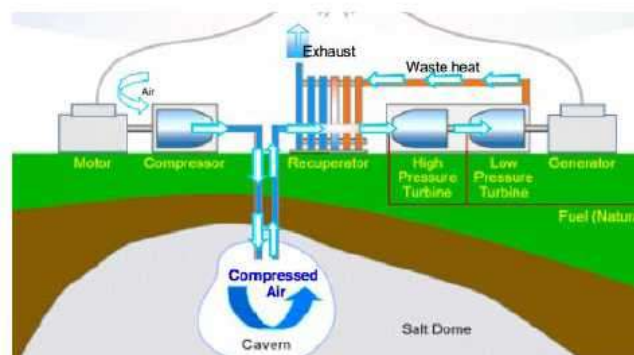




# Integrating Wind-Solar-CAES

Columbia University

2<sup>nd</sup> Compressed Air Energy Storage (CAES) Conference & Workshop



## PROGRAM

CAES 2010 Conference at Columbia University

NEW YORK CITY, OCTOBER 20<sup>th</sup>, 2010

### Location:

Davis Auditorium, Schapiro Center for Engineering and Physical Science Research  
520 West 120<sup>th</sup> St. (between Broadway and Amsterdam Avenue), New York City

**Sponsored by: New York State Energy Research and Development Authority (NYSERDA)**

**Organized by:**



Speakers  
CAES 2010 Conference



Archer, Cristina



Bailey, Bill



Bauer, Stephen



Cavallo, Alfred



Denholm, Paul



Drury, Easan



Fthenakis,  
Vasilis



Haaren, Rob van



Havel, Timothy



Kou, Li



Lucas, George



Mason, James



Miller, Harry



Nakhamkin,  
Michael



Nikolakakis,  
Thomas



Oldenburg,  
Curtis



Schinker,  
Robert



Simos, Nick



Steeley, William



Succar, Samir



Torpey, Mark



Wolf, Daniel



Zunft, Stefan

**WEDNESDAY, OCTOBER 20<sup>TH</sup>, 2010**

**8:15 AM Breakfast and Registration Material Pick-up**  
**(Lobby of Davis Auditorium –see map in back cover)**

**8:45 AM Welcoming Address:**

**Klaus Lackner, Chair, Earth and Environmental Engineering**  
**Vasilis Fthenakis, Director, Center for Life Cycle Analysis**

**Keynote Address: New York State Energy Planning**

**Mark R. Torpey, NYS Energy Research and Development Authority (NYSERDA)**

Mark currently serves as the Director of R&D at the New York State Energy Research and Development Authority (NYSERDA) where he manages the power systems, transportation, environmental and business development programs. Mark is also responsible for managing New York State's Renewable Portfolio Standard (RPS) initiative with an aggressive target to produce 30% of the State's electric energy consumption with renewable resources by 2015. Mark has been an active member of Governor Paterson's Climate Action Council which is responsible for developing a policy framework to achieve an 80% reduction in greenhouse gas emissions below 1990 levels by 2050 (a.k.a. the "80 by 50" Challenge). Mark recently helped establish the New York State Smart Grid Consortium (a not-for-profit 501 (c)6 corporation) to develop a long-term implementation strategy for deploying the "smart grid" in NYS. Mark is a Fellow of the American Society of Mechanical Engineers.

**Solar Energy Prospects in the U.S.**

**Vasilis Fthenakis, Columbia University and Brookhaven National Laboratory**

Prof. Vasilis Fthenakis is the founder and director of the Center for Life Cycle Analysis (CLCA) at Columbia University. He also leads the National Photovoltaics (PV) Environmental Research Center operating at Brookhaven National Lab (BNL) under the auspices of the DOE since 1982. The centers are synergistically engaging students and researchers in the two institutions and have formed close collaborations with the U.S. PV industry, the European PV Industry Association and several European Universities on the LCA area. He leads the International Energy Agency (IEA) Task on PV Environmental Health and Safety. He is the author or coauthor of 250 publications on energy and the environment and a Fellow of the American Institute of Chemical Engineers and of the International Energy Foundation.

