis of health and safety concerns, and the assignment of liability would address the issue of potential impacts of current decisions on future generations.

There is movement toward developing a CCS-specific legal and regulatory framework, both in this country and abroad. Previously, EPA published guidance for permitting underground injection of CO_2.[165] EPA announced it would develop regulations for commercial-scale geologic sequestration injection operations within the existing UIC program, established under the Safe Water Drinking Act.[166] DOE is working closely with EPA in developing CCS regulation strategies, with the goal of providing additional certainty for future deployments. Additionally, the international community has amended legal instruments to advance CCS development, and several countries are developing comprehensive domestic CCS-specific regulatory frameworks.[167] Liability approaches that balance the dual goals of rapid development of the industry with the strong desire for long-term quality in design, investment, and operational performance would appear to be the best way to positively affect both the pace and quality of CCS activities.

3. Building Public Understanding

Many CCS supporters believe one of the most important challenges faced by the technology is building public understanding, acceptance, and trust, based on openness and credibility stem-

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164. *See infra* Part III.A.4.

165. Memorandum from Cynthia C. Dougherty, Dir., EPA Office of Ground Water and Drinking Water & Brian McLean, Dir., EPA Office of Atmospheric Programs, to Water Mgmt. Div. Dirs. & Air Div. Dirs., EPA Regions I to X (Mar. 1, 2007), *available at* http://www.epa.gov/safewater/uic/pdfs/guide_uic_carbonsequestration_final-03-07.pdf.

166. *See id.* at 3.

167. *See* INT'L ENERGY AGENCY, CARBON CAPTURE AND STORAGE: FULL-SCALE DEMONSTRATION PROGRESS UPDATE 4–6 (2009), *available at* http://www.iea.org/G8/docs/ccs_g8july09.pdf.

ming from solid scientific and technical information. The potential disruption of the global climate, the large role played by CO_2 from fossil fuels, and the need for extensive deployment of CCS are all serious and complex issues. Resulting public concerns and objections could, at a minimum, slow CCS deployment if they are not adequately addressed. The need for public acceptance is both global (for the technology itself) and local (for specific projects). Additionally, CCS is an evolving area of innovation, which could lead to misunderstanding and faulty perceptions about the technology and its effects. Public engagement and education relating to CCS is an important priority that requires the devotion of extensive resources. A 2008 study by Harvard University's Belfer Center for Science and International Affairs and Clark University's Department of International Development, Community, and Environment found that "exposure to information from experts about CCS technology increases stakeholder understanding and support."[168] The study's findings also suggested "that those who understand CCS tend to support [its] advancement."[169]

C. *Interrelationship Among Technology, Markets, and Policy*

Finally, framing these technical and non-technical challenges as a group is the important inter-relationship between technology development, markets, and policy. Technological development is only one piece of the puzzle. To achieve acceptance in the marketplace, the technology must be attractive to investors, purchasers, and users, in terms of performance, convenience, and cost. Consequently, policies, regulations, and standards that create certainty and target performance characteristics can do much to spur technological development, help improve market attractiveness, and lead to widespread deployment. The development of definitive policies and regulations, as well as other incentives, will be required to overcome the barriers facing CCS.

A justifiable U.S. government role in this regard includes facilitating an interstate and international commercial CCS pipeline

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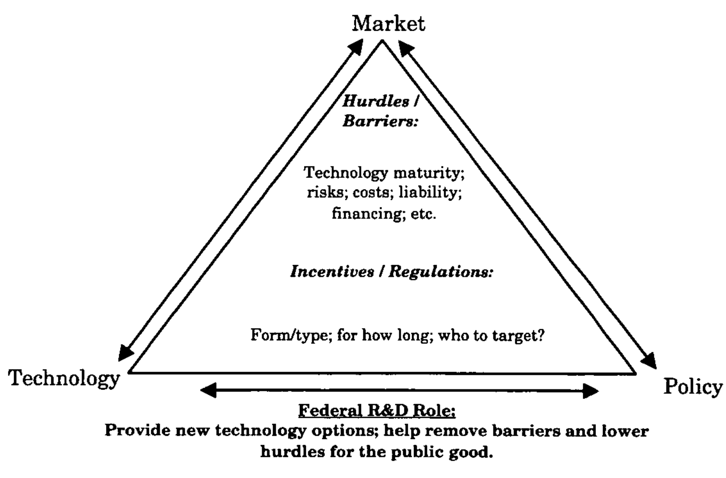
168. Jennie C. Stephens, Jeffrey Bielicki & Gabriel M. Rand, *Learning About Carbon Capture and Storage: Changing Stakeholder Perceptions with Expert Information,* 1 ENERGY PROCEDIA 4655, 4661 (2009), *available at* http://dx.doi.org/10.1016/j.egypro.2009.02.288.

