

Scientific Synthesis of Calera Carbon Sequestration and Carbonaceous By-Product Applications

Consensus Findings of the Scientific Synthesis Team

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Co-Chairs

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Chaired by Dr. Stephen O. Andersen and Mr. Durwood Zaelke; hosted by Professor Oran Young; and including Dr. Husamuddin Ahmadzai, Mr. Frederick Anderson, Mr. Michael Atkinson, Mr. Everett Carson, Dr. Robert J. Carson, Mr. Stig Christensen, Dr. Jan SJ Van Deventer, Ms. Stephanie Hanford, Dr. Volker Hoenig, Mr. Alan Miller, Dr. Mario Molina, Ms. Lynn Price, Dr. Veerabhadran Ramanathan, Dr. Helen Tope, Dr. John Wilkinson, and Professor Masaaki Yamabe

Section I. Preface

This report describes the technical and economic feasibility of using Calera Corporation (Calera) technology to capture carbon dioxide (CO₂) from fossil fuel power plants and other industrial sources and to sequester that carbon in geologically stable substances suitable for disposal, storage, and/or use as building materials. The Calera processes can also produce intermediate products and feedstocks that can displace production from other natural and manufactured sources. The mandate of the assessment is to describe and appraise Calera carbon capture and sequestration technology from the perspective of a multi-disciplinary team and to present the findings in a report useful to technical experts and climate policy makers. The findings are the consensus of the Scientific Synthesis

¹ The authors are grateful to the University of California Santa Barbara (UCSB) Donald Bren School of Environmental Science & Management for sponsoring this project, to Calera executives, scientists and engineers for their generous devotion of time and energy to the project and to the professors and students at the Donald Bren School and Department of Chemical Engineering for detailed mass balance calculations, case studies, and life cycle analysis. From Calera we are particularly grateful to Mr. Vinod Khosla (Founder of Khosla Ventures) and Dr. Brent Constantz (Founder and CEO) for their vision, confidence in technology, and concern with environmental protection; we also thank Calera's Ms. Jane Ricci, Dr. Randy Seeker, Ms. Aurelia Setton, Mr. Cristobal Undurruga, Dr. Michael Weiss, Dr. Laurence Clodic, Dr. Terrence Holland, Mr. Joshua Patterson, and Ms. Cecily Ryan. The UCSB *Mass and Energy Balance* was by Professor Michael F. Doherty and Dr. Anjana Meel; *the Economics and Optimization* was by Dr. Professor Charles Kolstad and Mr. Daniel Young; and *Life Cycle Greenhouse Gas Footprint* was by Professor Roland Geyer, Mr. Christian Del Maestro, and Mr. Adam Rohloff. The Project was professionally managed by Ms. Maria Gordon (Bren School of Environmental Science & Management) and Ms. Alexandra Viets (Institute for Governance & Sustainable Development). Mr. Nathan Borgford-Parnell, Mr. Dennis M. Clare, Mr. Peter Gabriel, Mr. Christopher Speedie, Ms. Xiaopu Sun, and Ms. Tai Ullmann from the Institute for Governance & Sustainable Development provided valuable research, editing and proofreading.

² See Appendix 8 for a complete list, with affiliations, of the Scientific Synthesis Committee, Calera Corporate Team, University of California Santa Barbara advisors to Calera, and project managers and collaborators. See Appendix 9 for biographical information on the members of the Scientific Synthesis Committee.

Team members and not necessarily the organizations where they are employed and should not be considered as a product endorsement or as investment advice.³

The Calera technology evaluated in this report is a platform technology to capture and mineralize CO₂ using a variety of feedstocks and manufacturing a range of products.

When Dr. Brent Constantz founded the Calera Corporation in 2007, the environmental vision was to produce green cement from mineralization of CO₂ captured from power plants using sea water and industrial waste sources of alkalinity.

That founding vision underwent a significant evolution after Calera engineers and critics outside the company determined that the use of sea water alone at the original Moss Landing California pilot plant design would require too much energy and that alkaline industrial waste would be too limited for sustainable operations at significant scale.⁴ Calera expanded its research on natural sources of alkalinity and into ways to manufacture alkalinity independently from natural resources using electrochemistry. In the summer of 2009, Calera identified what was believed at the time to be an ideal demonstration site at a brown-coal power plant in the Latrobe Valley Victoria Australia where 1) the Commonwealth government would subsidize part of the costs with a grant, 2) there was low-cost pipeline and barge access to Chinese cement markets, 3) the Victoria government would welcome green technology with expedited permitting, and 4) Commonwealth legislation was under consideration to put a price on carbon that would reward the Calera technology for both reducing CO₂ emissions from the power plant and potentially for avoiding CO₂ emissions from displaced cement manufacture.

³ The Scientific Synthesis Team is co-chaired by Dr. Stephen O. Andersen, Institute for Governance and Sustainable Development and Mr. Durwood Zaelke, Program on Governance for Sustainable Development, Bren School of Environmental Science and Management. The project grew out of ongoing work by Stephen O. Andersen and Durwood Zaelke to analyze fast-action climate mitigation strategies elaborated in their joint publication with Dr. Mario Molina, Dr. V. Ramanathan, K. Madhava Sarma and Donald Kaniaru published in the Proceedings of the National Academy Of Sciences USA in the Fall of 2009, *Reducing Abrupt Climate Change Risk Using the Montreal Protocol and Other Regulatory Actions to Complement Cuts in CO₂ Emissions*. In the course of their work, Andersen and Zaelke met Dr. Brent Constantz, the founder and CEO of Calera, and learned about the potential benefits of the Calera CCS process.

⁴ The vision of Dr. Constantz was to design an industrial process that bio-mimicked and accelerated how coral shells and reefs are made from calcium and magnesium in seawater. The concept was plausible enough to be featured in a Scientific American article (David Biello, *Cement from CO₂: A Concrete Cure for Global Warming?*, SCIENTIFIC AMERICAN (August 7, 2008), available at <http://www.scientificamerican.com/article.cfm?id=cement-from-carbon-dioxide>) and to be characterized as a breakthrough by WIRED MAGAZINE (Alexis Madrigal, *The Top 10 Green-Tech Breakthroughs of 2008*, WIRED SCIENCE (December 29, 2008), available at <http://www.wired.com/wiredscience/2008/12/the-top-10-gree/>) and featured in an exhibit at the California Academy of Sciences. Amid that enthusiasm, respected Stanford climate scientist Dr. Ken Caldeira publically challenged the original Calera seawater chemistry. Now that numerous patents have been issued to Calera, Dr. Constantz and his research team have more fully revealed the chemistry and processes involved in the technology. They have also developed new applications using inputs from brine rather than seawater and different sources of alkalinity. A description of this exchange can be found at <http://climateprogress.org/2009/04/02/calera-caldeira-green-cement-carbon-co2/>.

Calera improved the process to include new production methods for alkalinity from natural sources and manufacturing techniques and the use of new sources of cations from hard waters and geologic brines. Calera, with partner Industrie de Nora (Denora) scaled-up of an energy efficient electrochemical membrane process to supplement natural brine sources lacking the necessary blend of minerals.

In late 2010, as the Scientific Synthesis team was completing its report, Calera notified the team that analysis of the underground reservoir and geology had determined that the local brines at the Latrobe Valley were unsuitable for the Calera process, and that the Australian government abandoned the carbon legislation that would have made the Calera Latrobe project viable if the brines had been suitable.

Taking this into account as well as the coincidental failure of climate talks at Copenhagen and the failure of U.S. climate legislation, Calera chose to stop work on the Latrobe demonstration project. Calera notified both the Commonwealth and the State of Victoria and submitted a revised proposal for a different project to conduct research and development using electrochemically-produced alkalinity and other natural alkalinity and hard brine sources. Calera has also identified locations in the United States and China where suitable alkalinity and calcium are potentially available and is currently pursuing project development in these locations.

As of December 2010, Calera is reorganizing to profit from their innovative technology in feedstock and intermediate product markets less dependent on carbon pricing and in applications where access to suitable feedstocks are available. Calera is now focused on the scale-up of their newest continuous process in order to generate enough material to prove its revenue potential in various markets.

“The vision of Calera has not changed and remains to capture CO₂ from industrial emissions sources and convert it into new materials through efficient, scalable processes that benefit mankind and the environment. This vision requires the use of all available sources of alkalinity including waste products and by-products, extraction from natural minerals, and/or alkalinity electrochemically produced. The current effort consists in broadening the mix of mineral carbonates produced that can be used as mineral bicarbonate and carbonate chemical feedstocks and other intermediate products, with the future option to produce a larger volume of useable products such as building materials or to sequester carbon through reinjection of bicarbonate slurry.”

Randy Seeker, Calera Chief Technology Officer, December 5, 2010

The discovery and disclosure by Calera of the unsuitable brines at Latrobe and the decision by Calera to continue exploring opportunities for profitable operations without an existing carbon price came after this report was substantially written. Therefore, the findings of this report remain predicated on the assumptions that there are other locations with suitable resources for the Calera process and that concern for climate change will

eventually lead to carbon pricing and/or direct regulation that will incentivize reductions in CO₂-equivalent emissions.

Scientific Synthesis of Calera's Technology

The patented Calera process elaborated below has two stages. The first “carbon capture and sequestration (CCS)” stage can capture up to 90% of CO₂ from power plants using brines extracted from geological deposits and manufactured alkalinity and can convert the CO₂ into stable calcareous material and bicarbonate solution with an energy penalty ranging from about 10% to 40%, depending on power plant characteristics and availability of key inputs, particularly brines. The second stage is to further process and dry the calcareous material, where technically feasible, to replace a portion of either the product called “Ordinary Portland Cement” (OPC) or to replace or reduce OPC ingredients in blended cement, and thus potentially avoiding CO₂ emissions from cement manufacture. In the Calera process novel metastable carbonate minerals are formed that have cementitious characteristics when mixed into concrete or with water. In some cases, the combined reductions in greenhouse gas emissions from power plant CCS and avoided cement production are potentially greater than the total emissions of either process alone, but in some cases the carbon emissions from second stage processing may be greater than the carbon savings from the product substitution. The Calera process also has the potential to simultaneously capture not only CO₂, but also SO₂ and other acid gases and a suite of heavy metals. This is important because the Calera process may cost less than the costs of controlling all of these pollutants with conventional CCS, SO₂ scrubbers, and heavy metal control as practiced today.

At the Calera pilot plant located on the Pacific Ocean at Moss Landing California, third-party certification by the engineering firm R.W. Beck documented that, with sodium hydroxide, the Calera process has been able to capture up to 90% of CO₂ from the stack gases of a 10MW-equivalent power plant with a net energy penalty of about 5 to 10%. The 5 to 10% energy penalty applies only to the absorption process that produces aqueous calcareous material. It is noteworthy that a similar chemical process is hypothesized by others for gaseous storage of CO₂ in saline aquifers where slow mineralization is thought to take place.⁵

The bicarbonate aqueous slurry produced in the Calera process can be re-injected into the brine deposit together with excess waste brines or can be further processed into minerals, or substances suitable for building materials, storage, or land disposal

The advantage of the Calera process relative to other proposed CCS is that: it is available near-term at a lower estimated cost, it is modular retrofit to existing power plants making

⁵ J.M. Matter and P.B. Kelemen, *Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation*, 2 NATURE GEOSCIENCE 837-841 (December 2009); J.T Birkholzer, Q. Zhou, C.F. Tsang, *Large-scale impact of CO₂ storage in deep saline aquifers: a sensitivity study on the pressure response in stratified systems*, 3(2) INT. J. GREENHOUSE GAS CONTROL 181–194 (2009); and Q. Zhou, J.T. Birkholzer, C.F. Tsang, J. Rutqvist, *A method for quick assessment of CO₂ storage capacity in closed and semi-closed saline formations*, 2(4) INT. J. GREENHOUSE GAS CONTROL 626–639 (2008).

it scalable, and it has the potential to capture carbon while producing a useful product, whereas other long-term CCS is generally just an added cost. The market potential and profitability of Calera CCS and low-carbon building products depend on access to brines and other inputs in suitable quantity and quality, market demand, and industrial and environmental policy, particularly carbon pricing that would reward carbon sequestration and raise the price of building products sold by Calera that would otherwise have high carbon intensity. Site-specific impact assessment will be needed for access to brines and impact on the water balances and hydrogeology.

The Calera calcareous material might ultimately be used in large volumes as an ingredient in blended cements, as specialty building materials, or as aggregate. When used as an ingredient in blended cements, such material is classified as “Supplementary Cementitious Materials” (SCM). Use of the Calera material as an SCM in concrete and other building material applications has the potential to reduce climate forcing if the Calera material has lower life-cycle carbon-equivalent emissions than the materials replaced. If used as an ingredient in blended cements, the Calera will compete with readily available, proven, low-carbon materials including fly ash and blast furnace slag.

Calera has documented the suitability of the calcareous material as a partial replacement for cement clinker in cement in some non-structural applications, but has not yet proven publically the suitability of the calcareous material as a cement ingredient in concrete applications where other widely available low-carbon supplementary materials are not viable.

If the Calera process were applied to all power plants, the quantity of calcareous output would be far higher than the cement market can absorb in all but rapidly developing countries like China, where over half of global cement production occurs today. However, national and regional aggregate markets are sufficiently large to absorb the solid materials produced as a result of large-scale deployment of the Calera process.

These questions of technical suitability, market acceptance, process performance, environmental acceptability of brine extraction and reinjection, and net carbon sequestration of the Calera process will be progressively resolved as anticipated demonstration and commercial-scale plants come on line. The Calera technology proved infeasible in Latrobe Valley Australia when it was determined that the brines were chemically unsuitable for the process and not available in sufficient quantity. Calera has identified locations in the United States and China where suitable alkalinity and calcium are potentially available for the process and is currently pursuing project development in these locations. The Calera technology may be particularly valuable in China and other developing countries where there is strong growth in both the electric power and cement sectors and where there are also large markets for concrete as a building material. In markets with expanding electric power and cement markets, it is more likely that locations can be found with all the necessary inputs, including suitable fuel and brines. However, such locations have not yet been disclosed.

Section II. Project Overview and Origin

The meeting of Scientific Synthesis Team and experts from UCSB and Calera was held May 4-7, 2010 in Monterey, California and included a tour of the Calera Moss Landing pilot facility. Scientific Synthesis Team Subcommittee meetings were also held in Fish Creek, Utah; La Jolla, California; Madrid, Spain; Geneva, Switzerland; and Washington, DC.

The Scientific Synthesis Team is grateful to Calera experts, experts from the University of California Santa Barbara (UCSB), and peer reviewers. Drs. Michael Doherty, Roland Geyer, Charles Kolstad, and Anjana Meel and students at UCSB produced a series of useful studies on chemistry, life-cycle greenhouse gas (GHG) analysis, and cost analysis of carbon sequestration that were an important part of the foundation of this synthesis. The UCSB scholars applied rigorous academic analysis to the critical scientific issues of technical choice for climate protection. Calera organized detailed process descriptions and answered all the questions put forward by our team. Peer reviewers found the missing links in our text and directed us to answers. We appreciate their substantial contributions, but are solely responsible for our consensus conclusions.

Section III. Project Organization and Consensus Integrity

Professor Oran Young and Co-Chairs Durwood Zaelke and Stephen O. Andersen convened the Scientific Synthesis Team under the auspices of the UCSB Donald Bren School of Environmental Science and Management to undertake a rapid assessment of the technical, environmental, and economic feasibility of reducing greenhouse gas emissions using proprietary technology developed by the Calera Corporation. The assessment is based on the documentation and presentations at the Monterey meeting and on research by committee members.

All members of the Scientific Synthesis Team—including Host and Co-Chairs—worked without compensation. Costs of travel, lodging, meals and other project expenses were paid by a grant from the Calera Corporation to the University of California.⁶ Experts were selected for their academic training, practical experience, and membership in organizations and activities relevant to the assessment. The Team includes chemists, process engineers, environmental authorities, policy experts, and economists from research and standards organizations, national laboratories, universities, multi-lateral environmental treaty organizations, the United Nations, environmental non-government organizations, and corporations, located in Australia, Denmark, Germany, Japan, Kenya, Sweden, and the United States.

This report is organized to highlight the significant findings in the body of the report and to elaborate important information in Appendixes and Web Links.

⁶ The actual costs of travel lodging, meals and other expenses were paid from the grant to the University of California for members of the Scientific Synthesis Team requesting reimbursement (Lynn Price served without UCSB reimbursement of expenses).

- Appendix 1 defines the technical vocabulary used in the report,
- Appendix 2 spells out the acronyms,
- Appendix 3 describes mass balance,
- Appendix 4 summarizes the technical option “Road Map” to substantially reduce GHG emissions from conventional cement manufacture,
- Appendix 5 describes voluntary cement industry initiatives to encourage rapid adoption of those technical options,
- Appendix 6 catalogues companies, including web links, with emerging low-carbon cements and cement substitutes,
- Appendix 7 outlines finance opportunities for developing countries wishing to invest in new technology to help protect the climate, and
- Appendix 8 describes the qualifications of our Scientific Synthesis Team.