## TECHNOLOGY STATUS

SESSION CHAIR: VASILIS FTHENAKIS, COLUMBIA UNIVERSITY

**9:20 AM Dresser-Rand SmartCAES Technology**

**George Lucas, Harry Miller, Dresser-Rand**

We will present an overview of the experience with the machinery provided for the Power South 110MW CAES Plant as well as numerous enhancements made to the original equipment configuration which comprise the Dresser-Rand current SmartCAES 135 MW solution. Characteristics such as equipment ramp rate, turndown, heat rate, operational flexibility, and reliability will be discussed.

George M. Lucas has 34 years of experience in the design, analysis, and operation and maintenance of turbines, generators, and other large rotating equipment. George received B. Sc. and M. Eng. degrees from Cornell and started his professional career as a Design Engineer with FMC's Coffin Turbo-Pump Operation. He subsequently joined Dresser-Rand's Steam Turbine Division in 1978, where he held a number of positions including Director of Engineering. He led the design team responsible for the design and manufacture of the gas turbines for Alabama Electric Cooperative's McIntosh CAES plant and continues to support the CAES products, including developments and enhancements reflected in Dresser-Rand's SMARTCAES Solutions.

Harry Miller is the Product Manager- Marketing of Turbo Products at Dresser-Rand. His career in turbomachinery began 35 years ago with Dresser Clark, and he has held a variety of Design Engineering and Marketing positions, most recently, being Manager of Development Engineering and Leader of the DATUM Multistage Centrifugal Compressor Development Team. He received a B.S.M.E. degree from Northeastern University, and a M.B.A. degree from Lehigh University. His areas of expertise include turbo compressor and gas turbine design and application. He has authored several technical papers and has contributed to several patents, and has won the Dresser Industries Annual Technical Achievement Award.

**9:40 AM      180 MW and 300 MW Advanced 2nd Generation CAES Plants to Support Renewable Energy and Smart Grid**

**M. Nakhamkin, B. Kraft, R. Daniel, P. Conroy, *Energy Storage and Power***  
**R. Schainker, *EPRI***

We will present performance, operational and economic characteristics of 180 MW and 300 MW projects based on the 2nd Generation of the Compressed Air Energy Storage Technology (CAES2). These projects received DOE stimulus funds and are in initial execution stage. We will also present on upcoming 15 MW and 450 MW CAES projects. Compared to the first generation CAES technology in Alabama, the CAES2 technology is estimated to be less expensive to build, has lower operating costs, and has more flexible operating characteristics. The turbomachinery in this new CAES plant design uses standard multi-size compressors, new or existing combustion turbines and separate expansion turbines. The emissions from this type of CAES plant has NO<sub>x</sub> levels in the single digits due to very low heat rate of approximately 3800 Btu/kWh and the storage efficiency is in the 80% to 90% range.

Dr. Michael Nakhamkin, PE is the Chief Technology Officer and Founder of ES&P. He has been the preeminent voice in the power industry on compressed air energy storage for over two decades. Dr. Nakhamkin holds 16 patents that form the basis of ES&P's CAES and Power Augmentation technologies. In addition, he has supervised the development, engineering and execution of numerous combustion turbine and natural gas-based power projects worldwide during the course of his career. At Gibbs & Hill Dr. Nakhamkin was the Chief Engineer where he oversaw a 5,000 plus person engineering organization.

**10:10 AM      Adiabatic CAES: Opportunities and Challenges**

**Stefan Zunft, *German Aerospace Center (DLR)***

An increasing share of electricity from renewable sources is the stated aim of national and European energy policies. However, a grid-compatible integration of this fluctuating energy production to the European electricity systems is expected to be an issue in the mid-term – in particular in coast regions close to offshore wind farms. Large-scale storage technologies can substantially mitigate the expected shortages of balancing and transport capacities. The concept of Adiabatic Compressed Air Energy Storage is a promising candidate, representing a locally emission-free, pure storage technology with high storage efficiency and a high application potential in Europe. This talk will outline the technology and give an overview on past and present activities for this technology.