169. *Id.*

network crossing at least a dozen state boundaries[170] or federal lands with potentially different rules,[171] representing national interests when negotiating agreements with foreign nations also investing in CCS research, facilitating the sharing of innovative R&D option, gaining and retaining public confidence through effective safety and environmental policies, and working to remove barriers and lower hurdles for the public good. The federal government can serve as an enabler by supporting R&D programs and goals and by addressing such items as targets for CCS technology efficiency and environmental performance improvements; providing incentives (i.e., tax credits and loan guarantees); establishing government cost-sharing R&D partnerships with industry; and international forums to deal with global issues. In helping fulfill the federal R&D role, DOE's coal and carbon sequestration programs operate in partnership with the private sector to maximize the efficiency and performance of CCS technologies while minimizing costs and overcoming deployment hurdles.[172]

Figure 1. Technology/Market/Policy Interplay



170. U.S. Dep't of Transp., CO_2 Pipeline Database, National Pipeline Management System (2010) (on file with author).

171. *See* Nordhaus & Pitlick, *supra* note 162, at 93–94 (discussing the Bureau of Land Management's process for granting rights-of-way across federal lands).

172. See *infra* Part IV for a detailed description of DOE's programs.

IV. THE DOE PROGRAM AND ITS ROLE IN DEVELOPING CCS TECHNOLOGIES

The United States recognizes its role and responsibilities in dealing with CO_2 emissions and climate change challenges. Speaking before the UN Climate Change Summit in New York last September, President Obama noted: "We understand the gravity of the climate threat. We are determined to act. And we will meet our responsibility to future generations."[173] He also pointed out that the United States is investing billions of dollars to capture carbon emissions;[174] much of this investment is through DOE programs, which have assumed an internationally recognized leadership role in accelerating the development and use of CCS. It is also worth noting that during the Copenhagen climate meetings last December, the United States declared it would contribute its share of $100 billion annually in long-term financing to help developing nations adapt to climate change, contingent upon developing countries meeting their emissions targets.[175]

DOE's advanced coal program is directed towards developing both the core and supporting technologies through which CCS could become an effective and economically viable path for reducing CO_2 emissions. In partnership with the private sector, efforts are focused on maximizing efficiency and performance while minimizing the costs of these new technologies. DOE is also developing the knowledge base, technologies, best practices, and protocols to overcome barriers to the widespread deployment of CCS technologies so that sequestration can become a viable option in the near future.

With regard to geologic storage of CO_2, central to DOE's CCS research is its field test program, which is being implemented through the previously mentioned RCSPs.[176] These government/industry efforts are focused on determining the most suitable technologies, regulations, and infrastructure needs for CCS in different regions of the United States and Canada. They are iden-

173. President Barack Obama, Remarks by the President at United Nations Secretary General Ban Ki-Moon's Climate Change Summit (Sept. 22, 2009), *available at* http://www.whitehouse.gov/the_press_office/Remarks-by-the-President-at-UN-Secretary-General-Ban-Ki-moons-Climate-Change-Summit.

174. *Id.*

175. *See supra* Part II.

176. *See supra* Part III.

tifying and addressing the hurdles that need to be overcome for CCS to be successfully implemented on a large scale.