Section IV. Introduction: Need for Carbon Reduction and Carbon Negative Strategies

More than 120 countries, including all countries with major emissions of GHGs, have agreed under the 2009 *Copenhagen Accord* (CHA) to keep global average temperature increase below 2°C. This maximum acceptable temperature increase is based on recommendations by numerous scientific studies that warn that global temperature increases in excess of 2°C can trigger “dangerous anthropogenic interference with the climate system,” including climate-tipping points, with unmanageable consequences to water supply, agricultural productivity, sea-level rise, human habitability, and global security.⁷ This goal is all the more urgent because many respected scientists estimate that the concentration of CO₂ and other climate-forcing substances in Earth’s atmosphere already exceeds the safe level.⁸ Excellent review of climate change science, impacts, equity, strategy, and solutions are presented in the University of Copenhagen Synthesis Report and in the IPCC Fourth Assessment Report.⁹

⁷ V. Ramanathan & Y. Feng, *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, 105 PROC NATL ACAD SCI USA 14245–14250 (2008); H.J. Schellnhuber, *Global warming: Stop worrying, start panicking?*, 105 PROC NATL ACAD SCI USA 14239–14240 (2008); Meinshausen M, et al., *Greenhouse-gas emission targets for limiting global warming to 2°C*, 458 NATURE 1158–1162 (2009); E. Kriegler, J.W. Hall, H. Held, R. Dawson, H.J. Schellnhuber, *Imprecise probability assessment of tipping points in the climate system*, 106 PROC NATL ACAD SCI USA 5041–5046 (2009); J. Hansen, et al., *Target atmospheric CO₂: Where should humanity aim?*, 2 THE OPEN ATMOS SCI J 217–231 (2008); J. Rockstrom, et al., *A safe operating space for humanity*, 461 NATURE 472–475 (2009); S.H. Schneider, M.D. Mastrandrea, *Probabilistic assessment of “dangerous” climate change and emissions pathways*, 102 PROC NATL ACAD SCI USA 15728–15735 (2005).

⁸ Hansen, et al., *id.* By the end of 2009, the CO₂ concentration was 387 ppm, far greater than the maximum safe level of 350 ppm, and growing at nearly 2 ppm per annum. (Global Carbon Project, *Carbon Budget 2009* (21 November 2010), available at <http://www.globalcarbonproject.org/carbonbudget/>). Before the Industrial Revolution (1750), CO₂ concentrations were 280 ppm.

⁹ Katherine Richardson et al., SYNTHESIS REPORT, available at <http://climatecongress.ku.dk/pdf/synthesisreport/> (Climate Change, Global Risks, Challenges & Decisions 10-12 March, 2009, Copenhagen).

Undoing the damage that has already been done to the Earth and its atmosphere and returning atmospheric GHG concentrations to a safe and sustainable level will require simultaneous pursuit of five actions:

1. Reduce emissions of CO₂, the largest contributor to climate change, by transforming sectors with significant distributed CO₂ emissions—particularly, buildings, industrial activities, transportation, and appliances.
2. Reduce emissions of non-CO₂ climate-forcing substances in order to immediately delay global warming (black carbon soot, methane, tropospheric ozone, and high-global warming potential (GWP) halocarbons including ozone-depleting substances (ODSs)).¹⁰
3. Commercialize and implement CCS through processes such as the Calera process documented here.¹¹
4. Expand carbon negative strategies such as bio-sequestration (including biochar) and industrial processes that chemically mimic photosynthesis and sequestration and otherwise capture CO₂.¹²
5. Coordinate national air pollution laws that are currently reducing the emissions of cooling sulphates with controls on black carbon to ensure that the combined aerosol reductions minimize effect on warming.¹³

Section V. Policy Drivers for Low-Carbon Electricity and Cement

Concern over the financial and environmental consequences of climate change have inspired a wide range of policy responses that are now or may soon be applied to electricity and cement production. In the electricity sector, many countries offer tax-

¹⁰ Mario Molina, Durwood Zaelke, K. Madhava Sarma, Stephen O. Andersen, Veerabhadran Ramanathan, and Donald Kaniaru, *Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO₂ emissions*, 106 PROC NATL ACAD SCI USA 20616-20621 (December 2009) available at <http://www.pnas.org/content/early/2009/10/09/0902568106.full.pdf+html>; see also *Subtitle C, Achieving Fast Mitigation*, in Kerry-Lieberman Climate Bill (12 May 2010), available at <http://kerry.senate.gov/imo/media/doc/APAbill3.pdf>.

¹¹ See IPCC, SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE (eds. Metz, B, Davidson, O., de Coninck, H.C., Loos, M. & Meyers, L.A.) 197-265 (Cambridge Univ. Press, 2005); DOE/NETL, ADVANCED CARBON DIOXIDE CAPTURE R&D PROGRAM: TECHNOLOGY UPDATE (September 2010), available at <http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/CO2%20Capture%20Tech%20Update%20Final.pdf>; J.M. Matter and P.B. Kelemen, *Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation*, 2 NATURE GEOSCIENCE 837-841 (December 2009); D.W. Keith, M. Ha-Duong, and J.K. Stolaroff, *Climate strategy with CO₂ capture from the air*, 74 CLIMATE CHANGE, 17-45 (2006); K.S. Lackner, P. Grimes, and H-J. Ziock, *Carbon Dioxide Extraction from Air* (2001), available at http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/7b1.pdf; and S. Elliott et al., *Compensation of Atmospheric CO₂ Buildup through Engineered Chemical Sinkage*, 28 GEOPHYSICAL RESEARCH LETTERS 1235-1238 (2001).

¹² See Molina, et al., supra note 10, for a description of biochar.

¹³ V. Ramanathan and Y. Xu, *The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues*, 107 PROC NATL ACAD SCI USA 8055-8062 (May 2010) available at <http://www.pnas.org/content/107/18/8055.full.pdf>; M. V. Ramana, V. Ramanathan, Y. Feng, S-C. Yoon, S-W. Kim, G. R. Carmichael and J. J. Schauer, *Warming influenced by the ratio of black carbon to sulphate and the black-carbon source*, 3 NATURE GEOSCIENCE 542-545 (August 2010).

rebates for renewable energy investment, require electric utilities to provide an increasingly large portion of power from renewable energy, and make utility investments accountable for CO₂ emissions through sector agreements or “cap-and-trade” requirements. Cap-and-trade has been implemented in several countries and in the European Union to meet regulatory goals under the Kyoto Protocol, has been undertaken in the United States at the state and regional level and elsewhere as part of voluntary commitments, and is now being considered in China as part of its 12th Five-Year Plan period (2011-2015) to help it meet its 2020 carbon intensity target.¹⁴ However, many countries (including the countries with highest CO₂ emissions) have not yet agreed to legally enforceable emission limits and have not yet put in place economic incentives and disincentives necessary to avoid dangerous climate forcing. For example, in 2010 both Australia and the United States failed to enact climate legislation, which is cited by Calera as having a significant influence on their decision to develop a new business plan not immediately dependent on climate policy for economic viability.

Regulators in some jurisdictions complement economic incentives with requirements like the European Commission’s (EC’s) “Best Available Techniques” that require cement, lime and magnesium oxide industries to take specific action to reduce climate, ecosystem, and other impacts.¹⁵ Furthermore, many electric utilities offer customers low-carbon electricity at a small premium in price. In the cement sector, cap-and-trade or sector agreements can also internalize the cost of CO₂ emissions.¹⁶ Other proposals would require mandatory CO₂ sequestration linked to extraction and use of fossil fuels.¹⁷ Green building programs and government infrastructure projects (roads, bridges, and buildings) can account for the carbon emissions in cement and cement products, including emissions from fuel consumption and emissions from the process of calcining limestone and turning it, together with other mineral constituents, into cement clinker.¹⁸ In addition, many environmental regulations on air pollutants, waste disposal and toxic substances can have the co-benefit of encouraging low-carbon cement.

Examples of regulations encouraging greener cement include:

- Regulations restricting or prohibiting land disposal of fly ash and slag (increasing use in blended cement to offset OPC),

¹⁴ Li Jing, *Carbon trading in pipeline* (July 22, 2010), available at http://chinadaily.com.cn/china/2010-07/22/content_11033249.htm.

¹⁵ See European Commission Directorate General, INTEGRATED POLLUTION PREVENTION AND CONTROL: REFERENCE DOCUMENT ON BEST AVAILABLE TECHNIQUES IN THE CEMENT, LIME AND MAGNESIUM OXIDE MANUFACTURING INDUSTRIES (May 2010).

¹⁶ See e.g., US Environmental Protection Agency, US Department of Transportation and US Department of Energy, STUDY ON INCREASING THE USAGE OF RECOVERED MINERAL COMPONENTS IN FEDERALLY FUNDED PROJECTS INVOLVING PROCUREMENT OF CEMENT OR CONCRETE (2008), available at <http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1003EUM.txt>.

¹⁷ M.R. Allen, D.J. Frame and C.F. Mason, *The case for mandatory sequestration*, 2 NATURE GEOSCIENCE 813-814 (December 2009).

¹⁸ In the process of clinker production no lime is produced. CaCO₃ reacts partially in solid/solid reactions already at temperatures below the calcining temperature. The formed CaO is an intermediate compound which reacts in the clinker melt with the other minerals.

- Regulations reducing allowable atmospheric emissions of mercury and other heavy metals from power plants (rewarding the Calera process),
- Regulations such as the U.S. EPA's pending industry National Emission Standards for Hazardous Air Pollutants (NESHAP) requiring new or tighter controls on the emissions of mercury, total hydrocarbons, particulate matter and hydrochloric acid from cement manufacture (encouraging a wide range of innovation in cement and alternative building products), and
- Procurement rules by federal and local government agencies that can specify carbon footprint performance standards of cement or concrete (CO₂ per unit of product) or prescribe the ingredients of cement (favouring Calera, slag, or fly ash SCM).¹⁹

Voluntary industry-government partnership and leadership by industry associations can also be effective drivers of policy. Examples of industry-government partnerships include the U.S. EPA Coal Combustion Products Partnership (C2P2), which seeks industry partnerships to promote recycling of coal waste and other coal combustion residues (CCRs). Examples of cement association leadership are outlined in Appendix 5.

Finally, all efforts on low-carbon cement, including Calera's integration of carbon capture and cement offsets, fit well into the evolving corporate and national policies of "product stewardship," which incorporates product design and waste reduction/management in a life-cycle framework. The policy concept is to minimize waste (especially hazardous materials) and maximize the use of a necessary product through its life cycle. In essence, what the Calera process strives to accomplish is the reuse of CO₂ that would otherwise be climate-forcing atmospheric waste, to reduce CO₂ emissions from cement manufacture, to co-produce industrial chemicals (like HCl, bicarbonate and calcium carbonate) at lower input cost, and to provide co-benefits in partly isolating and sequestering sulphur, acid gases, and mercury and other toxic materials from coal combustion.

VI. Executive Summary: Calera Technology (capture power plant CO₂ and sequester it as mineral carbonates)

In late 2010, Calera suspended its Latrobe Valley demonstration project when available brines proved technically unsuitable in quality and quantity and Australia failed to enact business incentives for carbon sequestration. This report is a synthesis of the consensus finding that the same Calera technology is viable if locations with suitable brines and other natural mineral sources can be found and developed.

- The Calera process has been demonstrated in the laboratory and at the pilot plant scale using naturally occurring brines and waste materials with ideal characteristics and is undergoing additional improvements in process efficiency and optimization.

¹⁹ Exec. Order No. 13514 (2009) (requiring US federal organizations to reduce direct and indirect GHG emissions through changes in procurement guidelines and operations).

- The Calera core process chemistry is valid;
 - The mass and energy balance is confirmed but will vary dramatically depending on process inputs and outputs;
 - At the Moss Landing 10 MW demonstration scale plant, up to 90% of CO₂ was captured using sodium hydroxide as the source of alkalinity at less than 10% of the equivalent power output in the absorption process (as documented by R. W. Beck Company).
- The Latrobe Valley large-scale demonstration project was suspended and an alternative research and development proposal was submitted by Calera in late 2010 when the brine quality and quantity proved unsuitable and Australian carbon legislation failed to pass that would have provided substantial financial incentives to Calera and other companies for carbon sequestration and greenhouse gas emission reductions.
 - The Calera Technology, which captures power plant CO₂ and sequesters it as carbonaceous material, is most economic when power plants are sited near appropriate brines, alternative alkalinity, and mineral sources, but may be less competitive with conventional carbon sequestration at locations far from brine and mineral sources.
 - The Calera Technology has substantial environmental, technical and economic advantages if, and only if, brines or other sources of alkalinity in suitable quantity and quality are available, including:
 - Verified CO₂ capture efficiency using Calera's patented Mineralization via Aqueous Precipitation (MAP);
 - Lower leakage or other environmental hazards when the CO₂ sequestered in solid Calera products is protected from acids, in contrast to the hazards of compressed CO₂ sequestration in geological formations or in ocean depths;
 - Ability to capture and safely isolate and sequester in calcium carbonate precipitate sulphur dioxide and other acid gases, mercury, and other heavy metals (e.g., Ag, As, Ba, Cd, Cr, Pb, and Se);
 - Application of the energy efficient "Alkalinity Based on Low Energy" (ABLE) electrochemistry process where brines and other natural alkalinity and mineral sources are inefficient;
 - Lower energy penalty compared to other CCS processes if off-peak and low-carbon energy sources can be used for alkalinity manufacturing;
 - Potential to utilize power from off-grid solar and wind generation at remote locations to manufacture alkaline products that can be shipped to power plants where CO₂ is captured, in contrast to conventional CCS where the majority of the parasitic power demand is required during capture and transfer; and
 - Ability to capture (recycle) and use CO₂ that otherwise becomes climate-forcing atmospheric pollution.

- The Calera Technology has some potentially significant challenges, including:
 - Depends on a suitable quantity and quality of brines, alternative natural alkalinity resources and/or minerals being available near the power plant or the availability of low-carbon, low cost, electricity for manufactured alkalinity;
 - Increases in coal mining and associated impacts (but less than other sequestration) to compensate for parasitic energy use;
 - Produces more calcareous material and more HCl when deployed on a massive scale than current markets would be able to accept (this will be an advantage if markets are found for socially desirable uses);
 - Potential impact on water balances and hydrology from extraction and reinjection of brines;
 - Competes with available technologies to reduce cement and concrete carbon footprints;
 - Building material products require proof of technical suitability, acceptance by standards organizations, and market acceptance; and
 - Requires environmentally acceptable management of brines and bicarbonate solution that would be pumped from and into geologic formations.

- Outcomes must be managed carefully as the Calera Technology proceeds. Coal will become a cleaner source of power. Cement and concrete may have improved carbon footprints. With the Calera capture and safe geologic bonding of sulphur and heavy metals, coal previously uneconomic due to high concentrations of these contaminants may be available at potentially lower net economic impact. Employment will be increased in some sectors and locations and decreased in other sectors and locations. Domestic coal may replace a portion of imported fuels, with benefits in domestic energy sector employment, energy independence, and regional economic development but loss of employment in overseas operations and transportation sectors. Jobs in conventional limestone mining may decrease, while jobs in carbon capture and mineralization increase.

- Calera SCM as a 20% replacement in blended cement has satisfied existing performance standards for setting behaviour (ASTM C191), flow characteristics (ASTM C1437), and compressive strength (ASTM C109).
 - It appears technically feasible, but not yet demonstrated, that if produced with consistent and reproducible physical and chemical properties (particle size, particle size distribution, and/or ratio of carbonate/bicarbonate) the Calera SCM can be a replacement for aggregate and a portion of OPC in some blended cement applications with easily achieved technical performance.
 - With further technical development—depending on the availability of continuous funding support for research, development, and application engineering—it is possible that Calera SCM will supply an increasingly

- Under the most favourable circumstances—where suitable brines and other feedstocks, and markets for SCM are available near coal-fired power plants—the co-production of electricity and the Calera carbon capture has the potential to reduce power plant emissions by up to 90% with offsetting CO₂ emission from the Calera process of 10 to 30% or more, depending on the power plant characteristics and availability of inputs. In addition, Calera SCM—and other supplementary materials such as limestone, fly ash and slag--have the potential to replace a portion of OPC in concrete. These speculative estimates of cost-effectiveness can only be informed by the realized economics of demonstration projects.
 - If Calera SCM replaced 20% of OPC in the US, cement production would decrease from 75 million tons per annum (Mt p/a) (2009) to 60 Mt and associated CO₂ emissions would be reduced by approximately 13 Mt p/a CO₂ (assuming an emissions factor of 0.88 tCO₂/t cement).
 - If Calera SCM replaced 20% of OPC in China, cement production would decrease from 1.4 Gt p/a (2009) to 1.12 Gt and associated CO₂ emissions would be reduced by approximately 246 Mt p/a CO₂ (assuming an emissions factor of 0.88 tCO₂/t cement).
 - The cost, net energy, and environmental impact of the Calera process at favourable site locations with suitable brines and other feedstock quantity and quality are lower than the near-future costs of other proposed carbon sequestration technologies, according to UCSB analysis.
- A price on carbon via emissions trading or carbon tax or regulation will stimulate a wide range of climate change benefits, including: 1) carbon sequestration from fossil fuel power plants, 2) comparative advantage of renewable and low-carbon power sources (nuclear, hydroelectric, wind, solar, biomass), 3) energy efficiency, 4) greater use of SCMs (including available Calera products), and 5) technical innovation. Economic forces will encourage a new least-cost equilibrium of energy supply, energy efficiency, and carbon sequestration. Price impacts in the cement sector may reward the Calera technology and also incentivize the substitution of fly ash, blast furnace slag, and other supplementary materials in blended cement and the substitution of other cements for OPC in specific applications where alternatives satisfy performance criteria.
- Using less clinker in cement and more SCM, such as fly ash, blast furnace slag, and the cementitious material produced by the Calera process, can reduce the carbon footprint of concrete.²⁰ The carbon footprint of thermal energy used for

²⁰ Technically feasible lime cement clinker substitutes include ashes from coal power plants, blast furnace slag from the steel industry, ashes from the combustion of mining waste, pozzolans (mined or as by-

the manufacture of cement can be reduced by improvements in cement kiln energy efficiency, by the use of renewable energy (biomass, hydroelectric power, etc.) and by carbon sequestration. The carbon footprint of electrical energy and shipping can be reduced by improvements in energy efficiency and by the use of renewable energy.