Dr. Stefan Zunft studied at the Universities of Hannover and Stuttgart, graduated as a mechanical engineer from the University of Stuttgart in 1991 and received his Ph.D. degree in 2002. In 1991, he joined the Institute of Technical Thermodynamics of the German Aerospace Center (DLR). His research interests and his previous work in numerous international projects have been focussed on solar thermal energy and rational energy use in industrial processes. Currently, he is a research area manager of the institute's industrial heat transfer and heat storage activities.

**10:30 AM      Adsorption-Enhanced Compressed Air Energy Storage**

**Timothy F. Havel, *Energy Compression Inc.***

Adsorption-Enhanced Compressed Air Energy Storage (AE-CAES) uses an adsorbent for air to reduce the volume needed to store a given quantity of compressed air at pressures well below those previously regarded as practical for CAES. This can not only free it from the geological or topographical constraints of underground or underwater air storage, but also has the potential to substantially reduce its cost compared with other forms of "surface" CAES in several ways: a) the cost of the tank needed to confine the air is reduced along with its volume; b) the cost of efficient air

compressors and expanders goes down with the pressure they must handle; c) the use of an adsorbent changes the effective equation of state of the system, making it practical to operate it at essentially constant pressure by cycling the temperature instead; d) whereas existing high-pressure CAES facilities use the combustion of natural gas to reheat the expanding air, AE-CAES would need only low-temperature (ca. 100°C) heat.

Dr. Tim Havel received his PhD in Biophysics from the Univ. of California Berkeley in 1982. He did postdoctoral work at the Swiss Federal Technical Institute in Zürich and subsequently held positions at the Scripps Research Foundation in La Jolla, the University of Michigan in Ann Arbor, the Harvard Medical School in Boston and the Dept. of Nuclear Science and Engineering at MIT, where he helped to demonstrate the first prototypes of quantum computers by means of NMR. He is presently an Affiliate of the MIT Dept. of Mechanical Engineering, assisting with the development of “supersprings” based on carbon nanotubes, and the CTO and Founder of a nanotechnology-based “clean-tech” company, Energy Compression Inc.

**10:50 AM Coffee Break**

**TECHO-ECONOMIC INTEGRATION STUDIES**

**SESSION CHAIR: JOHN P. MARTIN, NYSERDA**

**11:10 AM Insights from EPRI’s CAES Economic Benefit-Cost Analyses**

**Robert B. Schainker, William Steeley, *EPRI***

Economic value justification to build energy storage plants are often focused on arbitrage benefits: buying low and selling high. However, the energy arbitrage benefit stream is only one of a number of potential benefit streams provided by a CAES plant—perhaps not even the most significant benefit stream. This paper summarizes a number of EPRI benefit-to-cost analyses on CAES plants, with a special focus on identifying a full set of benefit types CAES plant offer and how that these benefit types are quantified and then compared to a CAES plants capital costs. As such, this type of analysis is useful to utility decision makers when making CAES plant “build” decisions. The types of benefit types investigated, beyond arbitrage benefits, include capacity credit, ancillary services (including frequency regulation, spinning reserve, ramping, VAR support, and black-start capability), renewable support, and CO<sub>2</sub> reduction benefits. The paper will conclude with estimates (high and low) for each benefit type based on a wide set of EPRI utility analyses.

Dr. Robert Schainker is Senior Technical Executive in the EPRI Power Delivery and Utilization Sector. His research activities cover energy storage, generation and transmission technologies with special focus on compressed air energy storage, battery energy storage, strategic planning, electric grid dynamic stability, transmission substations, high voltage power flow controllers, transformers, and power quality.

William (Bill) Steeley is Senior Project Manager in the Energy Storage and Distributed Energy Resources Program at the Electric Power Research Institute. His responsibilities include development of several high profile projects in the Energy Storage and Distributed Generation Program as well as in the CAES Demo area. His research areas include: energy storage technology assessments & evaluations, economic analyses, field demonstration projects, utility case studies and integration of energy storage in the emerging smart-grid. A major thrust of his work has centered on the proper electrical interconnection and integration of distributed generation and energy storage systems into the electric utility T&D system.