Research is also directed to developing technology options that dramatically lower the cost of capturing CO_2 from existing fossil fueled power plants. This research can be categorized into at least three distinct paths—post-combustion, pre-combustion, and oxy-combustion. Post-combustion processes capture CO_2 from the stack gas after a fuel has been combusted in air.[177] The pre-combustion approach converts fuel into a gaseous mixture of hydrogen and CO_2.[178] The CO_2 is then separated and the hydrogen is combusted.[179] Compared with post-combustion, the pressure and concentration of CO_2 resulting from pre-combustion processes is relatively high, making CO_2 separation easier to achieve and offering the potential to apply novel capture technologies, such as membranes, solvents, and sorbents.[180] Oxy-combustion is an approach where a hydrocarbon fuel is combusted in nearly pure oxygen rather than air to produce a mixture of CO_2 and water that can easily be separated to yield carbon dioxide at pipeline purity.[181] These carbon capture efforts encompass not only improvements to state-of-the-art technologies, but also development of several innovative concepts that separate and concentrate the carbon for subsequent capture, such as metal organic frameworks,[182] ionic liquids,[183] and biomimetic enzyme-based systems.[184] In addition, advanced technology such as the supersonic shock-wave compression system and other present and future options offer the promise of more efficiency and lower costs.[185]

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177. José D. Figueroa et al., *Advances in CO_2 Capture Technology—The U.S. Department of Energy's Carbon Sequestration Program*, 2 INT'L J. GREENHOUSE GAS CONTROL 9, 12 (2008), *available at* http://www.netl.doe/gov/technologies/carbon_seq/refshelf/CO2%20 Capture%20Paper.pdf.

178. *Id.*

179. *Id.*

180. *Id.* at 16–17.

181. *Id.* at 17–18.

182. NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, CARBON SEQUESTRATION: CARBON DIOXIDE SEPARATION WITH NOVEL MICROPOROUS METAL ORGANIC FRAMEWORKS (2008), *available at* http://www.netl.doe.gov/publications/factsheets/project/proj315.pdf.

183. NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, CARBON SEQUESTRATION: DESIGN AND EVALUATION OF IONIC LIQUIDS AS NOVEL ABSORBENTS (2008), *available at* http://www.netl.doe.gov/publications/factsheets/project/Proj332.pdf.

184. NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, BIOMIMETIC MEMBRANCE FOR CO_2 CAPTURE FROM FLUE GAS (2007), *available at* http://www.netl.doe.gov/publications/factsheets/project/Proj469.pdf.

185. Electric Energy Online.Com, AEP Joins Effort to Build More Efficient CO_2

To help facilitate the development and testing of CO_2 capture technologies, DOE opened the National Carbon Capture Center ("NCCC") at the Southern Company Services' Power Systems Development Facility ("PSDF") in Wilsonville, Alabama.[186] Developing and testing new CO_2 capture technologies at pilot scale and in commercially representative conditions is critical before CCS can be fully deployed. The PSDF can provide such a setting by delivering coal-derived syngas and flue gas over a wide range of process conditions. Long-term testing will be conducted at the NCCC "to establish the durability and reliability of new technologies."[187] The testing at the NCCC will provide an important step in the scale up process of CCS technology toward commercial size.[188]

The success of DOE's CCS research will ultimately be judged by the extent to which emerging technologies are deployed in domestic and international markets. However, both technical and financial challenges to this deployment abound. As new, increasingly complex, and bigger research proposals become, in some cases, prohibitively expensive to test for technical and financial feasibility, computer simulations, laboratory bench-scale experiments, and larger scales are utilized to save money and effort.[189] Commercial-scale demonstrations help industry to understand and overcome start-up and component integration issues and to gain the experience necessary to reduce risk and secure private financing and investment for future CCS projects. Consequently, DOE is implementing several large-scale programs, such as the Regional Partnerships' geologic storage field tests, industrial CCS projects, and the Clean Coal Power Initiative ("CCPI") demon-

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Compression System (Dec. 15, 2009), http://www.electricenergyonline.com/?page=show_news&id=124690.

186. Press Release, U.S. Dep't of Energy, DOE Establishes National Carbon Capture Center to Speed Deployment of CO2 Capture Processes (May 27, 2009), *available at* http://fossil.energy.gov/news/techlines/2009/09034-National_Carbon_Capture_Center_Est.html.