- Preliminary studies conducted on flue gas from combustion of different coal types at the Calera pilot scale plant achieved 77 to 86% total mercury capture in the calcium carbonate precipitate and significant capture of other heavy metals (e.g. Ag, As, Ba, Cd, Cr, Pb, and Se). In these studies, when coal flue gas-derived carbonate precipitates were mixed as a 20% replacement for OPC, leachable levels of mercury and all other heavy metals were two to three orders of magnitude less than the Toxicity Characteristic Leaching Procedure (TCLP) federal hazardous waste standards and less than drinking water limits. The safety of other blended cement/OPC mixtures and potential non-OPC products will need to be verified experimentally and as part of quality control for any commercial process.
- An increased supply of SCM has a modest potential to lower the price of products made with cement and concrete, including buildings, bridges, roads, sidewalks, and culverts. In these applications, cement and concrete compete against wood, steel, plastics and other materials.
- Environmental and economic benefits of the Calera process may be particularly important in China and other fast-growing developing countries where there is high demand for electric power from fossil fuel; aggregate for concrete, asphalt, and road base; and for cement for a wide variety of applications. In these situations, new power plants can be co-located with sources of feedstock to minimize costs and maximize environmental benefit.
- Independent analysis and performance investigations of the Calera technology at each stage of development are critical in providing to policy makers, cement companies, cement customers, and citizens proof of potential benefits of quickly moving this technology forward. The importance of independent verification was made readily apparent by the experience at Latrobe Australia where brines proved to be unsuitable for the Calera process.

VII. Cement Carbon Footprint Overview

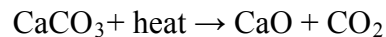
Cement is produced in virtually all countries as an important construction material that sets and hardens to bind other materials together. Cement is the dry powder substance that is combined with water, additives, and aggregate materials—notably sand and gravel—to form concrete and mortar. Concrete is second only to water as the most

products of industrial silica industries and from palm oil fuel ashes), limestone, and gypsum (up to about 5%).

consumed substance on Earth.²¹ OPC was perfected in the mid-1850s to provide a combination of economy, consistency, desirable setting time, strength and durability.

The main ingredients in Portland cement are calcium silicates and calcium aluminates made by heating a calcareous rock (limestone) to drive off CO₂ in the presence of alumina-silicate clays or other ingredients, sintering it together to become clinker that in turn is ground with a small amount of gypsum into the powder OPC. When water is added to the OPC, the calcium silicates are involved in complex reactions to form paste that sets and hardens to form a strong material. In the case of aluminous cements, hydraulic hardening involves the formation of calcium aluminate hydrates.²² Blended cements are produced by blending and sometimes inter-grinding fine materials with clinker and gypsum. The most commonly used supplemental materials in blended cement are blast furnace slag, fly ash, silica fume, calcined clay, and other pozzolans. The ingredients used in blended cements or in concrete are called Supplementary Cementitious Materials (SCMs).

Cement manufacture emits the GHG CO₂ both directly through the production of CO₂ when calcium carbonate is heated, and indirectly from burning fossil fuels used for process energy. About 50% of the cement carbon footprint is from the chemical transformation of limestone (CaCO₃) into lime (CaO). The simplified stoichiometric relationship is:



An additional 40% of the carbon footprint is from thermal energy necessary for this calcination to occur (the reaction requires 1,700 MJ/t of clinker) and 10% is from electricity to operate the plant and for raw material transportation.

The carbon footprint of cement and concrete can be reduced by using less clinker and more SCMs such as fly ash, blast furnace slag, and the cementitious material produced by the Calera process. The carbon footprint of thermal energy can be reduced by improvements in kiln energy efficiency, by the use of renewable energy (such as biomass, alternative fuels containing biomass, hydroelectric power, etc) and by carbon sequestration. The carbon footprint of electrical energy and shipping can be reduced by improvements in energy efficiency and by the use of renewable energy. Appendix 4 presents the technical option “Road Map” to substantially reduce GHG emissions from conventional cement manufacture.

²¹ International Finance Corporation, *A Guide to Biodiversity for the Private Sector*, available at [http://www.ifc.org/ifcext/enviro.nsf/AttachmentsByTitle/BiodivGuide_SectorSummary_Cement/\\$FILE/Cement.pdf](http://www.ifc.org/ifcext/enviro.nsf/AttachmentsByTitle/BiodivGuide_SectorSummary_Cement/$FILE/Cement.pdf).

²² European Commission Directorate General, INTEGRATED POLLUTION PREVENTION AND CONTROL: REFERENCE DOCUMENT ON BEST AVAILABLE TECHNIQUES IN THE CEMENT, LIME AND MAGNESIUM OXIDE MANUFACTURING INDUSTRIES (May 2010).

Supplementary Cementitious Materials (SCMs)	
Calera SCM	Up to 20% in selected applications
Fly Ash (from coal power plants)	30-50% for high fly ash volume cements
Granulated Blast Furnace Slag (from iron making)	Up to 80% for slag cements (80% is the EU standard, up to 90% is allowed for special applications)
Ashes from incinerating mining waste	Limited experience
Manufactured Pozzolans (palm oil fuel ash)	Limited supply of recoverable natural and waste sources
Natural Pozzolans (volcanic ash & silica)	Vast quantities available, but no supply chain.
Limestone	Up to 20% to 35% depending on standards and regulatory requirements (20% is the EU standard) ²³

Alternative Geopolymer Cementitious Materials (Replacing 100% of OPC)	
Geopolymers	Traditional geopolymers use sodium hydroxide or sodium silicates to activate pozzolans. Traditional geopolymers have about 20% the CO ₂ emissions of OPC when pozzolans are naturally sourced or using recycled material, but have higher CO ₂ emissions when pozzolan is specially produced. Zeobond geopolymers use an alkali activator as part of the starting material, which reduces the carbon footprint to a level significantly below traditional geopolymer formulations. ²⁴

The IPCC reported that global cement production grew from 594 Mt in 1970 to 2,200 Mt in 2005.²⁵ In 2004, developed countries produced 570 Mt (27% of global production), and developing countries produced 1560 Mt (73%).²⁶ In 2005, China produced 1,000 Mt (about 45% of global production), India produced 130 Mt (about 5% of global production) and other developing countries produced about 500 Mt (20% of world production).²⁷ Global cement consumption is growing at about 2.5% p/a.²⁸ Based on

²³The addition of limestone to OPC concrete reduces the capacity to include more ash or slag. Ash and slag addition contributes beneficial properties to OPC, like enhanced durability and reduced alkali aggregate reaction. In contrast, the addition of limestone does not improve the concrete, but reduces the capacity to utilize the beneficial effects of ash and slag.

²⁴ Use of surplus HCl from the Calera process on natural rock might supply a specially produced pozzolan aluminosilicate that could reduce the need for slag in geopolymerisation.

²⁵ IPCC, *Industries*, in CLIMATE CHANGE 2007: MITIGATION OF CLIMATE CHANGE, CONTRIBUTION OF WORKING GROUP III TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 467 (2007).

²⁶ *Id* (citing to USGS, *Minerals Yearbook 2004* (2005)).

²⁷ *Id* (citing to USGS, *Minerals commodity summary: cement* (2006)).

average emission intensities, IPCC estimated total emissions in 2003 was 1,587 Mt CO₂ (432 MtC) to 1,697 Mt CO₂ (462 MtC), or about 5% of global CO₂ emissions, half from process emissions and half from direct energy use.²⁹

The IPCC report estimated that global average CO₂ emissions per tonne cement production range from a low of 700 kg in Western Europe, 730 kg in Japan and South Korea, 900 kg in China, 930 kg in India, and to a high of 935 kg in the United States.³⁰ The differences in emission intensity are attributed to differences in the clinker content of the cement produced, the extent to which SCM are blended into the cement, the energy efficiency of the specific processes, the carbon intensity of the clinker fuel and the carbon intensity of power generation used at each stage.³¹

Over half of the electricity demand of the United States is supplied by coal-fired power plants, with emissions of about 2 billion metric tons of CO₂ per annum, representing about 33% of US energy-related CO₂ emissions.³²

Forty percent of global electricity is generated in fossil fuel power plants per annum, with emissions of about 33% (9.5 billion metric tons) of global energy related CO₂ emissions of approximately 28.8 Gt in 2007.³³

The US building materials market, including cement and aggregate, requires about 3.9 billion tonnes annually; the world requires about 24 to 34 billion tonnes annually:

²⁸ *Id.*

²⁹ *Id.*

³⁰ *Id.*

³¹ *Id.* (citing to K. Humphreys and M. Mahasanen, *Towards a sustainable cement industry - Substudy 8: Climate Change* (2002); Y. Kim and E. Worrell, *CO₂ emission trends in the cement industry: An international comparison*, 7 MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE 115-33 (2002); and E. Worrell, L.K. Price, N. Martin, C. Hendriks, and L. Ozawa Meida, *Carbon dioxide emissions from the global cement industry*, 26 ANNUAL REVIEW OF ENERGY AND ENVIRONMENT 303-29 (2001).); see also M. Natesan, S. Smith, K. Humphreys, Y. Kaya, *The Cement Industry and Global Climate Change: Current and Potential future Cement CO₂ Emissions*, PROCEEDINGS OF THE 6TH INTERNATIONAL CONFERENCE ON GREENHOUSE GAS CONTROL TECHNOLOGIES 995-1000 (2003); E. Worrell, L. Price, and N. Martin, *Energy efficiency and carbon dioxide emissions reductions opportunities in the US iron and steel sector*, 26 ENERGY 513-536 (2001); E. Worrell, R. van Berkel, Z. Fengqi, C. Menke, R. Schaeffer and R. Williams, *Technology transfer of energy efficient technologies in industry: a review of trends and policy issues*, 29 ENERGY POLICY 29-43 (2001); Y. Kim and E. Worrell, *International comparison of CO₂ emission trends in the iron and steel industry*, 30 ENERGY POLICY 827-838 (2002).

³² U.S. Energy Information Administration, U.S. Department of Energy, EMISSIONS OF GREENHOUSE GASES IN THE UNITED STATES 2008 (2009).

³³ International Energy Agency, WORLD ENERGY OUTLOOK 2009 44 (2009) (“The Reference Scenario sees a continued rapid rise in energy-related CO₂ emissions through to 2030, resulting from increased global demand for fossil energy. Having already increased from 20.9 gigatonnes (Gt) in 1990 to 28.8 Gt in 2007, CO₂ emissions are projected to reach 34.5 Gt in 2020 and 40.2 Gt in 2030 — an average rate of growth of 1.5% per year over the full projection period.”).

2009 Buildings Materials Market (including cement and aggregate)

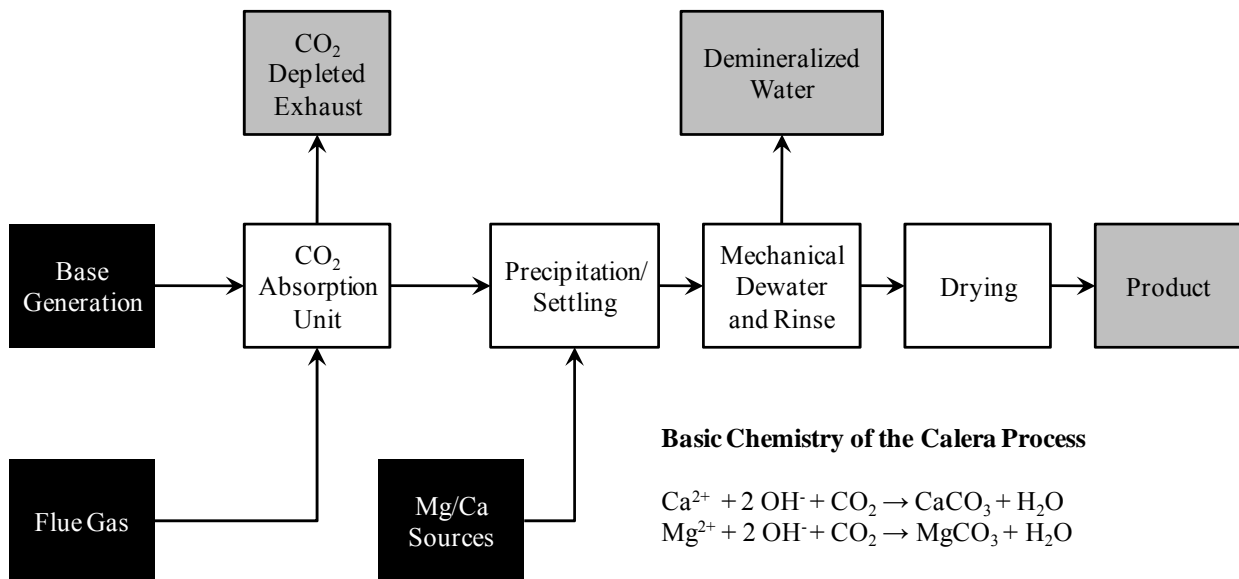
	Portland Cement (Metric tonnes)	Supplementary Cementitious Material (SCM) (Metric tonnes)	Aggregate (Metric tonnes)	Totals
USA	75 million	15 million	3 billion	3.90 billion
World	2.8 billion	1.4 billion	20-30 billion	24.2 to 34.2 billion

Source: U.S Geological Survey, *Mineral Commodity Summaries* (January 2010).

VIII. The Uniqueness of the Calera Technology

The Calera technology is a new process that uses alkaline brines, minerals, waste materials, and/or manufactured alkalinity from an electrochemical process in combination with brines or dissolved minerals heavy in calcium and/or magnesium (which are not bound as carbonates) to capture CO₂ emissions from power plant flue gas, and transforms that carbon into geologically stable carbonate solids in the form of liquids or dewatered powders suitable for storage or use in building materials. Calera calls this new process “Mineralization via Aqueous Precipitation” (MAP).

CALERA PROCESS DIAGRAM



MAP is analogous to the biological process marine organisms use in extracting calcium carbonate from seawater to build reefs and also comparable to the geological processes that turns calcareous mud into rock (such as micrite, a fine-grained limestone). For example, in the 1940s, aircraft runways were constructed on Pacific islands by taking

calcareous mud from the intertidal zone and washing away salt with fresh water to harden the surface. Re-crystallization causes microscopic particles of calcium carbonate to become a strong, solid material.

The Calera process makes a cementitious material with the consistency of mud, which when de-watered, becomes an aggregate-like solid. In the Calera process, novel metastable carbonate minerals can be formed that have cementitious characteristics when mixed into concrete or with water. These novel carbonate “polymorphs” are produced in the Calera process via control of the precipitation process and are, unlike mined limestone, inherently reactive. These Calera materials are reactive with OPC when used in concrete mixes and harden in the presence of water because the metastable carbonates recrystallize into more stable polymorphs.³⁴

Prior and parallel to the Calera process breakthroughs, other inventors had envisioned similar processes and some of that work is ongoing (*see* Appendix 6).

The Calera process makes meta-stable carbonate “polymorphs” by adding CO₂ to the ions in brines at controlled pH and water content. The Calera reactive carbonates are generated at low temperatures with controlled precipitation in the MAP process without the need for calcination. In contrast, traditional OPC is produced by heating mined limestone and small quantities of other materials such as clays to high temperatures in order to make reactive calcium silicates and calcium aluminates in addition to other compounds. GHG emissions from cement manufacture are reduced if the Calera meta-stable calcium carbonates can displace a portion of the cement produced by high temperature processes.

The liquid or dewatered Calera powders can be stockpiled or immediately used as:

- SCMs that may replace a portion of clinker in blended cements,
- Hardened cementitious paste for potential use in concrete,
- Coarse Synthetic Aggregate that can replace gravel and crushed rock in concrete, asphalt and road base,
- Fine Synthetic Aggregate that can replace sand in concrete, asphalt and road base, and
- Stand-Alone Cement, still at the early stages of development and not yet proven, that can potentially replace OPC in some applications.

The use of the Calera material in any of these applications requires that it satisfies the relevant technical, environmental, and safety performance criteria. The Calera corporate strategy is to first market their products into uses with easily achievable technical

³⁴ The Calera reactive carbonates are generated at low temperatures with controlled precipitation in the MAP process without the need for calcination. The Calera reactive carbonates participate in the cement curing process when mixed with OPC allowing a displacement of the cement produced by high temperature processes with material that contains CO₂ from the flue gas. They are also reactive enough that they can be made to self-cement without the addition of OPC and can be used as aggregate or precast concrete components.

performance criteria and low consequence of product failure and later to expand into additional uses when and if the product satisfies stringent laboratory and field trials and applicable industrial and construction standards.

Process auditing of Calera's 10 MW Moss Landing demonstration-scale plant by the engineering firm R.W. Beck and life-cycle analysis by UCSB scientists confirms that up to 90% of CO₂ emitted from the Moss Landing gas-fired power plant can be captured.

The December 2010 Calera estimate of minimum parasitic energy penalty for capture and mineralization of 70% of CO₂ stack gas is:

- As low as five to ten percent in potential locations with suitable brine availability and where the aqueous solution of bicarbonate material is re-injected,
- Ten to twenty five percent in potential locations with suitable alkaline waste streams and hard brines and where solid calcareous material is land-filled or used as supplementary cement product,
- Eighteen to forty percent in locations with suitable natural alkaline brines supplemented with up to fifty percent ABLE electrochemistry and where bicarbonate products are generated,
- Thirty to sixty percent in locations with suitable natural alkaline brines supplemented with up to fifty percent ABLE electrochemistry and where the calcareous slurry is land filled or products are generated, and
- Higher in situations where manufactured alkalinity is used in larger percentages and dried carbonate products are generated.

The Calera technology is able to simultaneously mitigate emissions of sulphur and heavy metals including mercury, from stack gases and to chemically bind them as sulphates and carbonates (e.g. as insoluble salts), reducing acid rain and human health exposure, while also lowering costs otherwise incurred in removing these pollutants. The Calera Process, however, needs to be carefully managed to avoid soluble mercury (e.g. HgCl₂), and to minimize elemental mercury, which may not be captured. OPC has been used to treat and immobilize hazardous wastes in the United States and elsewhere since the 1950s. The cement can physically and chemically bond the hazardous constituents thereby preventing their migration out of the solid cement matrix. Physical stabilization changes the physical form of the waste. The cementation process binds free water, increases the pH and alters other chemical properties of the mixture, reduces the surface area, and increases strength. Chemical stabilization changes the chemical states of the waste so that the hazardous constituents exhibit lower aqueous solubility or leachability. For inorganic wastes, such as mercury, the chemistry of cement stabilization is predominantly driven by hydrolysis of the metal constituents to form precipitates of hydroxides, oxides, or other salts such as carbonates, sulphites, sulphates, and sulphides.

Preliminary studies conducted on flue gas from combustion of different coal types at the Calera Moss Landing pilot scale facility captured 77 to 86% of total mercury in the calcium carbonate precipitate. That calcium carbonate precipitate containing mercury and seven other heavy metals (Ag, As, Ba, Cd, Cr, Pb, and Se) was incorporated into

cement mortar paste samples (80% OPC and 20% Calera SCM) for leaching studies using the U.S. EPA Toxicity Characteristic Leaching Procedure (TCLP, EPA Test Method 1311) to determine the mobility of both organic and multiphase wastes.³⁵ After the standard 20-day cure time, samples were ground, leached, and analyzed for the concentration of leachable heavy metals. Leachable levels of mercury and all other heavy metals were found in trace quantities ranging from two to three orders of magnitude less than the TCLP federal hazardous waste classification limits and less than drinking water limits.

This preliminary analysis confirms that the heavy metals can be chemically bound in the matrix. However, additional studies and quality control procedures will be necessary to assure that leachable levels from precipitants and cement samples remain substantially below relevant hazardous waste classification limits for all metals of concern during commercial operations of power plants fitted with Calera technology.

The basic chemistry along with the mass and energy balance of the carbon capture to solids has been confirmed in the laboratory and at the pilot plant.

Calera had preliminarily identified over 40 coal-fired power plants and other large-scale CO₂ sources in United States with suitable brine quality and quantity within 100 miles (subject to exploration and verification), and with reasonable access to cement and aggregate markets large enough to meet expected SCM output. However, the experience at Latrobe Valley reinforces the importance of site-specific geotechnical investigations and the advantage of proving the brine suitability as a precondition of going forward with investment. Financial viability is contingent on the availability of suitable brines and alternative alkalinity resources and economic incentives for carbon sequestration, the ability of Calera to satisfy the technical performance criteria of the local cement markets and also on the ability of Calera to overcome the normal market resistance to new technology replacing proven technology. Furthermore, to accelerate its full potential of carbon sequestration and carbon emission avoidance for climate protection, economic incentives will be necessary because the quantity of Calera material will ultimately saturate the cement market and require either disposal without sales revenue or sale into markets like aggregate where less carbon is displaced and prices per unit of output are far lower than for SCM.

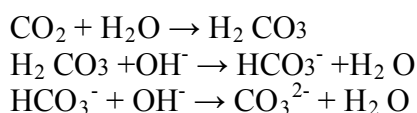
The climate, public health, and economic development benefits of the Calera process may be particularly important in China and other fast-growing developing countries where there is high demand for coal-generated electric power, cement, and concrete. In these countries, new power and cement plants can be co-located to minimize costs and maximize environmental benefit. In some cases, an integrated facility may be located at a “brine mouth” because it is less costly and more carbon efficient to move coal than brines.

³⁵ The manual: Test Methods for the Evaluation of Solid Waste, Physical/Chemical Methods, otherwise known as SW-846, which describes the test procedures for the TCLP (Method 1311) as well as other waste analysis methods is available at www.ntis.gov/products/sw846.aspx.

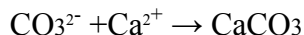
IX. Basic Chemistry of the Calera Process

The first step in the Calera process is to mix CO₂ and water, making bicarbonate ions. Without any calcium ions present, this would result in carbonic acid. The reaction turning calcium and bicarbonate ions into calcium carbonate (or the reverse) is dependent on pH, temperature, and pressure. With calcium ions present in brines and with the increased pH of the Calera process, the bicarbonate in solution reacts with calcium ions to make solid calcium carbonate. This process is similar to the natural way corals are formed from seawater into reefs of calcium carbonate.

In the first step, the CO₂ in the flue gas is absorbed into the alkaline water at ambient temperature and converted into carbonate and bicarbonate anions:



In the second step, the precipitation of calcium carbonate/bicarbonate takes place through the reaction with calcium ions:



The calcium carbonate is an intentional ingredient in Calera's basic cement and aggregate. In addition to calcium carbonates, stable bicarbonates can be formed under certain circumstances via control of the reaction media and conditions. Through control of the chemical process of absorption and precipitation, Calera must prove that the various reactive calcium carbonate mineral structures can be manufactured to meet the requirements of specific cement, aggregate and other uses.

In sites that do not have sufficient quantity or quality of alkaline brine resources, Calera patented technology includes a unique Electrochemical Process that Calera has named "Alkalinity Based on Low Energy" (ABLE) with the potential to generate caustic soda with low energy at locations where saline waters are available. The ABLE electrochemistry process is unique compared to those in the conventional chlor-alkali industries because a three-compartment membrane cell configuration has been developed to electrolyze sodium chloride to sodium hydroxide and to hydrogen chloride (not to chlorine gas). This innovative process has been jointly developed and taken to pilot scale under a partnership with the Italian firm Industrie de Nora (Denora), a leading supplier of specialized electrochemical cells, membranes and electrodes. The next step is integrating the ABLE technologies with CO₂ capture to allow even more advanced electrochemistry processes with lower capital costs. The innovative and elaborate electrolytic cell design may be revolutionary in reducing costs and possibly GHG emissions from other chlor-alkali processes.

X. Calera Process Options

The tables below present a range of process options and expected outcomes taking into account the CO₂ emission from the Calera energy demand and the speculative CO₂ emissions avoided if the Calera cement offsets Portland cement or aggregates in applications where other lower carbon SCM is unsuitable or unavailable. In each case, the Calera process energy must be replaced with increased power output with CO₂ emissions dependent on the source of emissions and the carbon footprint of the electricity fuel mix supplying the power. Options with ABLE electrochemistry requirements could source the portion of power for E-Chem at the facility (if operating below capacity), from the grid (peak or off-peak), or from off-grid power sources such as wind and solar with chemicals transported to the Calera facility.

Process option 1: CO₂ coal stack gas to bicarbonate for aqueous reinjection

Project under development in California.

Flue gas	Alkalinity	Calcium and/or Magnesium feedstock(s)	Criteria Pollutants	Parasitic Energy Demand of Calera Process	Product/Revenue
Supercritical Coal	Adequate brines	Not required	Sulphur and mercury chemically bound and secure	Low	Bicarbonate for aqueous reinjection – No SCM or cement revenue – Requires economic incentive or price on carbon to offset costs

Process option 2: CO₂ natural gas to cementitious material replacing a portion of OPC

Flue gas	Alkalinity	Calcium and/or Magnesium Feedstock(s)	Criteria Pollutants	Parasitic Energy Demand of Calera Process	Product/Revenue
Natural Gas	~100% ABLE E-Chem	Calcium and magnesium from brine desalination retentate	Not applicable (only trace quantities in natural gas)	Significant energy use for production of sodium hydroxide alkalinity, which can be minimized with use of off-grid renewable and/or off-peak power	Cementitious material or aggregate for low risk markets; Requires economic incentive or price on carbon to offset costs

Process option 3: CO₂ coal stack gas to calcium carbonate for concrete

Project under development for Wyoming or similar locations where there are large deposits of solid alkaline substances.

Flue gas	Alkalinity	Calcium and/or Magnesium feedstock(s)	Criteria Pollutants	Parasitic Energy Demand of Calera Process	Product/Revenue
Supercritical Coal	~50% solid alkalinity, use of fly ash, ~50% ABE E-Chem	Calcium from waste waters, produced water, minerals, and from fly ash	Sulphur and mercury chemically bound and secure	Significant energy use for electrochemical production of sodium hydroxide alkalinity, which can be minimized with use of renewable and/or off-peak power.	Cementitious material for concrete applications + bicarbonate reinjection requiring economic incentive or price on carbon to offset costs

Process option 4: CO₂ coal stack gas to SCM for concrete

Competes with and complements other technical options—such as ground limestone, fly ash and blast furnace slag, where available and allowed—that reduce the carbon footprint of cement and concrete. Project in development in the United States and China but suspended for Latrobe Valley Australia.

Flue gas	Alkalinity	Calcium and/or Magnesium feedstock(s)	Criteria Pollutants	Parasitic Energy Demand of Calera Process	Product/Revenue
Supercritical Coal	~50% liquid brines and mineral alkalinity, ~50% ABE E-Chem, plus fly ash use	Calcium from fly ash, mineral dissolution and/or brines	Sulphur and mercury chemically bound and secure	Large CO ₂ offset due to a high percentage of product to CO ₂ ratio	Revenue from SCM sales may offset a portion of the costs of carbon sequestration

Process option 5: Greenfield integrated coal electric power and cement production

At an early stage of development in China.

Flue gas	Alkalinity	Calcium and/or Magnesium feedstock(s)	Criteria Pollutants	Parasitic Energy Demand of Calera Process	Product/Revenue
Greenfield Coal (Ultra Supercritical)	~50% liquid brines alkalinity, ~50% ABLE E-Chem, plus fly ash use	Calcium from brines, mineral dissolution and fly ash	Sulphur and mercury chemically bound and secure	Lower with integrated plant design and low alkalinity requirement for bicarbonate cement	Bicarbonate based cement replacement +bicarbonate sequestration if justified by carbon price

The choice of the process and the plant configuration will depend on the circumstances of each project. For example, in jurisdictions where sulphur control is required, the Calera process may be able to avoid the cost of scrubbers by integrating sulphur capture in the MAP.

The CO₂ sequestered by the Calera process is environmentally safe when undertaken with proper environmental, health and safety measures typical for industrial facilities operating in countries with effective regulation, governance, and enforcement. The carbon sequestered by the Calera process in cement, aggregate, concrete, and other products is geologically stable with little, if any, emission of CO₂ when the products are placed in applications protected from strong acids.

In addition, the Calera technology has a potential co-benefit of mitigating sulphur and mercury from stack gases and chemically binding them as insoluble sulphates and carbonates, reducing acid precipitation (acid rain) and human health exposure. Mitigation of mercury and other toxic contaminants from Calera plant emissions is especially beneficial because of the known neurotoxic effects.

After decades of research and application experience, much is known about the interactions between clinker and commonly-used SCMs (such as fly ash or slag) and therefore industry has confidence in their proper use for specific applications. With less known about the chemical interactions between the Calera products and clinker, it will be important to determine the acceptable levels of ingredients that can be tolerated in each application and also the extent to which the properties and durability of the concrete are affected, including protection of the steel reinforcement. Therefore, the Calera SCM is likely to initially supplement, rather than displace, existing proven SCM sources.

The Calera process has site-specific environmental impacts from extraction and reinjection of brines and there are potential negative side effects from the disposal of HCl and solids that cannot find productive markets.

XI. The Importance of Systems Analysis

Calera has the potential to become a significant player in both the energy and buildings material sectors and, under specific conditions, to be a superior option for CCS. Existing businesses that produce fly ash and blast furnace slag as process waste are not reliant on revenue from sales of SCMs but appreciate the availability of markets for these wastes under increasingly stringent environmental standards for disposal. Power companies facing environmental concerns of ash disposal and carbon sequestration will appreciate the advantage of solutions like Calera that have the potential for lower combined compliance costs.

Adding a Calera process to a power plant may look like a marginal extension of the facility, but the changes are significant when considered with respect to the large volumes of brines, HCl, and sequestered carbon into carbonate materials involved and even the volume of additional coal needed to make up for the energy consumed in the process. In fact, it is the scale of the carbon emissions from power plants that must be sequestered that necessarily makes these numbers large. Because of the potential scale and market penetration of this technology, the economic and GHG impact analysis must consider significant systems effects of energy demand and prices, and the technological response in energy efficiency.

For example, the energy penalty of introducing the Calera process at a significant portion of power plants will have two simultaneous effects: first to increase the output to make up for the lost generation, and second to decrease the output in response to decreases in electricity demand when the price of carbon capture is added to electricity rates and consumers invest more in energy efficiency or otherwise spend their money. Relative to the status quo, the new power sector equilibrium will likely be lower carbon emissions, lower electricity demand, higher prices for electricity from fossil fuel, higher market share for renewable and low-carbon generation (because coal plants take on the cost of CCS), and higher investment in end-use energy efficiency. Relative to the status quo, the new cement sector equilibrium will likely be lower cement and concrete prices, higher demand for these lower cost products, and lower demand for mined products replaced with Calera materials.

This means that the value of the Calera process may be superior, in some circumstances, to other CCS technologies and that its market penetration will encourage other CO₂ mitigation options like:

- Cost-effective energy saving in households and companies,
- Renewable energy sources of power generation,
- Substitution of competing building materials for cement and concrete, and
- Relatively low-carbon power generation like natural gas and combined heat and power.

Similar systems effects are relevant for the brine and water balances. The volume of brines and alkaline content has significant influence on the cost base and the

environmental balances related to the Calera process. Access and costs of water resources and brines and the subsequent recirculation and disposal is still uncertain and not fully understood. Furthermore, the cost of transportation and electrochemical refinement are site-specific cost components that are only resolved as investment goes forward. Therefore, the economics and environmental impacts of changing the water balances with the volumes needed by the Calera process seem to require location-specific assessments.

The most important and uncertain systems effect is related to the use and the potential value of Calera products. Geologic injection or land disposal of Calera products without further refinement is possible with limited environmental impacts, but without product revenue the full costs of Calera operations would have to be covered by payments for carbon sequestration. However, refining and enhancing it as a bulk material has potential implications in different sub-segments of this sector, i.e. as a partial substitute for cement, aggregates, and/or potentially as new cement-like products.

The technological basis is widely accepted for the use of fly ash, slag, and ground limestone SCMs to produce lower clinker factor cements. Future systems analysis will want to consider the qualities and applications of each of these existing cement products.

If the Calera products have the anticipated qualities, the potential volume of product coming out of the Calera process and the known market volumes for specific SCM applications will be fundamentally changed. The CO₂ impacts of this substitution depend on how the production and use of the displaced produce will change after Calera product penetration.

Thus, the carbon- and water-footprints and the basic economics of the Calera process and products are the basis for assessing the efficiency of the Calera process as a financially viable CO₂ mitigation option and under which conditions it can be made financially attractive - for investors and society.

XII. Saturation of regional cement markets and global HCl markets

If the Calera process were implemented at all coal-fired power plants, more calcareous material and more HCl would be produced than current markets would be able to accept.

The highest revenue for Calera SCM will be in cement and building material applications where it can satisfy the demanding technical standards and satisfy customers and regulatory authorities. Once the cement and building materials market is saturated, the second highest revenue for SCM will be as a substitute for mined aggregate in local markets. Once the aggregate market is saturated, the SCM could be stored for potential future use or the Calera process could be modified to produce bicarbonate at a lower parasitic electric load for disposal through reinjection or landfill.

Tables 1 to 3 (next page) show the calculations that have been used as a basis for the following evaluations. It has to be stressed that the calculations are based on the Yallourn case, where the efficiency is quite low.

The highest potential for the by-product HCl from the Calera process will be in markets where HCl is not readily available from recycled or other by-product sources. If the Calera process using electrochemistry were developed at a large scale, industrial demand might increase in response to lower prices and at significantly low HCl prices there may be new markets such as solution mining for generation of calcium and silicate feedstocks. All such uses will need to be scrutinized to avoid or minimize CO₂ emissions.

Australia

Table 1 shows the figures if the Calera technology would be applied to a hypothetical plant comparable to the total Yallourn power plant, assuming that the suitable brines had been available as previously expected (1480 MWeI; 7000 operation hours per annum, same efficiency assumed).