187. *Id.*

188. *Id.*

189. For an example of an instance where particular research utilized these different methods, see NAT'L ENERGY TECH. LAB., U.S. DEP'T OF ENERGY, SOLID SORBENTS FOR CO_2 CAPTURE FROM POWERPLANT EXHAUST STREAMS (2007), *available at* http://www.netl.doe.gov/publications/factsheets/rd/R&D122.pdf (explaining the project's use of a large-scale experiment, bench-scale tests, and simulated operating cycles).

stration projects to establish the technology base to shift CCS from concept to reality.[190]

The geologic storage field tests entered the large-scale development phase in 2009, the last step needed to support routine commercial use.[191] Nine large-scale CO_2 injection tests have been approved and will test for safety, durability, and compliance of implementing very large and deep geologic reservoirs at injection rates ranging up to one million tons per year in a broader and more diverse set of geologic formations than had been previously attempted.[192] An important aspect of this research is that it will allow scientists to examine the behavior pattern of stored carbon dioxide.[193]

The "CCPI is primarily focused on component and subsystem testing at commercial scale to gain operational integration experience."[194] The CCPI competition specifically targeted advanced coal-based systems and subsystems that captured or separated CO_2 for sequestration or for beneficial use.[195] The competition was also open to any coal-based advanced carbon capture technologies

190. *See* Nat'l Energy Tech. Lab., Clean Coal Technology Compendium, http://www.netl.doe.gov/technologies/coalpower/cctc/index.html (last visited Feb. 25, 2010) (explaining the details of the Clean Coal Power Initiative); U.S. Dep't of Energy, Carbon Capture and Sequestration from Industrial Sources, http://fossil.energy.gov/recovery/projects/industrial_ccs.html (last visited Feb. 25, 2010) (discussing twelve projects aimed at "captur[ing] carbon dioxide from industrial sources for storage or beneficial use"); U.S. Dep't of Energy, Carbon Sequestration Regional Partnerships, http://fossil.energy.gov/sequestration/partnerships/index.html (last visited Feb. 25, 2010) (discussing the DOE's Regional Carbon Sequestration Partnerships and their planned large-scale geologic injections).

191. *See* Press Release, U.S. Dep't of Energy, First U.S. Large-Scale CO_2 Storage Project Advances (Apr. 6, 2009), *available at* http://www.fe.doe.gov/news/techlines/2009/09022-Large-Scale_CCS_Advances.html (stating that drilling for the first large-scale carbon dioxide well was nearly complete).

192. *See* Nat'l Energy Tech. Lab., Regional Carbon Sequestration Partnerships—Development Phase, http://www.netl.doe.gov/technologies/carbon_seq/partnerships/development-phase.html (last visited Feb. 25, 2010); U.S. Dep't of Energy, Carbon Sequestration Regional Partnerships, http://fossil.energy.gov/sequestration/partnerships/index.html (last visited Feb. 25, 2010).

193. Nat'l Energy Tech. Lab., *supra* note 192.

194. *DOE's Research Efforts in Carbon Capture and Storage: Hearing on S.1013 Before the S. Comm. on Energy and Natural Resources*, 111th Cong. 7, 7 (2009) (statement of Victor K. Der).

195. *See* U.S. Dep't of Energy, Clean Coal Technology and the Clean Coal Power Initiative, http://fossil.energy.gov/programs/powersystems/cleancoal/index (last visited Feb. 25, 2010).

that result in efficiency, environmental or economic improvement co-benefits.[196]

As previously mentioned,[197] the ARRA signed into law in 2009 provided funding specifically for initiatives to expand and accelerate commercial deployment of CCS technology.[198] These funds targeted activities expanding and accelerating the commercial deployment of CCS technology, in effect speeding up the development of advances needed for future plants.[199] Specifically, the conference report accompanying ARRA identified four major initiatives that complement and accelerate efforts in the overall DOE coal program:

- Enhance the Fossil Energy R&D program;
- Provide additional funds to support CCPI;
- Expand geologic site characterization in geologic formations, building upon and complementing the existing characterization base created by the RCSPs; and
- Initiate a geologic sequestration training and research grant program, emphasizing advancing educational opportunities across a broad range of colleges and universities.[200]