The annual consumption comes up to 905 million tonnes/annum (t/a) of alkaline brines and 330 million t/a of Ca²⁺ brines, with 1.2 billion t/a of brines that would have to be reinjected. SCM production would be 24.9 million t/a. Total cement production in Australia was 9.2 million t/a, equivalent to 37% of SCM production of the Yallourn Australia power plant only (Table 2). If 20% of the cement would be replaced, only 1.8 million t/a would be needed.

United States

Cement production is about 75 million t/a. Ninety percent CO₂ capture by Calera technology would lead to SCM production of 3.7 billion t/a. 20% addition to cement would consume 15 million t/a. If 50 % of the power plants applied Calera technology with the ABLE electrochemical processes, an additional 170 million t/a of HCl would be produced.

Germany

CO₂ emission from fossil fuel power plants in Germany was 385 million t/a (2007). Cement production was 33.4 million t/a. Ninety percent CO₂ capture by Calera technology would lead to SCM production of 714 million t/a at power plants with 35% average efficiency (compared to 23% efficiency at Yallourn). 20% addition to cement would consume 6.7 million t/a. If 50% of the power plants applied Calera technology with the ABLE electrochemical process, about 32.4 million t/a additional HCl would be produced.

According to information from Wikipedia, total world hydrochloric acid production, expressed as HCl, is estimated at 20 million t/a.

These preliminary calculations show that Calera technology, if widely implemented, would ultimately saturate existing markets for cement and HCl.

In populated areas with stringent environmental regulations it likely will be difficult to get permits for the use and reinjection of very large quantities of brines required for each power plant.

Also the quantity of produced SCM and HCl makes it indispensable to search for new, environmentally responsible markets for both products.

Table 1: SCM production and brine input/output

unit		Yallourn 1 MWel(net)	Yallourn 200 MWel Demo	Yallourn 1480 MWel
General parameters				
Operating hours	hours/a	7000	7000	7000
total capacity	MWel	1	200	1480
Calera with brines only				
net capacity	MWel	0,86	171,8	1271
net power output	GWh/a	6,01	1200	8880
used alkaline brines	mio. t/a	0,71	122,3	905
used Ca2+ brine	mio. t/a	0,26	44,6	330
waste water	mio. m3	0,013	2,17	16,1
brines reinjected	mio. t/a	0,96	165,2	1222
SCM output	mio t/a	0,01962	3,36	24,86
Calera with E-Chem				
net capacity	MWel	0,72	143,4	1061
net power output	GWh/a	5,02	1004	7428
used alkaline brines	mio. t/a	0,73	104,2	771,0
used Ca2+ brine	mio. t/a	0,31	44,8	331,3
waste water	mio. m3	0,015	2,18	16,12
brines reinjected (excl. HCl)	mio. t/a	1,02	146,9	1087,2
HCl reinjected	mio t/a	0,00213	0,31	2,26
SCM output	mio t/a	0,02351	3,37	24,94

Table 2: SCM production and cement substitution

	Cement production mio t/a	CO2 from fossil power production (Yallourn PP only) mio t/a	CO2 from fossil power production mio t/a	SCM production if 90% of total CO2 from power plants is abated (Australia: only Yallourn) mio t/a	SCM use if 20% of total cement production is replaced (Australia: only Yallourn)
Australia	9,2	13,14	---	24,9	1,84
United states	120	---	2000	3708	24
Germany (2007)	33,4	---	385	714	6,7

Table 3: Assumptions from UCLA report on GHG Emission Analysis ...

CO2 capture	90	%
SCM per MWh (brines only)	2,803	t/MWh(net)
SCM per MWh (incl. E-chem)	3,358	t/MWh(net)
SCM per t CO2 abated	2,06	t/t

Footnote: European standards have been used for decimal points (comma instead of dot).

XIII. The Carbon Benefits of Calera SCM

The emissions of CO₂ from power plants are far greater than the amount of Calera SCM that can be utilized in cement, concrete and other building materials. Furthermore, Calera will be one of several CCS technologies which will be implemented worldwide and one of many options to reduce the carbon footprint of cement and concrete production. The bottom line is that Calera has a promising process for capturing and sequestering CO₂, but to realize the full potential in both sequestering CO₂ emissions from power plants and avoiding CO₂ emissions by offsetting OPC production, a carbon price is generally required to make it profitable.

Global fossil fuel based power generation emits about 9.5 billion tonnes of CO₂ p/a according to the International Energy Agency. If the Calera process can capture 90% of this and if the Calera SCM is 2.1 tonnes per ton of CO₂ captured, then $9.5 \times 0.9 \times 2.1 = 18$ billion tonnes p/a of potential building products will be available.

Calera has the potential to replace a large portion of the existing quarried aggregate supply and part of the OPC production, provided that the Calera product is technically sound and accepted in the market.

With the current global cement production of about 3 billion t/a, and with a high degree of vertical integration in the building materials market, it will be very difficult for Calera and other competing new technology to achieve meaningful penetration into the cement market without the embrace of that industry and its customers.

If Calera technology were further improved to replace 40% of clinker in cement production or cement in concrete production, $0.4 \times 3 = 1.2$ billion tonnes of cement would be replaced and, at .88 tCO₂/t cement, about 1.06 billion tonnes of CO₂ emissions would be replaced. 1.4 billion t/a cement would be replaced if Calera were successful in capturing all of the global SCM market. (That would imply that about 15 billion t/a of Calera material would be available to the aggregate market, reinjection, or land disposal.)

It is possible, but challenging, to assimilate this quantity in the global aggregate market of 32 billion t/a. However, climate change itself may create large markets for aggregate used as protection against sea level rise, storm surges, or for use in building inland dikes. Such large product push into the market may result in a substantial decline in the price of aggregate, with the implication that the major source of revenue for its aggregate will be carbon sequestration payments.

Once the cement and building materials markets are saturated, the Calera process can continue to sequester CO₂ as an aqueous solution or as solid material safely disposed or stored for future use.

XIV. Summary, Conclusions, and Way Forward

The Calera Technology demonstration at Latrobe Valley Australia was suspended when the brines were determined to be unsuitable in quantity and quality and because anticipated legislation incentivizing CCS was not enacted. Calera has identified locations in the United States and China where the prospects for alkalinity and calcium are potentially ideal for the process and is currently pursuing project development in these locations.

The Calera Technology has potentially significant advantages, including:

- Good and proven CO₂ capture efficiency,
- Solid and safe product as an alternative to compressed CO₂ storage,
- Very energy efficient ABLE electrochemistry process, and
- Potentially low energy penalty compared to other carbon capture processes.

The Calera Technology has some potentially significant challenges, including:

- Depends on a suitable quantity and quality of cations and alkalinity from brines and alternative alkalinity sources being available near the power plant,
- Increases coal mining and associated impacts (but less than other sequestration),
- Produces more calcareous material and more HCl than current markets can accept,
- Competes with available solutions to reduce cement and concrete carbon footprints, and
- Requires environmental acceptability of pumping brines from and into geologic formations.

What has been accomplished:

- Unique Calera advantage: vision, motivation, finance, recruiting, agility...;
- Daunting challenges—markets, product performance...;
- Recognition of the importance of carbon price and other incentives;
- The role of power plant, cement, and standards organizations in new technology;
- Opportunity in China (market share of new power and cement consumption); and
- Timeline for success at ‘Calera Speed’.

What has not yet been accomplished:

- The identification and demonstration of the Calera technology at a location where suitable brines and/or other natural inputs are available;
- The technical demonstration of Calera concrete mix design and long-term performance;
- Product-by-product calculations of carbon avoidance with Calera SCM;
- Systems analysis of the future pattern of Calera and conventional SCMs;
- Projection of the realistic global potential of Calera technology to sequester CO₂ from power plants and other industrial facilities and to simultaneously avoid CO₂ emissions by replacing the technically feasible portion of OPC production.

Appendix 1:

Glossary of Uncommon Vocabulary Used in this Report

(Adapted from WBCSD/EIA Cement Technology Roadmap, from the IPCC and other sources)

Aggregates:	Materials used in construction, including sand, gravel and crushed stone.
Alkalinity:	A measure of the capacity of a solution to neutralize acids.
Biomass:	The total mass of living and recently dead plant material.
Black carbon:	Defined on the basis of light absorption and chemical reactivity and/or thermal stability; consists of soot, charcoal, and/or possible light-absorbing refractory organic matter.
Blended cement:	Blended cements are produced by blending and sometimes inter-grinding clinker with a fine primary material and gypsum. The most commonly blended primary materials are blast furnace slag, fly ash, silica fume, calcined clay, and other pozzolans.
Calcareous:	Materials containing calcium carbonate (CaCO ₃), usually at 50% or more (see “carbonaceous”).
Carbon cycle:	The term used to describe the flow of carbon (in various forms such as CO ₂) through the atmosphere, ocean, terrestrial biosphere, and lithosphere.
Carbon dioxide (CO ₂):	A naturally occurring gas, a by-product of burning fossil fuels and biomass, and an emission from land-use changes and other industrial processes. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1. A substantial fraction—20-25%—remains in the atmosphere for millennia once emitted.
Carbon Negative:	Products or processes that extract more CO ₂ from the atmosphere than they contribute for this action.
Carbon Offsets:	“Credit” for actions that “offset” carbon emissions in another activity. Carbon offsets allow a company or individual to claim they are “carbon neutral” if the net calculated carbon emissions are zero, or “carbon negative” if the net calculated carbon emissions are less than zero.
Carbon Positive:	Products or processes that release CO ₂ from materials and fossil fuels into the atmosphere.

Carbon Capture & Sequestration (CCS):	The process of removing ('capturing') carbon from the atmosphere and depositing ('sequestering') it in a permanent reservoir. CCS is large-scale sequestration of industrially produced CO ₂ using subsurface saline aquifers, geological reservoirs, ocean water, aging oil fields, or other carbon sinks. Calera is a form of CCS called "carbon mineralization".
Carbonaceous:	Materials containing carbon, and suggesting coal or other organic material (see "calcareous").
Cement:	A building material made by grinding clinker together with various mineral components such as gypsum, limestone, blast furnace slag, coal fly ash, and natural volcanic material. It acts as the binding agent when mixed with sand, gravel or crushed stone, and water to make concrete. While cement qualities are defined by national standards, there is no worldwide, harmonized definition or standard for cement. In the WBCSD – CSI Protocol and the "Getting the Numbers Right" database, "cement" includes all hydraulic binders that are delivered to the final customer, including all types of OPC, composite, and blended cements, but excluding clinker. See section 6.3 of the WBCSD – CSI Cement Protocol for the precise definition.
Cementitious products:	Total of all cements and clinker produced by a cement company, plus ground granulated slag and fly ash delivered to the concrete mixers, excluding the clinker purchased from another company and used to make cement. The precise definition of cementitious product in this context is according to section 6.2 of the WBCSD – CSI Cement Protocol. Cement is equal to cementitious product when the net balance of clinker sold and purchased is zero.
Clinker:	Intermediate product in cement manufacturing and the main substance in cement. Clinker is produced by burning a mixture of limestone, clay and other minor corrective materials like sand etc. at temperatures of up to 1450°C. During this process the limestone is decarbonated and thereby releases CO ₂ into the atmosphere both from the calcination process and from the fuel combustion used to heat the clinker.

Climate Co-benefits:	The benefits to health, safety, economic development, prosperity, sustainability, equity and other objectives.
Commercial-Scale:	A full-scale facility intended to continuously operate at a profit under prevailing or anticipated market and regulatory conditions.
Co-processing:	The use of waste materials in industrial processes, e.g., cement, as a substitute for primary fuel or raw materials.
Cost-effective:	A criterion that specifies that a technology or measure delivers a good or service at equal or lower cost than current practice, or the least-cost alternative for the achievement of a given target.
Demonstration-Scale:	A full-scale facility to demonstrate the continuous operation of a particular design to confirm the process reliability and financial feasibility.
Desalination Permeate:	The input fluid to a desalination process.
Desalination Retenate:	The output (potable or industrial) water from desalination.
Economic potential:	Greenhouse gas emissions reductions or energy efficiency improvements that could be achieved cost-effectively through the creation of markets, reduction of market failures, or increased financial and technological transfers.
Fly ash:	Exhaust-borne particulate matter generated during the combustion of coal and captured at coal-fired power plants using particulate control equipment.
Geopolymer cement:	Cement made from mixtures of water-soluble alkali metal salts and aluminosilicate mineral powders such as fly ash, slag, and metakaolin with chains or networks of mineral molecules potentially producing 80–90% less CO ₂ than OPC.
Global Warming Potential:	An index, describing the radiative characteristics of well-mixed greenhouse gases, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of CO ₂ .
Gross CO ₂ emissions:	All direct CO ₂ emissions (excluding on-site electricity production) excluding CO ₂ emissions from biomass, which are considered climate neutral.
Greenhouse gas:	Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit

radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. This property causes the greenhouse effect. Water vapour (H₂O), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and ozone (O₃) are the primary greenhouse gases in the Earth's atmosphere. Moreover there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Besides CO₂, N₂O, and CH₄, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF₆), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

- Hydraulic cement: Hydraulic cement is a broad term encompassing OPC, modified Portland cement, and blended cements. For example, American Society for Testing and Materials (ASTM) C1157 recognizes six types of hydraulic cements.
- Inter-grinding: Inter-grinding is the process of grinding two or more solid materials at the same time. Inter-grinding materials with similar hardness produces uniform particle size but inter-grinding materials with dissimilar hardness produces relatively fine particles for the softer material and coarse particles for the hard material. Inter-grinding may be done by design with ash or slag as part of the grinding process to shift the particle size distribution.
- Leapfrogging: The opportunities to bypass several stages of technology development historically observed in industrialized countries, and apply the most advanced presently available technologies through investments in technological development and capacity building.
- Net CO₂ emissions: Gross CO₂ emissions, minus CO₂ captured, plus CO₂ produced during the capture process.
- Ordinary Portland Cement (OPC): Most common type of hydraulic cement; formed via the calcination of limestone in the presence of clays and other minerals. Typical OPC consists of over 90% ground clinker and about 5% gypsum, but there are variations in grain size and ingredients to produce cement with different strength development and for specific purposes and performance. For

example ASTM C150 (Standard Specification for Portland Cement), recognizes ten types, while Euro Code EN 197 (Standards for Cement) recognizes five types.

Parasitic Load: The percentage of power station electricity output or equivalent power from the grid that is required to power the CCS process.

Pilot-Scale: Small scale experimental facility to confirm feasibility, test process inputs and options, or to improve design and process control.

Pozzolans: Material that, when combined with calcium hydroxide, exhibits cementitious properties.

Precalciner kiln: A rotary kiln equipped so that most of the limestone calcination is accomplished in a separate apparatus ahead of the rotary kiln, more energy-efficient than having all of the calcination take place in the kiln itself.

Rapid climate change: The non-linearity of the climate system may lead to expected or unexpected climate change such as a dramatic reorganization of the Thermohaline circulation, rapid deglaciation, or massive melting of permafrost.

Sintering

Supplementary Cementitious

Material (SCM): A pozzolanic or hydraulic material which reacts with Portland cement to become strong and solid. The most commonly used SCMS are slag cements, fly ash, silica fume, calcined clay, and other pozzolans. One of the proposed uses of the Calera material is as a SCM.

Appendix 2:

Acronyms

ABLE	Alkalinity Based on Low Energy
Ag	Silver
As	Arsenic
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigeration & Air Conditioning Engineers
ASTM	American Society for Testing and Materials
Ba	Barium
C40	Large City Leadership in Climate
Cd	Cadmium
CO ₂	Carbon Dioxide
CDM	Clean Development Mechanism
CFO	Carbon Footprint Offset
CHA	Copenhagen Accord
CIF	Climate Investment Funds
Cr	Chromium
CSI	Cement Sustainability Initiative; see www.wbcscement.org
EC	European Community
EU	European Union
EOL	End of Life
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GWP	Global Warming Potential
HCl	Hydrochloric Acid
HFC	Hydrofluorocarbon
IEA	International Energy Agency; see www.iea.org
IGSD	Institute for Governance and Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
kW	Kilowatt
LCA	Life Cycle Analysis
MAP	Mineralization via Aqueous Precipitation
ODS	Ozone-Depleting Substance
OPC	Ordinary Portland Cement
P/A	Per/Annum (each year)
Pb	Lead
PFC	Perfluorocarbon
SCM	Supplementary Cementitious Materials
Se	Selenium
TCLP	Toxicity Characteristic Leaching Procedure
TEAP	Technology and Economic Assessment Panel
UCSB	University of California Santa Barbara
UNEP	United Nations Environment Programme

US United States
VDZ German Cement Works Association
WBCSD World Business Council for Sustainable Development; see www.wbc.org

Appendix 3:

Explanation of Mass Balance

Mass balance is a well-known method for quantitatively monitoring or auditing process performance. Underlying the method is the principal of conservation of mass that proposes that for any transformative process, the total mass of the component inputs to a process equals the mass of the outputs plus any accumulation. Outputs include products, by-products, wastes and fugitive emissions.

If the Calera process is considered to be continuous and steady state, then a measurement of all input and output streams could be taken at any point in time. Such data may be available from the on-line monitoring and process control. The Calera process is more likely to be considered continuous but non-homogeneous in time. For such a process, an integrated mass balance will be required to be performed over a suitable period of time. Furthermore, validation of the process performance with regard to CO₂ sequestration will require careful component-by-component analysis of each of the input and output streams.

Statistically valid sampling, monitoring, analysis and measurement methodologies must be carefully designed and implemented for each of the input and output streams to ensure validity of the mass balance analysis. When measuring large process streams or components it is often impracticable to quantitatively characterise the entire stream, and there is often a strong likelihood of non-homogeneity. For this reason any and all sampling of materials must be statistically designed and validated to ensure that analyzed stream samples are representative of the entire stream. All instrumentation must be calibrated and all measurements performed to recognised standards. All methods, results and calculations should then be audited for compliance with the recommended standards.

The Calera Process is a complex process with several input and output streams. Design of a mass balance analysis for process validation will require very careful design, implementation, validation and audit.

Appendix 4:

Technical Option Road Map

Future development of global cement production and CO₂ reduction potentials

Several different studies (e.g. IEA, McKinsey) have focused on potential cement industry emissions reductions. Although these studies use different scenarios, baseline emissions, and future demand forecasts, they nevertheless reach broadly similar conclusions, and highlight the potential benefits of the four levers for achieving significant carbon emissions reductions using current technology available worldwide:

1. Thermal and electric energy efficiency – deployment of existing state of the art technologies in new cement plants and retrofit of energy efficiency equipment where economically viable.
2. Alternative fuels – use of less carbon-intensive fossil fuels in the clinker burning process, including biomass fuels and combustible wastes that may otherwise be incinerated or land filled without taking advantage of the energy content.
3. Clinker substitution – substituting carbon-intensive clinker with other, lower carbon materials with cementitious properties.
4. Carbon capture and storage (CCS) – capturing CO₂ from cement production facilities and storing it securely.

There is one other lever with the emerging potential for achieving significant carbon emissions reductions worldwide:

5. Low-carbon or carbon-free cements or building materials (including Calera SCM).

The physical properties (e.g. strength development) of some of the low-carbon, carbon free, and carbon capture cements appear to be similar to those of Portland cement. However, these new processes are still at the development and pre-commercial stages. There may also be an opportunity to revive ancient building practices to avoid the use of cement or to reduce the carbon footprint. For example, sticky rice-lime mortar based on the formula derived from samples taken from the Ming dynasty section of the Great Wall (about 600 years ago) tested superior to modern mortar.³⁶

³⁶The inorganic component is calcium carbonate and the organic component is amylopectin. Mortar reformulated to the original recipe tested superior in consistency, water retentivity of fresh mortar, shrinkage, bulk density of fresh and hardened mortar, mechanical strength of hardened mortar, and water and vapour absorption of hardened mortar. See Fuwei Yang, Bingjian Zhang, and Qinglin Ma, *Study of Sticky Rice-Lime Mortar Technology for the Restoration of Historical Masonry Construction*, 43 ACCOUNTS OF CHEMICAL RESEARCH 936-944 (June 2010).

According to the “Cement Technology Roadmap”, published by the International Energy Agency (IEA), cement production (and consumption) will increase from 2.6 billion t/a in 2006 to 3.7 - 4.4 billion t/a in 2050. CO₂ emissions from cement production would increase in the base scenario (business as usual) from 1.88 (2006) to 2.34 billion t/a in 2050 (*see figure 1*).

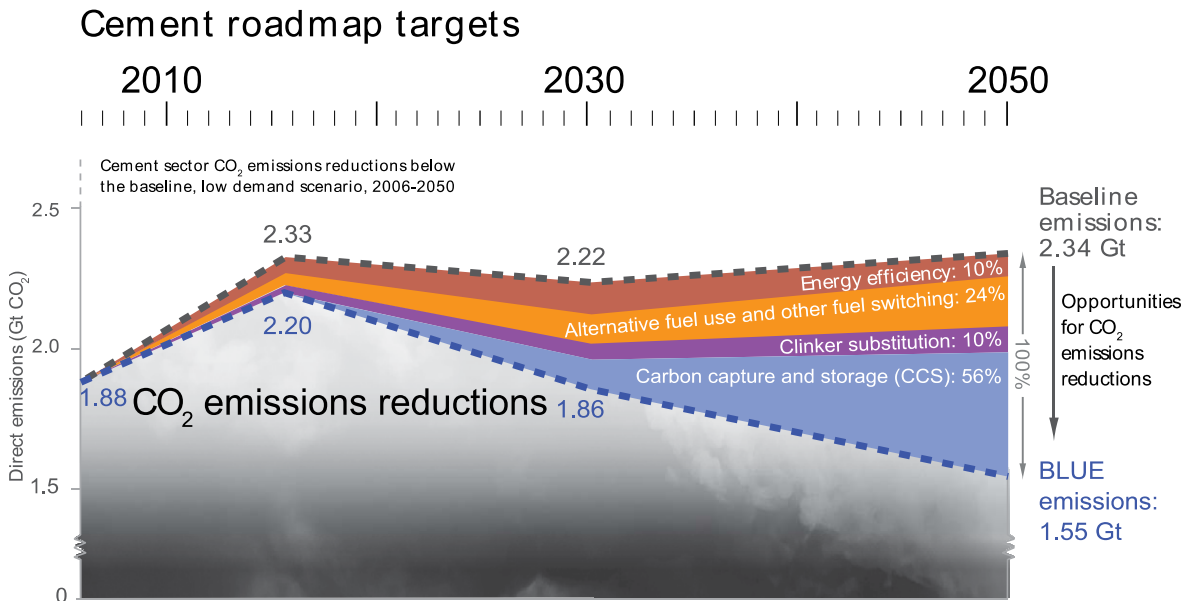


Figure 1: CO₂ emissions of cement production 2006 to 2050

Source: IEA, WBCSD, CEMENT TECHNOLOGY ROADMAP 2009 - CARBON EMISSIONS REDUCTIONS UP TO 2050 (2009).

The impact of energy efficiency technologies on CO₂ reduction has been estimated to be 10%. This is mainly due to installation of new efficient cement kilns and the replacement of existing kilns with less efficient technology by new and more efficient ones. Fuel switching from coal to alternative fuels with lower CO₂ emission factors and biomass shall contribute 24% of the required reduction while reduction of clinker content in cement may lead to another 10%. CCS will have to be implemented in the cement industry to a large extent if the international reduction targets are to be met. Based on these calculations, IEA has estimated (in the low scenario) that the cement industry will be able to reduce its emissions by 18% despite an estimated increase of cement production by 43%.

Costs for the implementation of the measures, calculated by IEA, needed in the “low production scenario” are US \$354 - 572 billion and in the “high production scenario” US \$474 - 854 billion. The share of CCS needed to achieve the set targets mainly determines costs.

Appendix 5:

Cement Leadership Partnerships and Publications

The World Business Council for Sustainable Development (WBCSD) and the International Energy Agency (IEA) published *The Cement Technology* in 2009 calling for strong national policies to activate known CO₂ mitigation actions that the cement sector can take now. It also issues a call to action to develop commercially viable CCS technologies as a method for further reducing global CO₂ emissions from the cement industry.

Transforming the Market: Energy Efficiency in Buildings, the 2009 report issued by the WBCSD's Energy Efficiency in Buildings Project (EEB), a four-year, \$15 million dollar project sponsored by 14 multi-national companies such as Lafarge, United Technologies Corp and CEMEX examines the lifecycle opportunities of buildings in Brazil, India, China, Europe, Japan, and the US.

The Project shows how energy use in buildings can be cut by 60 percent by 2050 – an essential step to meeting global climate change targets – requiring immediate action to transform the building sector. Since the issuance of the report, the WBCSD has proposed a manifesto to all of its members inviting them to take action by creating large-scale demand for energy-efficient buildings through sending strong messages to the market, stakeholders, and employees.

“The importance of buildings in cutting energy consumption and greenhouse gas emissions has been underestimated and this report will help to change that. It highlights that the market alone will not achieve the necessary progress – policy and behaviour changes are also essential to stimulate the market and achieve low-energy buildings.”

-- Klaus Topfer, Chairman of the Assurance Group, EEB Project

Large City Leadership in Climate (C40)

In October 2005, representatives of 18 leading world cities met in London to discuss joining forces to tackle global warming and climate change. The representatives saw the need for action and cooperation on reducing greenhouse gas emissions and pledged to work together toward achieving that goal. Now partnering with the Clinton Climate Initiative, the cities have promised a number of action points in the area of buildings, including the creation of procurement policies, codes, energy audits, and alliances to accelerate the uptake of climate-friendly technologies and influence the market place.

Appendix 6:

Catalogue and web links to emerging low-Carbon Cements and Cement Substitutes

Company/ Headquarters/ Website	CO ₂ captured from power plants	CO ₂ avoided by substitution of low-carbon cement for OPC in concrete and other building materials	CO ₂ reduced from cement manufacture energy use	Other
Calera/ Los Gatos CA, USA/ www.calera.com	Up to 90%	Calera SCM offsets up to 20% of emissions or more	Calera SCM offsets up to 20% of emissions or more	Captures mercury, sulphur, & other pollutants
C-fix/ Netherlands/ www.c-fix.com	No	Petroleum- based material replaces concrete in some applications	Petroleum- based material replaces concrete in some applications	
Calix/ Sydney, Australia www.calix.com.au	No	The fuel and electricity used during the process generates 14 kilograms of CO ₂ for every ton of concrete ultimately produced	Low energy rapid calcination of dolomite	Patent has been filed, but process has not been demonstrate d
Carbon Sciences/ Santa Barbara, CA, USA/ www.carbonsciences.com	Magnesium- and calcium-rich mine waste water and power plant flue gas form cementitious materials			Requires proximity of power plants and mines
Carbon Sense Solutions/ Halifax Nova Scotia, Canada/ www.CarbonSenseSolutions.com	Freshly poured concrete absorbs CO ₂ from power plant flue gas as it cures	No	No	Pre-casting concrete at power plants may increase CO ₂ emissions from transport
GreenMag Group and University of Newcastle/ Newcastle, NSW, Australia/	The mineral carbonation process fuses	Magnesium carbonate could be used	Potential to reduce CO ₂ emissions	

www.GreenMagGroup.com Novachem London, UK www.newcastle.edu.au/www.novachem.com	carbon dioxide with serpentinite to create magnesium carbonate	in the production of bricks, pavers, cement and agricultural silicates		
Lafarge/ Paris France/ www.Lafargececo.com	“BCSAF” clinkers, (belite, calcium sulfoaluminate and calcium alumino-ferrite)	Cementitious magnesia compounds in blended cement	Manufacture emits about 25% less CO ₂ than OPC	
Novacem/ London, UK/ www.novacem.com	No	Magnesium silicates are converted into magnesium oxide using a low-carbon, low temperature process; mineral additives accelerate strength development and CO ₂ absorption. Yes, offsets 80% of emissions or more	Potential to reduce CO ₂ emissions	Potential to absorb atmospheric CO ₂ as the cement cures
TecEco/ Glenorchy Tasmania, Australia/ www.tececo.com	Perhaps	Cementitious magnesium compounds in blended cement	Potential to reduce CO ₂ emissions	
Zeobond/ Melbourne Victoria, Australia/ www.zeobond.com	No	Yes, offsets 80% of emissions or more	Yes, offsets 80% of emissions or more	

Appendix 7:

Potential Sources of Concessional Finance For Introducing Calera Technology in Developing Countries

Innovative power plant and cement technology like that proposed by Calera will have to be widely deployed in both developed and developing countries to achieve the largest reduction in global GHG emissions. Such technology will be particularly important to deploy in rapidly growing countries, particularly China, that are expected to dominate future growth in use of both fossil fuels and basic materials.³⁷

New donor funds have been created to encourage investment in clean energy and GHG mitigating technologies in developing countries. Each fund, described on the table below, has its own eligibility requirements, scope, and accessibility from a private sector perspective. A few of the listed funds are specifically available to ensure borrowers against the risks associated with the introduction of new technologies, notably the Global Environment Facility (GEF) (www.thegef.org) and Clean Technology Fund (CTF) (www.climateinvestmentfund.org). The GEF has been a source of funding for demonstrations and risk capital for several early stage technologies including stationary and mobile fuel cells, grid-connected solar photovoltaic power, and concentrating solar power.

New bilateral and multilateral climate funds for Mitigation (M) and Adaptation (A)		
Fund	Total amount (\$ millions)	Period
Funding under UNFCCC		
GEF 5 Replenishment	1,350 (M)	2010-14
Strategic Priority on Adaptation	50	GEF 3-GEF 4
Least Developed Country Fund	172	As of October 2008
Special Climate Change Fund	91	As of October 2008
Adaptation Fund	135	As of June 2010
Bilateral initiatives		
Cool Earth Partnership (Japan)	10,000 (A+M)	2008–12
ETF-IW (United	1,182 (A+M)	2008–12

³⁷ IEA, *World Energy Outlook 2008 Fact Sheet* (2008), available at http://www.worldenergyoutlook.org/docs/weo2008/fact_sheets_08.pdf (The International Energy Agency projected in its 2008 World Energy Outlook that “three-quarters of the projected increase in energy-related CO₂ emissions arises in China, India and the Middle East, and 97% in non-OECD countries as a whole.”).

Kingdom)		
Climate and Forest Initiative (Norway)		2,250 (M)
UNDP-Spain MDG Achievement Fund	22 (A) / 92 (M)	2007–10
GREEF (European Commission)	€108 million (mobilization of private risk capital)	2010-11
GCCA (European Commission)	84 (A) / 76 (M)	2008–10
International Climate Initiative (Germany)	200 (A) / 564 (M)	2008–12
IFCI (Australia)	160 (M)	2007–12
Multilateral initiatives		
GFDRR	15 (A) (of \$83 million in pledges)	2007–08
Carbon Partnership Facility (World Bank)		500 (M) (140 committed)
Climate Investment Funds, includes	6,200 (A+M)	2009–12
Clean Technology Fund		4,800 (M) (fully committed 3/2010, but additional donor contributions may be forthcoming)
Strategic Climate Fund, including		1,400 (A+M)
Forest Investment Programme		350 (M)
Scaling up renewable energy		200 (M)
Pilot Program for Climate Resilience		600 (A)
<i>Source:</i> World Bank, WORLD DEVELOPMENT REPORT 2010: DEVELOPMENT AND CLIMATE CHANGE 253 (2010); GEF May 2010 press release, at www.thegef.org .		

A potential additional source of risk capital may be the carbon markets. Credits are potentially available for innovative energy efficiency technologies with approved methodologies. One challenge for achieving eligibility for carbon credits in developing countries is to obtain an approved methodology for evaluating the emission reductions relative to some baseline of standard practice or behaviour, a fundamental requirement for the issuance of credits under the climate convention Clean Development Mechanism

(CDM).³⁸ So far, emission reduction allowances for carbon sequestration projects have been controversial.³⁹

The *Copenhagen Accord* signed in December 2009 and so far endorsed by over 120 countries, created an expectation of substantial new and additional funds for climate change projects. The “fast start” commitment made by signatory donors is to collectively provide “new and additional resources, including forestry and investments through international institutions, approaching USD 30 billion for the period 2010-2012 with balanced allocation between adaptation and mitigation.” According to the World Resources Institute, donor pledges roughly equivalent to the promised amount had been announced as of early June 2010.⁴⁰ Beyond the fast start commitment, the Accord includes a target of \$100 billion per annum in public and private funds by 2020.

Donor funds may be available to help Calera accelerate the introduction of its technology into developing countries for a variety of purposes including demonstration projects, capacity building efforts (e.g., bringing developing country officials to visit Calera facilities in the US or Australia), project development costs, and other expenses associated with first-of-a-kind projects.

³⁸ Detailed information about the status and process for approving methodologies is available at the website of the UN Framework Convention on Climate Change: cdm.unfccc.int.

³⁹ World Bank, *STATE AND TRENDS OF THE CARBON MARKET 2010* (2010), available at http://siteresources.worldbank.org/INTCARBONFINANCE/Resources/State_and_Trends_of_the_Carbon_Market_2010_low_res.pdf. For a brief history of the consideration of the eligibility of CCS for credits under the CDM, see <http://cdm.unfccc.int/about/ccs/index.html>.

⁴⁰ WRI maintains a detailed list of pledges and general information about their scope and status. WRI, *Summary of Climate Finance Pledges Put Forward by Developed Countries* (2010), available at <http://www.wri.org/stories/2010/02/summary-climate-finance-pledges-put-forward-developed-countries>.