DOE is subsequently using this funding to achieve these goals, including projects to capture and sequester CO_2 from industrial sources, as well as putting CO_2 to beneficial use. Recovery Act funds are also being used to expand CCPI with CCS. Other projects are aimed at characterizing high-potential geologic formations that could store CO_2, facilitating transfer of knowledge

196. Press Release, U.S. Dep't of Energy, Secretary Chu Announces Two New Projects to Reduce Emissions from Coal Plants (July 1, 2009), *available at* http://www.netl.doe.gov/Publications/press/2009/09043-DOE_Announces_CCPI_Projects.html; *see* Nat'l Energy Tech. Lab., Clean Coal Demonstrations: Clean Coal Power Initiative, http://www.netl.doe.gov/technologies/coalpower/cctc/ccpi/index.html (last visited Feb. 25, 2010).

197. *See supra* Part III.

198. James Markowsky, Assistant Sec'y for Fossil Energy, U.S. Dep't of Energy, Remarks to the National Mining Association Fall Board and Annual Members Meeting in Washington, D.C. (Sept. 25, 2009), *available at* http://www.fe.doe.gov/news/speeches/2009/092509-Markowsky_speech_to_NMA.html.

199. PETER FOLGER, CONG. RESEARCH SERV., CARBON CAPTURE AND SEQUESTRATION (2009), *available at* http://ncseonline.org/nle/crs/abstract.cfm?NLEid=1813.

200. Gene Kight, Dir., Finance and Procurement, Office of Fossil Energy, Fossil Energy Research and Development: American Recovery and Reinvestment Act Projects, Address at the 10th Annual U.S. Dep't of Energy Small Business Conference (Aug. 12, 2009), *available at* http://diversity.doe.gov/documents/fossilenergy.pdf.

and technologies required for CCS projects, and providing research and training opportunities for graduate and undergraduate students.[201]

V. THE ROLE OF INTERNATIONAL COOPERATION IN MITIGATING CLIMATE CHANGE

The climate change challenge is global, both in terms of sustaining economic growth and in taking effective steps to reverse the growth in CO_2 and other GHGs. It is a challenge that no one nation or small group of nations, no matter how powerful, can meet alone. Because it has the most resources, the developed world must lead the CCS effort over the next decade, but with the goal of spreading the technology to developing economies. An international effort of developed and developing countries setting a further precedent in technical, political, and scientific cooperation, will be required for an effective solution.[202]

Recognizing this, DOE plays a leading role in the CSLF, an international climate change initiative focused on fostering the deployment of CCS technologies worldwide.[203] Formed in 2003, the CSLF is a ministerial-level organization that comprises twenty-three countries and the European Commission.[204] CSLF member countries represent about 3.5 billion people, or approximately 59% of the world's population, and about 77% of the world's CO_2 emissions and economic activity.[205] Forum members have formally recognized thirty CCS projects around the world.[206]

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201. Klara, *supra* 124, at 10–11.

202. Peter Bohm, *Efficiency Issues and the Montreal Protocol on CFC's*, *in* 2 THE ENVIRONMENT AND EMERGING DEVELOPMENT ISSUES 308, 308 (Partha Dasgupta & Rari Goran Mater eds., 1997); *see* U.N. FRAMEWORK CONVENTION ON CLIMATE CHANGE, KYOTO PROTOCOL REFERENCE (2008), *available at* http://unfcc.int/resource/docs/publications/08_unfccc_kp_ref_manual.pdf.

203. U.S. Dep't of Energy, Key R&D Programs and Initiatives, http://www3.fossil.energy.gov/programs/sequestration/ (last visited Feb. 25, 2010); *see supra* Part III.

204. Carbon Sequestration Leadership Forum, *supra* note 142.

205. Ruth Herbert, Vice-Chair, Carbon Sequestration Leadership Forum Policy Group, Capturing a Solution for Climate Change: The Role of Carbon Capture and Storage and the Carbon Sequestration Leadership Forum, Presentation at the U.N. Climate Change Conference in Copenhagen (Dec. 10, 2009), *available at* http://www.cslforum.org/pressroom/publications/cslf_cop15_rherbert121009.pdf.