Appendix 8:

Scientific Synthesis Team, Calera Expert Team, UCSB Consultants to Calera, and Contractors to Calera Providing the Basis for This Report

Scientific Synthesis Team Co-Chairs

Dr. Stephen O. Andersen, Institute for Governance and Sustainable Development
Mr. Durwood Zaelke, Program on Governance for Sustainable Development,
Bren School of Environmental Science and Management

Project Host

Professor Oran Young, Program on Governance for Sustainable Development,
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Executive Project Managers from the Bren School and IGSD

Ms. Maria Gordon, Bren School of Environmental Science and Management
Ms. Alexandra Viets, Institute for Governance and Sustainable Development

Scientific Synthesis Team

1. Dr. Husamuddin Ahmadzai, Swedish Environment Protection Agency and Nordic Environmental Finance Corporation
2. Mr. Frederick R. Anderson, McKenna Long & Aldridge LLP.
3. Mr. Michael Atkinson, Energy International Australia
4. Mr. Everett “Brownie” Carson, Natural Resources Council of Maine
5. Dr. Robert J. Carson, Department of Geology and Environmental Studies, Whitman College
6. Mr. Stig Christensen, COWI, Copenhagen Denmark
7. Dr. Jan SJ Van Deventer, Zeobond and Department of Chemical & Biomolecular Engineering, University of Melbourne
8. Dr. Stephanie Hanford, Connectivity Consulting, Florida
9. Dr. Volker Hoenig, German Cement Works Association (VDZ)
10. Mr. Alan Miller, International Finance Corporation
11. Dr. Mario Molina, Department of Chemistry and Biochemistry, University of California, San Diego
12. Ms. Lynn Price, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory
13. Dr. Veerabhadran Ramanathan, Scripps Institution of Oceanography, University of California, San Diego
14. Dr. Helen Tope, Energy International Australia
15. Dr. John Wilkinson, Vulcan Chemicals (consulting), Washington DC
16. Dr. Masaaki Yamabe, Japan National Institute of Advanced Industrial Science & Technology
17. Dr. Oran Young, Bren School of Environmental Science and Management, University of California, Santa Barbara

University of California, Santa Barbara Evaluation Team

Mass and Energy Balance

1. Dr. Michael F. Doherty, Chair, Department of Chemical Engineering
2. Dr. Anjana Meel, Post-Doctoral Fellow in Chemical Engineering
Economics and Optimization
3. Dr. Charles Kolstad, Professor, Department of Economics
4. Mr. Daniel Young, Graduate Student, Department of Economics
Life Cycle Greenhouse Gas Footprint
5. Dr. Roland Geyer, Assistant Professor, Environmental Science & Management
6. Mr. Christian Del Maestro, Graduate Student, Environmental Science &
Management
7. Mr. Adam Rohloff, Graduate Student, Environmental Science & Management

Calera Corporation Advisors to the Science Synthesis Team

1. Vinod Khosla, Founder of Khosla Ventures
2. Dr. Brent Constantz, Calera Founder
3. Jane Ricci, Assistant to Brent Constantz
4. Dr. Randy Seeker, Chief Technology Officer (CTO)
5. Aurelia Setton, Director of Strategic Planning
6. Dr. Marty Devenney, VP of Materials Technology
7. Dr. Michael Weiss, Process Engineer
8. Dr. Laurence Clodic, Senior Scientist, Concrete
9. Dr. Terrence Holland, Senior Fellow Concrete Technology
10. Joshua Patterson, Calera SCM Performance Engineer
11. Dr. Ryan Gilliam, Director, Electrochemistry

Consultants to Calera Providing Detailed Technical Support

1. Bechtel
2. Schlumberger
3. R. W. Beck

Peer Reviewers

1. Dr. Rosina Bierbaum, School of Natural Resources and Environment, University
of Michigan
2. Dr. Peter Duxson, Chief Operating Officer, The Zeobond Group, Melbourne
Australia
3. Dr. William Moomaw, Fletcher School, Tufts University, Boston USA

Institute for Governance and Sustainable Development (IGSD)

1. Dennis M. Clare, New York USA
2. Peter Gabriel, Sydney Australia

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5. Alexandra Viets, Walnut Creek USA
6. Nathan Borgford-Parnell, Washington DC USA
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Appendix 9:

Biographies: Scientific Synthesis Team Co-Chairs

Dr. Stephen O. Andersen

Stephen Andersen is Director of Research for the Institute for Governance & Sustainable Development (IGSD) in Washington, D.C. and Co-Chair of the Montreal Protocol Technology and Economic Assessment Panel. Formerly, he was employed by the United States Environmental Protection Agency (EPA) in a variety of senior positions including Director of Strategic Climate Projects at Climate Protection Partnership Division, Deputy Director of the Stratospheric Protection Division, and liaison to the Department of Defense on Ozone and Climate Protection. He organized the first EPA industry-government partnerships and the EPA Stratospheric Ozone and Climate Protection Awards. With Mario Molina, Durwood Zaelke, K. Madhava Sarma, Veerabhadran Ramanathan and Donald Kaniaru, “Reducing Abrupt Climate Change Risk Using the Montreal Protocol and Other Regulatory Actions to Complement Cuts in CO₂ Emissions,” in the Proceedings Of The National Academy Of Sciences, PNAS 2009 106:20616-2062; with K. Madhava Sarma and Kristen N. Taddonio *Technology Transfer for the Ozone Layer: Lessons for Climate Change*, Earthscan Press, London 2007; with Durwood Zaelke *Industry Genius: Inventions and People Protecting the Climate and Fragile Ozone Layer*, Greenleaf Press, London 2003; and with K. Madhava Sarma, he authored *Protecting the Ozone Layer: The United Nations History*, Earthscan Press, London 2002. He has earned governmental and non-governmental awards from the United Nations, Brazil, Japan, Vietnam, and the United States, including the prestigious 2008 Service to America Career Achievement Medal, the 2007 United Nations Montreal Protocol Visionaries Award, and the 1998 United Nations Environment Programme Global 500 Roll of Honour. His Ph.D. is from the University of California, Berkeley.

Mr. Durwood Zaelke

Durwood Zaelke is the Co-Director and co-founder (with Dr. Oran Young and Matthew Stilwell) of the Program on Governance for Sustainable Development at the Bren School of Environmental Science & Management, University of California, Santa Barbara; the President and founder of the Institute for Governance & Sustainable Development in Washington, D.C. and Geneva; and Director of the Secretariat for the International Network for Environmental Compliance & Enforcement in Washington, D.C. and Geneva. Previously, Mr. Zaelke was President and co-founder of the Center for International Environmental Law in Washington DC and Geneva (1989-2003); co-founder of the Foundation for International Environmental Law & Development in London (formerly CIEL-UK); Director and founder of the International & Comparative Environmental Law Program at the American University law school (1990-2004); Director and founder of the International Program at Earthjustice (formerly the Sierra Club Legal Defense Fund) (1988-89); director of the Alaska and D.C. office of the Sierra Club Legal Defense Fund (1980-89); and co-founder of the Policy, Legislation & Special Litigation Section, and the Energy Conservation Section (disbanded by the subsequent Reagan Administration), both in the Environmental Division of the Justice Department (1978-80). Mr. Zaelke is the co-author of several books and many journal articles in the

fields of the climate protection, environment, and environmental law; and currently teaches at UC Santa Barbara's Bren School of Environmental Science & Management and American University law school. He also has taught at Yale Law School, Duke Law School, and Johns Hopkins. In 2008, Mr. Zaelke received both an Ozone Protection Award and a Climate Protection Award from the U.S. EPA. He is a graduate of Duke Law School and UCLA.

Biographies: Scientific Synthesis Team and Peer Reviewers

Dr. Husamuddin Ahmadzai

Dr. Husamuddin Ahmadzai is Special Adviser to the Nordic Environment Finance Corporation (NEFCO), the Nordic Investment Bank, and Senior Adviser to the Swedish EPA. Dr. Ahmadzai is also a member and former Chair of the Executive Committee of the Multilateral Fund of the Montreal Protocol (MP) and Member of the European Union (EU) Committees on Ozone Protection including the Swedish Negotiating Delegation to the MP. He also serves on the Scientific Programme Committee of the Stockholm International Water Institute and is the founding partner of Mensa Milieu, a consultancy in the field of environment, energy, and resource efficiency. Dr. Ahmadzai has led the Swedish OSPAR delegations for protection of the North-East Atlantic and participated in the EU Integrated Pollution Prevention and Control Bureau working groups on industry, energy, and cross media issues. He has advised LIFE, the EU's financial instrument supporting environmental and nature conservation projects throughout the EU. As a member of the UNEP Montreal Protocol Technology and Economic Assessment Panel (TEAP), Dr. Ahmadzai chaired its Process Agent Working Group and served as a Member of the TEAP's Technical Options Committee on Solvents, Coatings & Adhesives. He has also served as a consultant to the Swedish International Development Cooperation Agency, the World Bank, the United Nations Development Programme, the United Nations Environment Programme, and the United Nations Development Organization. Dr. Ahmadzai has about 36 years of industrial, academic, regulatory, implementation, financial and management experience, and is a Chartered Engineer and Chartered Professional–Environment and a member of several professional organizations. He holds degrees from the Universities of the Punjab, New South Wales, Gothenburg, and the Royal Institute of Technology (Kungliga Tekniska Högskolan).

Mr. Frederick R. Anderson

Frederick R. Anderson is a partner in the Washington office of the law firm of McKenna Long & Aldridge LLP. This year he received the American Bar Association's highest Award for Excellence in Environmental, Energy, and Resources Stewardship. Also this year the Center for International Environmental Law created the annual Frederick R. Anderson Award for Outstanding Accomplishment in Addressing Climate Change. His practice involves strategic corporate counselling, regulatory affairs, litigation, enforcement, and crisis management. He is involved with a number of climate change and alternative energy projects, the Clean Air Act, and environmental impact assessment of domestic and international projects. He represents wind energy projects off Cape Cod and on Lake Ontario and clients seeking federal green tech and safety and security energy funding. He advises on emerging climate regimes, particularly in Congress and the U.S.

EPA, and on greenhouse gas transactions for allowances and offsets. His clients have included Fortune 10 manufacturing, energy, aerospace, metals, minerals, and chemical companies, and national governments. He engages regularly with major federal agencies, the White House, and the global financial institutions based in Washington. He serves on the executive committee of the National Academy of Science's Committee on Science, Technology & Law, and in 2010 completed a three-year term as a member of the Academy's Board on Atmospheric Sciences and Climate. He was Dean of the law school at the American University and President of the Environmental Law Institute. He serves on six non-profit boards and chairs the board of the Institute for Governance and Sustainable Development and serves on the Board of Visitors to the Institute for the Environment at the University of North Carolina (UNC). He holds degrees from the UNC, Oxford University, and Harvard University. He is the author of several books and textbooks, and many articles in his field.

Mr. Michael Atkinson

Michael Atkinson is a Director of Energy International Australia providing strategic and technical advice and services to government, industry and other non-governmental organizations on climate change, energy and energy efficiency, and other environmental issues. A physics graduate, he has extensive experience in application of physical and analytical chemistry to industrial processes, with specific expertise being developed in the aluminium industry where he was the leader for seven years for all research and development projects of smelter atmospheric emissions projects for Comalco Aluminium's Research & Technology. From 1992 to 1998, he was a central member of the team that developed the Comalco Dry Scrubbing Process from laboratory-scale R&D phase through conceptual engineering and physical modelling, pilot plant engineering, construction and testing, through FEED and EPC and technology transfer to routine operation of complete dry scrubbing packages at two smelters in New Zealand and Australia. Implementation at the Bell Bay smelter won the Tasmanian Award for Environmental Excellence in the category of "Mining and Minerals Processing." He co-chaired the expert panel for the aluminium sector for the IPCC Good Practice Guidance in National Greenhouse Gas Inventories from 1998 to 2001. He has co-authored an APEC study of CO₂ reduction options in fossil fuel electricity generation (2004), and was principal consultant for the Iranian Fuel Conservation Organisation's National Laboratories basic and detailed design. He has been trained as an independent verifier for the greenhouse friendly programs and in carbon accounting.

Dr. Rosina Bierbaum (Peer Reviewer)

Dr. Rosina Bierbaum is Dean of the School of Natural Resources and Environment (SNRE) at University of Michigan. Prior to joining the School of Natural Resources and Environment, Bierbaum was acting director of the Office of Science and Technology Policy (OSTP) from January 2001, and preceding that, she was Associate Director for Environment of OSTP. She served as the William Clinton's senior scientific advisor on environmental research and development, with responsibilities for scientific input and guidance on a wide range of national and international environmental issues including global change, air and water quality, biodiversity, ecosystem management, environmental monitoring, and energy research and development. In April 2009, President Obama

selected Dr. Bierbaum as one of the twenty members of the President's Council of Advisors on Science and Technology (PCAST) to advise the President and Vice President directly on science, technology and innovation policy. Dr. Bierbaum is the co-author of "Confronting Climate Change: Avoiding the Unmanageable and Managing the Unavoidable" prepared at the request of the Commission on Sustainable Development (2007); primary author of *Changing By Degrees: Steps to Reduce Greenhouse Gases* and she directed and was the primary author of the two volume study, *Preparing for an Uncertain Climate*, which outlines a sustainable development strategy for the United States (1993). Dr. Bierbaum co-authored and co-directed the 2010 World Bank World Development Report, which focuses—for the first time—on how Nations can mitigate and adapt to climate change while simultaneously achieving sustainable development. She is a Fellow of the American Academy of Arts and Science as well as a Fellow of the American Association for the Advancement of Science. She serves as a trustee of the University Corporation for Atmospheric Research (UCAR); and as a board member for the Federation of American Scientists, The Energy Foundation, the Gordon E. and Betty I. Moore Foundation, and the Environmental and Energy Study Institute. She is also a member of the John D. and Catherine T. MacArthur Foundation's Science Advisory Council, the International Advisory Board for the journal "Frontiers in Ecology and the Environment," the National Research Council's Board on Atmospheric Sciences and Climate, the Design Committee for The Heinz Center's The State of the Nation's Ecosystems project, and the Executive Committee for the Tyler Prize for Environmental Achievement. Dr. Bierbaum the U.S. Scientific Expert, Permanent Court of Arbitration of Disputes Relating to Natural Resources and/or the Environment, in the Hague. In 2000 she was awarded the Waldo E Smith medal of the American Geophysical Union for 'extraordinary service to geophysics' and in 1999 she was awarded the Environmental Protection Agency's "Climate Protection Award."

Mr. Everett "Brownie" Carson

Since 1984, Brownie Carson has been Executive Director of The Natural Resources Council of Maine (NRCM). Founded in 1959, NRCM is Maine's leading environmental advocacy organization. NRCM's major project areas include Clean Air and Clean Energy Production, Watershed Protection and Restoration, Forest Conservation, and Toxics Use Reduction. Carson is a graduate of Bowdoin College (1972) and the University of Maine School of Law (1977). He is a Vietnam Veteran, having served as an infantry platoon commander in 1968-69. Before joining The Natural Resources Council, Carson worked for the U.S. Office of Education, The Office of Economic Opportunity, and as an attorney for the Legal Services Corporation in Maine. During Carson's tenure, NRCM has established leading edge environmental policy for the State of Maine: early expansion of the Returnable Container Law to include juice, all alcoholic beverages, and bottled water; design work on the first multi-state greenhouse gas allocation and auction program-- the northeast's Regional Greenhouse Gas Initiative ("RGGI"); legislation that requires producers to collect and safely recycle electronic products at the end of their useful life; and the first state program requiring removal and recycling of all mercury-activated switches from automobiles before they are scrapped. Carson was a leader of the 10 year campaign to remove Edwards Dam from the Kennebec River, the success of which has led to an unprecedented rebirth of anadromous fish in Maine's second largest watershed.

Dr. Robert J. Carson

Dr. Robert Carson is Phillips Professor of Geology and Environmental Studies at Whitman College in Walla Walla, Washington. He earned an A.B. in geology with a minor in chemistry from Cornell University, an M.S. from Tulane University, and a Ph.D. from the University of Washington. Prior to joining Whitman College, Dr. Carson worked for Texaco Inc. exploring for oil and gas in Louisiana and exploring for phosphate in Florida; then for the Washington Department of Ecology and the Washington Division of Geology and Earth Resources. At Whitman College, his interests are in the earth and environmental sciences; his courses deal with human interaction with the biosphere including: global climate change, glaciers, volcanoes, water, landforms, and natural hazards. A white-water guide and a member of the American Alpine Club, he has led field trips in Africa, Eurasia, South America, and throughout North America. His books include *Hiking Guide to Washington Geology*, *Where the Great River Bends*, and *East of Yellowstone*. Dr. Carson has studied the proposed carbon sequestration in basalt geological formations.

Mr. Stig P. Christensen

Mr. Stig P. Christensen is presently Senior Research & Development director of COWI A/S, responsible for cross cutting strategic development related to climate change based on COWI's 3E – Engineering, Environment, and Economics – competence profile of its 6,000 employees. Until 2008, he was Vice-president for the Economics, Management, & Planning business unit and on the founding team of COWI's Economics profile. Mr. Christensen has directed a large number of multidisciplinary projects within the sectors of transportation, energy, and environment for national and international clients, mainly in a wider European context. He is presently leading COWI's global activities related to climate change, building on his earlier activities related to the Montreal Protocol. He has made a significant footprint for COWI's activities in Central and Eastern Europe, developing COWI companies in Russia, Hungary, Turkey, Serbia and Brussels, often from a “Montreal Protocol” business development platform.

Dr. Peter Duxson (Peer Reviewer)

Dr. Peter Duxson is the Chief Operating Officer of the Zeobond Group and an Honorary Research Fellow in the Department of Chemical and Biomolecular Engineering at the University of Melbourne in Victoria, Australia. Peter is a leading expert on commercialisation, regulation and sustainability issues of environmental concrete and the building materials industry and is one of the most highly cited cement and concrete authors in the past five years. Peter serves on technical committees in Australia and abroad responsible for drafting standards for low carbon concrete technologies. He is a pioneer in the commercial development of geopolymers at Zeobond, including technology of slag and fly ash-based geopolymer concrete marketed under the trade name ‘E-Crete’ that is a total replacement for OPC in some applications. He is a specialist in demonstrating how technical issues relating to creating practicable low-carbon concrete can be solved, and how business issues relating to competitive price point, commercial risk and insurance, and customer confidence have been overcome. Dr. Duxson holds a B.A. in Chinese (2001), a B.E. (Honours) in Chemical Engineering (2001) and a Ph.D. in geopolymer engineering (2006), all from the University of Melbourne.