206. CARBON SEQUESTRATION LEADERSHIP FORUM, CSLF RECOGNIZED PROJECTS, (Oct. 2009), http://www.cslforum.org/pressroom/publications/projects_background_30project.pdf.

In addition to the CSLF, DOE is currently cooperating with numerous countries through bilateral agreements and multilateral activities. Last year DOE signed a bilateral agreement with Italy's Ministry of Economic Development to "cooperate on a wide variety of CCS projects and issue areas, including power generation processes, advanced coal gasification technologies, power system simulations, characterizing subsurface carbon sequestration potential, and exchanging CCS researchers."[207] In April 2009 the United States joined twenty-four governments, forty-two industry groups, and three finance institutions in launching Australia's Global Carbon Capture and Storage Institute.[208] Additionally, U.S. CCS technology advances and expertise are being shared in such initiatives as the Australian Otway Basin project, the European Union funded CO2SINK project in Germany, the In Salah industrial-scale CO_2 storage project in Algeria, the Ordos Basin Agreement in China, the North Sea Sleipner Project in Norway, and the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project, the Zama Acid Gas Project, and the Fort Nelson Project, all in Canada.[209] On the bilateral front, the United States and China recently signed a memorandum of understanding to create a joint Clean Energy Research Center that includes collaborative research on CCS.[210]

There is much discussion about the level of project development and investment worldwide that will be required to make commercial CCS deployment a reality. But undertaking the process is essential: An "IEA analysis suggests that without CCS,

207. Press Release, U.S. Dep't of Energy, U.S. and Italy Sign Agreement to Collaborate on Carbon Capture and Storage Technologies (May 23, 2009), *available at* http://www.energy.gov/news2009/7419.htm.

208. Grant Keys, China Projects Manager, Australian Embassy in Beijing, Global Carbon Capture and Storage Initiative, Presentation at Tsinghua University (Japan) (May 13, 2009), *available at* http://www.ccap.org/docs/fck/file/Australia%20-%20Global%20Carbon%20Capture%20and%20 Storage%20Initiative.pdf.

209. Nat'l Energy Tech. Lab., Technologies: Carbon Sequestration, http://www.netl.doe.gov/technologies/carbon_seq (last visited Feb. 25, 2010). For a complete list of initiatives using U.S. CCS technology, download the CCS database Google Earth Layer, *available at* http://www.netl.doe.gov/technologies/carbon_seq/database/index.html. *See also* Nat'l Energy Tech. Lab., Plains CO_2 Reduction Partnership—Development Phase (Apr. 2009), http://www.netl.doe.gov/publications/factsheets/project/Proj600.pdf; Nat'l Energy Tech. Lab., Plains CO_2 Reduction Partnership—Validation Phase (Apr. 2009), www.netl.doe.gov/publications/factsheets/project/Proj446.pdf.

210. Press Release, U.S. Dep't of Energy, U.S.-China Clean Energy Announcements, U.S.-China Clean Energy Research Center (Nov. 17, 2009), *available at* http://www.energy.gov/news2009/18292.htm.

overall costs to reduce emissions to 2005 levels by 2050 increase by 70%."[211] The IEA has stated that

> OECD governments will need to increase funding for CCS demonstration projects to an average annual level of USD 3.5 to 4 billion (bn) from 2010 to 2020. In addition, mechanisms need to be established to incentivise commercialisation beyond 2020 in the form of mandates, GHG reduction incentives, tax rebates or other financing mechanisms.[212]

VI. CONCLUSION

Developed and developing nations around the world share the desire for economic development, for which affordable, secure, and available energy is a prerequisite. With growing global demand for fossil fuels, especially coal, it is imperative to expeditiously develop and deploy technologies that enable us to be more efficient and environmentally conscious stewards of these presently essential energy sources. Technological development should be guided by the continually evolving science of climate change. Accumulating data suggest that nations will need to work collaboratively to counter climate change within the harrowingly short time frame of ten years or less to avoid IPCC predictions of dire consequences.[213] International collaboration makes possible the sharing of risks, benefits, and progress of technology development and deployment through the coordination of priorities and strategies. The scale of both the problem and the solution would represent a major precedent of global effort. The consensus is that we need to accelerate the R&D process. At the same time, we need to assure that we are not only working quickly, but also achieving effective solutions that will result in long-term positive outcomes.