Ms. Stephanie Hanford

Ms Stephanie Hanford is President of Connectivity Consulting and a Fellow at the Institute for Governance and Sustainable Development. Ms. Hanford specializes in designing business and policy strategies linked to sustainability. She worked internationally for over ten years with leading environmental organizations such as the World Business Council for Sustainable Development (WBCSD) in Geneva, The Center for International Environmental Law (CIEL) in Geneva, and the Brazilian Business Council for Sustainable Development (CEBDS) in Rio de Janeiro. At the WBCSD Geneva she contributed to the strategic development of the Cement Sustainability Initiative (CSI). She has designed extensive stakeholder engagement projects in Europe, Asia, Africa, and North and South America to promote multi-sector partnerships. She consults for a range of companies and institutions, including British Petroleum, Caterpillar, the U.S. Environmental Protection Agency and The Green Media Group. Ms. Hanford holds a master's degree in International Law and Diplomacy from The Fletcher School, Tufts University, and a BA from Loyola College in Maryland. She is fluent in French and Portuguese.

Dr. Volker Hoenig

Dr. Volker Hoenig, since 1997, is presently head of the Environment and Plant Technology Department of Verein Deutscher Zementwerke e.V. (VDZ/FIZ). In addition, he is serving as head of VDZ's Thermal Process Technology subdivision, as quality auditor and vice head of FIZ-Zert, the certification body for environmental, quality, health and safety, and energy management systems as well as CO₂ emissions according to the European Union Emission Trading System. Previously, he worked for the Technical University, Stuttgart on process and environmental engineering. Dr. Hoenig's work focuses on the field of thermal process engineering and environmental technology of mineral processing industry. Dr. Hoenig's research activities include environmental protection in cement manufacture; emission abatement of NO_x, SO₂, HCl, heavy metals and organic compounds; CO₂ reduction by energy efficiency optimization and post combustion carbon capture; environmental impact of cement plant emissions on ambient air quality; and cement process technology. His service to industry spans topics from cement kiln operation, emission prognoses, atmospheric modelling, and environmental impact studies. Dr. Hoenig's technical consultancy takes in projects from process technology to emission abatement and energy efficiency measures. Furthermore, he is member of numerous bodies/committees dealing with climate change issues, including WBCSD/CSI, CEMBUREAU (European cement association), BDI (German Business association), and ECRA (European Cement Research Academy). In this context he has been involved in many international projects with WBCSD/CSI, IEA, APP, UNIDO, ECRA and other organizations. He teaches at VDZ and the European Cement Research Academy. His PhD is from the University of Stuttgart.

Mr. Alan Miller

Mr. Alan Miller currently is Principal Climate Change Specialist in the Environment Department at the International Finance Corporation (IFC), the private sector lending arm of the World Bank Group. Prior to joining the IFC in October 2003, he was Climate Change manager at the Global Environment Facility (GEF) Secretariat overseeing a

portfolio of more than 100 clean energy projects in developing countries. He also created and directed the Center for Global Change at the University of Maryland (1989-96). He is a widely published author on climate change, energy, and development including a leading environmental law textbook. He holds an A.B. degree from Cornell University and a J.D. degree from the University of Michigan J.D. He was a Fulbright Scholar in Australia (1977) and Japan (1987).

Dr. Mario Molina

Mario Molina's studies in physical chemistry brought him to the University of California in Berkeley where he obtained his Ph.D. In 1974, he co-authored a paper published in the journal *Nature*. The article, published well before the first measurements of the Antarctic ozone hole became available, described how chlorofluorocarbon gases that were widely used in industry at the time destroy the atmospheric ozone layer that protects life on Earth from the sun's harmful UV-radiation. In 1995, Molina was honoured with the Nobel Prize in Chemistry for his work on ozone depletion. As Professor of Chemistry and Professor of Earth, Atmosphere, and Planetary Sciences at the Massachusetts Institute of Technology, Molina continued his research on the various ways in which human society affects the chemistry of the atmosphere. In 2004, he joined the faculty at the University of California in San Diego.

Dr. William Moomaw (Peer Reviewer)

Dr. William Moomaw is Professor of International Environmental Policy at the Fletcher School of Law and Diplomacy, Tufts University, where he is the founding director of the Center for International Environment and Resource Policy, the Tufts Climate Initiative and co-founder of the Global Development and Environment Institute. He graduated from Williams in 1959, and is a physical chemist with a PhD from MIT. He works to translate science and technology into policy terms using interdisciplinary tools. He was a coordinating lead author of the 2001 Intergovernmental Panel on Climate Change chapter on greenhouse gas emissions reduction, and for the special report on renewable energy due in 2010. He was a lead author of three other IPCC reports (1995, 2005 and 2007). He was the first director of the Climate, Energy and Pollution program at the World Resources Institute, and directed the Center for Environmental Studies at Williams. He has received Teaching Awards at both Williams and at The Fletcher School, and an Honorary Doctorate from the University of Belgrade for his work on sustainable development. As an AAAS Congressional Science Fellow, he worked on legislation that eliminated American use of CFCs in spray cans to protect the ozone layer, and also worked on energy and forestry legislation. Dr. Moomaw currently serves on the Board of Directors of The Climate Group, Clean Air-Cool Planet (which he co-founded), Earthwatch Institute, Center for Ecological Technologies and the Consensus Building Institute. He has facilitated sessions with negotiators of international treaties.

Ms. Lynn Price

A Staff Scientist in the China Energy Group of the Energy Analysis Department, Environmental Energy Technologies Division, of Lawrence Berkeley National Laboratory (LNBL), and has worked at LNBL since 1990. Ms. Price has been a member since 1994 of the Intergovernmental Panel on Climate Change (IPCC), which won the

Nobel Peace Prize in 2007, and was an author on the industrial sector chapter of the IPCC Fourth Assessment Report on Mitigation of Climate Change. Since 1999, Ms. Price has provided technical assistance to the Energy Foundation's China Sustainable Energy Program related to international experience with industrial sector energy efficiency policies. Ms. Price is currently providing technical assistance for China's Top-1000 Enterprise Program as well as for a number of projects focused on improvement of energy efficiency and emissions reductions in China's industrial sector. Funding for her work has been provided by the U.S. Department of Energy, U.S. Environmental Protection Agency, the U.S. State Department through the Asia Pacific Partnership for Clean Development and Climate, the World Bank, the United Nations Development Program, the U.S. Agency for International Development through the Institute for Sustainable Communities, Dow Chemical, and the Energy Foundation's China Sustainable Energy Program. Ms. Price has a M.S. in Environmental Science from the University of Wisconsin-Madison.

Dr. Veerabhadran Ramanathan

Dr. V. Ramanathan is a Distinguished Professor of Applied Ocean Sciences, Climate & Atmospheric Sciences at the Scripps Institution of Oceanography, University of California, San Diego (UCSD). In the 1970s, he discovered the greenhouse effect of CFCs and numerous other manmade trace gases, and forecasted in 1980, along with R. Madden, that the global warming would be detectable by the year 2000. With Paul Crutzen, he led an international team that first discovered the widespread atmospheric brown clouds (ABCs). Dr. Ramanathan showed that ABCs lead to large scale dimming, decreased monsoon rainfall and rice harvest in India, and played a dominant role in the melting of the Himalayan glaciers. His team developed unmanned aerial vehicles with miniaturized instruments to measure black carbon in soot over South Asia and to track pollution from Beijing during the Olympics. He has estimated that reduction of black carbon can reduce global warming significantly, and is following this up with climate mitigation Project Surya, which will reduce soot emissions from bio-fuel cooking in rural India. He chaired the committee that produced the National Academy report calling for a major restructuring of the Climate Change Science Program, a report received favourably by the Obama administration. His numerous awards include the 2009-Tyler prize, the Volvo Prize, the Zayed prize, the Rossby Medal and the Buys-Ballot Medal for pioneering studies in climate and environment. He has been elected to the American Philosophical Society, the US National Academy of Sciences, the Pontifical Academy (by Pope John Paul II) and the Royal Swedish Academy of Sciences.

Dr. Helen Tope

Dr. Tope is Director of Planet Futures and Principal Consultant of Energy International Australia, providing strategic, policy, and technical advice and facilitation services to government, industry and other non-governmental organizations on climate change, ozone-depleting substances, and other environmental issues. Since 1995, she has served on the Montreal Protocol Medical Technical Options Committee and Technology and Economic Assessment Panel, and has co-chaired the Montreal Protocol's Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride Technical Options Committee (ATOC), now the Medical Technical Options Committee (MTOC). As part of her work

with the Environment Protection Authority (EPA Victoria), Australia, Dr. Tope managed the reviews of Victoria's Industrial Waste Strategy and hazardous waste regulations in 1996-2000, and managed Victoria's ozone layer protection program from 1999-2006. Also in her role with the EPA Victoria, Dr. Tope served, 2005-2006, as senior team leader for strategic global issues, overseeing the development of ozone layer and climate change protection policy. Dr. Tope was honoured with a United Nations Environment Programme TEAP Champions Award 2007, a US EPA Best-of the Best Stratospheric Ozone Layer Protection Award 2007, and a US EPA Stratospheric Ozone Layer Protection Award 1997. She also received acknowledgement for her contributions to the scientific and technical reports that earned the Intergovernmental Panel on Climate Change the 2007 Nobel Peace Prize shared with Al Gore. She has recently worked on a United Nations Environment Programme (UNEP) project involving investment metrics for identifying technology that minimizes climate and other impacts when replacing ozone-depleting and high-GWP substances.

Dr. Jannie Van Deventer

Jannie van Deventer was educated in South Africa, where he was Head of Chemical Engineering at the University of Stellenbosch. In 1995, Jannie and his family immigrated to Australia where he became Professor of Mineral and Process Engineering at the University of Melbourne, serving as Dean of Engineering from 2003 to 2007. He has been an Honorary Professorial Fellow since 2010, and continues his research into geopolymers and mineral processing. Jannie holds honours degrees in chemical engineering and finance, and three doctorates in chemical engineering, mineral processing and business economics. His publication record of 450 papers includes 240 journal papers. He regularly gives keynote talks and serves on the editorial board of four journals. Jannie's international reputation in both mineral processing and geopolymers has been the basis of several awards. He is the Chair of the International Union of Testing and Research Laboratories for Materials and Structures (RILEM) Technical Committee on Alkali Activated Materials. Jannie has commercialized technologies in mineral processing and computer vision. Since 2006, Jannie has been the Chief Executive Officer of Zeobond, which is commercializing low carbon geopolymer concrete products. Zeobond operates a pre-mix and a pre-cast plant and has licensing and joint venture agreements in Australia, China, the U.S. and UAE.

Professor Masaaki Yamabe

Professor Yamabe has served on the Montreal Protocol Technology and Economic Assessment Panel (TEAP) since 1990 and has been co-chair of the Chemicals Technical Options Committee (CTOC) since 2005. He also served as a Coordinating Lead Author of Chapter 10 in the "IPCC/TEAP Special Report Safeguarding the Ozone Layer and the Global Climate system: Issues on Related to Hydrofluorocarbons and Perfluorocarbons" in 2005. He had long been involved in the research and development of fluorinated chemicals in Asahi Glass Company and was a Director of Central Research and a Member of the Board in Asahi Glass Company from 1997 to 1999. Professor Yamabe is the inventor of HCFC-225, which is a transitional substance under the Montreal Protocol in the phase-out of ozone-depleting substances and is a substitute for CFC-113 in solvent applications. He was invited in 2001 to the National Institute of Advanced Industrial

Science and Technology (AIST) as Research Director. He also served as Research Coordinator for Energy and Environmental Technologies in AIST during 2004-2009. He is now a research advisor in AIST. In 1997, he was awarded the Best of the Best Stratospheric Ozone Protection Award from the United States Environmental Protection Agency and the United Nations Environment Program Technology & Economic Assessment Panel (TEAP) Champion Award in 2007.

Dr. John Wilkinson

Following a varied career, including experience in analytical chemistry, research and development, government regulation, and lobbying at both the state and federal levels, John Wilkinson Consulting continues John's three decades representing corporations in their efforts to participate in the creation of effective environmental regulations. He recently served as a team leader in a World Bank sponsored CTC (carbon tetrachloride) verification process throughout China. He consulted on the use of CTC in the chlor-alkali industry. For several years, he was involved in the Montreal Protocol and the UNECE Persistent Organic Pollution (POPs) processes. He has been a member of UNEP's technical committees dealing with ozone depletion and in UNECE's POPs criteria. He has participated in the Canadian Strategic Options Process on wood preservation. He also worked on EPA's pesticide re-registration matters related to the wood preservative pentachlorophenol, and chlorine used as a disinfectant. John has worked for two chemical companies for approximately 40 years. He holds a B.S. and M.S. in chemistry.

Dr. Oran Young

Oran Young is a professor at the Bren School of Environmental Science & Management at the University of California, Santa Barbara. Dr. Young also serves as Co-Director (with Durwood Zaelke and Matthew Stilwell) of the Program on Governance for Sustainable Development at the Bren School, specializing in the analysis of environmental institutions with particular reference to international regimes. He served for six years as Founding Chair of the Committee on the Human Dimensions of Global Change of the National Academy of Sciences and chaired the Scientific Steering Committee of the international project on the Institutional Dimensions of Global Environmental Change (IDGEC). An expert on Arctic issues, Dr. Young served as Vice-president of the International Arctic Science Committee, Chair of the Board of Governors of the University of the Arctic, and Co-chair of the Arctic Human Development Report. He presently chairs the Scientific Committee of the International Human Dimensions Programme on Global Environmental Change (IHDP). The more than 20 books he has authored include *The Institutional Dimensions of Environmental Change and Governance in World Affairs* and the forthcoming *Institutional Dynamics: Emergent Patterns in International Environmental Governance*.

UCSB SCIENCE, TECHNOLOGY & ECONOMICS EXPERTS

Seascape Meeting Participants

Dr. Michael Doherty

Michael F. Doherty is Professor and Chair of the Chemical Engineering Department at the University of California Santa Barbara. He received his B.Sc. in Chemical

Engineering from Imperial College, University of London in 1973, and his Ph.D. in Chemical Engineering from Trinity College, University of Cambridge in 1977. His research interests are in process design together with the associated chemical sciences necessary to support the design activity. He has published extensively on design and synthesis of non-ideal separation systems, especially the coupling of separation with chemical reaction, and crystallization of organic materials from solution. He is the holder of four patents, has published over 200 technical papers, and one textbook. He has received numerous honours and awards for his teaching and research. Dr. Doherty has served as a consultant for many multinational companies in the area of process design & separation technology, and as a member of the Corporate Technical Advisory Boards for The Dow Chemical Company and Rhone-Poulenc.

Dr. Roland Geyer

Roland Geyer is Assistant Professor at the Bren School of Environmental Science and Management, University of California at Santa Barbara. Prior to this appointment, he held positions as research fellow at the Centre for Environmental Strategy, University of Surrey, UK, research associate at the Centre for the Management of Environmental Resources, INSEAD, France, and consultant in financial risk management for AMS (now part of CGI) in Germany. Since 1998 he has worked with a wide range of governmental institutions, trade associations, and companies on environmental sustainability issues. In his research he uses the approaches and methods of industrial ecology, such as life cycle assessment and material flow analysis, to quantify the environmental performance and improvement potential of production and consumption systems. Roland also combines these approaches with research methods from production and operations management in order to explore the relationship between the environmental and economic performance of such systems. He has a graduate degree in theoretical physics and a PhD in engineering.

Dr. Charles Kolstad

Charles Kolstad is an internationally known economist who once served as a Peace Corps volunteer in Ghana and has taught at universities in the U.S, Russia, and Belgium. He is interested in the role information plays in environmental decision-making and regulation, and does much of his applied work in the area of climate change and energy markets. He was a lead author for the Intergovernmental Panel on Climate Change (co-recipient of the 2007 Nobel Peace Prize), was a member of the National Academy of Sciences committee charged with evaluating the U.S. Climate Change Research Program, and is an advisor to the California Air Resources Board. He is a former president of the Association of Environmental and Resource Economists, and editor of the journal *Review of Environmental Economics & Policy*. His more than 100 publications include the undergraduate text *Environmental Economics*. He is currently chair of the UCSB Department of Economics and co-director of the newly established UC Center for Energy & Environmental Economics, a joint undertaking of UC Berkeley and UCSB. He is a University Fellow at Resources for the Future and a Research Associate at the National Bureau of Economic Research.

Dr. Anjana Meel

Dr. Anjana Meel is currently working on carbon mineralization as a researcher in the group managed by Professor Mike Doherty at the University of California, Santa Barbara. She holds M.Sc. and Ph.D. degrees both in Chemical and Biomolecular Engineering from the University of Pennsylvania, gained under the supervision of Professor Warren D. Seider. Dr. Meel's thesis work focused on dynamic risk assessment of inherently safe chemical processes using Bayesian Theory. She obtained Bachelor's and Master's of Technology degrees in chemical engineering from the Indian Institute of Technology (IIT), Bombay, specializing in Process System Design and Engineering. She worked at The Dow Chemical Company (formerly Rohm and Haas Company) for two and half years in various functions and business units, including research, process development, manufacturing, and supply chain.