Advanced CCS technologies are innovative and transformational; they are aimed at providing cost-competitive technology options for controlling CO_2 emissions and enabling the continued use of fossil fuels in a carbon constrained world. They will be

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211. Int'l Energy Agency, *supra* note 132, at 4.

212. *Id.*

213. *Time for the World to Act Collectively on Climate Change to Avoid Catastrophe, Warns Ban*, UN NEWS CENTRE, Oct. 1, 2009, http://www.un.org/apps/news/story.asp?NewsID=32388&Cr=climate+change&Cr1.

most effectively utilized as part of a portfolio response to CO_2 emission mitigation that includes wider use of renewable and nuclear energy and increased energy efficiencies. Even as the research toward commercialization and deployment moves forward, simultaneous progress must be made internationally on a legal and regulatory framework for CCS that deals with the varied liability issues connected to long-term CO_2 storage. The previously mentioned CSLF projects[214] are helping to accumulate the data that will assist in this important endeavor. Finally, the cost of deployment—identified as one of the biggest single hurdles for CCS to overcome—must continue to be addressed. Efforts such as the DOE research program are essential to making significant strides in helping reduce the "energy penalty" and other issues associated with today's commercially available technologies. Throughout these and other initiatives, continuous efforts must be maintained to build public understanding, acceptance, and trust, based on accurate and credible information. Without public understanding, CCS is unlikely to reach the goals needed to begin the process of mitigating atmospheric CO_2 buildup.

All nations would be affected by the impacts of global climate change. The good news is that technology and energy choices may provide policymakers with the basis for meeting their economic, energy, and environmental needs. Credible studies indicate that CCS technology will help the world reconcile its growing energy demand with the need to mitigate climate change risks while continuing to leverage existing fossil fuel infrastructure investments. Among other benefits, CCS offers stationary carbon dioxide emitters a potential retrofit option. Developing CCS to its full potential is the impetus behind the research, development, and deployment program the United States is pursuing through DOE and its industrial and international partners. Along with other initiatives around the globe, these efforts have helped establish the groundwork for worldwide cooperation and collaboration, but there is still much to do, as the earlier discussion of challenges facing the technology suggests.

Innovative CCS technology appears necessary for helping address the paradox of reconciling forecasted fossil fuel consumption with the need for CO_2 emission reductions.[215] CCS can, as part of a

214. CARBON SEQUESTRATION LEADERSHIP FORUM, *supra* note 206.

215. *See supra* notes 5–8, 67, 82 and accompanying text.

portfolio solution, provide the international community with a near and long-term opportunity to positively impact the world environment, energy supply, and perhaps economic growth and stability as well.[216] How well and to what extent this opportunity is realized will likely depend to a large degree on the level of cooperation achieved, not only in technical and scientific areas, but also the political and policy arenas,[217] as evidenced by the appeal in the Copenhagen Accord for "[e]nhanced action and international cooperation."[218] This is perhaps the ultimate practical challenge posed by the complex climate change issue. But success is possible by working together globally in common purpose and endeavor.[219] Time is not on our side if we are to stem the tide of climate change; we must collectively act with a sense of urgency in addressing the challenge.

216. *See* David G. Hawkins et al., *Clean Coal Technology Is the Future of Energy, in* COAL: OPPOSING VIEWPOINTS 63–64 (2008).

217. Interview by Michelle Nijhuis with Mark Udall, U.S. Senator from Colo., NAT'L GEOGRAPHIC (COLLECTOR'S ED.), Mar. 2009, *available at* http://ngm.nationalgeographic.com/2009/03/energy-issue/udall-field-notes.

218. *Copenhagen Accord*, *supra* note 82, at ¶ 2.

219. Chu, *supra* note 25.

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