**11:30 AM New York Power Authority’s Investigation of Compressed Air Energy Storage in New York State**

**Li Kou, Guy Sliker, *New York Power Authority***

**Robert Schainker, *EPRI***

New York Power Authority (NYPA) in collaboration with Electric Power Research Institute (EPRI) performed a feasibility study of a utility-scale underground compressed air energy storage (CAES) facility in New York State. The proposed plant has 300MW generation capacity with 10 hours storage capacity. The feasibility study evaluated the engineering, economics and geologic siting of such a plant. A second generation CAES plant design was chosen which avoids the need for an expensive,

high-pressure combustor, that in turn helps reduce CO<sub>2</sub> emissions per kWh. It is estimated that the second generation CAES design will be about 25 – 30% less expensive in capital and 10% less in operational costs than a first generation design. Based on NYPA's forecast on fuel costs, load profiles, and hourly electricity prices, it is shown that arbitrage benefits alone serve to offset capital costs for a 300MW CAES plant in NYC region. However, for the Central region, ancillary and capacity benefits will be critical components of the benefit mix. The focus of the present study is on salt mine opportunities in NYS.

Dr. Li Kou is the Senior Research and Technology Development Engineer for New York Power Authority. Dr. Kou joined NYPA in August 2007 and has been working on evaluation and implementation of various technologies, including solar, distributed wind, energy storage, biomass and waste-to-energy. Prior to joining NYPA, Dr. Kou worked for Siemens Power Generation on research and development of Solid Oxide Fuel Cells for 6 years. She holds a Ph.D. and M.S. degree in Chemical Engineering from Illinois Institute of Technology and holds a B.S. in Chemical Engineering from Zhejiang University, China.

## **11:50 AM Energy Storage and Geographic Aggregation: Mutually Reinforcing Strategies for Integrating Wind Power**

**Samir Succar, NRDC**

**Robert H. Williams, Princeton University**

The incorporation of wind resource aggregation into the optimization framework for a hybrid wind/CAES baseload power facility demonstrates that strategies for variable energy resource integration can be mutually reinforcing. By leveraging the geographic diversity of wind energy resources, the cost and emissions of baseload wind systems can be significantly reduced as a result of reduced capital cost requirements for balancing aggregated wind resources. Specifically, re-optimizing the CAES configuration, including the relative capacity of the compression and turboexpander trains as well as the storage capacity of the geologic reservoir, in response to changes in wind resource characteristics, yields significant capital cost reductions for the CAES system which translates into lower levelized cost for baseload power from wind/CAES and lower GHG emissions. This approach results in significantly reduced carbon entry prices for wind/CAES relative to alternative low carbon baseload systems.

Samir Succar is an Energy Analyst working in NRDC's New York office as part of the Center for Market Innovation. Samir's work focuses on the integration of renewable energy and the role of T&D infrastructure upgrades, demand resources, energy storage and other enabling technologies. He received a BA from Oberlin College and earned a Ph.D. in Electrical Engineering at Princeton University researching the technical and economic feasibility of utility scale wind coupled to bulk energy storage systems.

## **12:10 PM CAES Studies at the National Renewable Energy Laboratory**

**Paul Denholm, Easan Drury, NREL**

NREL is involved in several projects to analyze the role of CAES in high-renewable futures. This paper will review these activities which include:

- a) Analysis of the value of CAES in wholesale energy markets considering co-optimization with ancillary services. These studies include the part-load performance of CAES plants, as well as the constraints on operating the expansion turbine while offering spinning reserves. Several advanced cycles which improve performance or lower capital cost are also considered.
- b) The value of CAES in reducing transmission constraints for remote wind and solar projects. Given the difficulty of transmission siting, a number of analyses have proposed combining wind energy and storage to increase transmission line loading and reduce transmission costs. This study quantifies the benefit of co-location considering the tradeoffs between reduced transmission costs and increased transmission constraints on CAES operation
- c) The role of CAES in reducing wind and solar curtailment at high penetration. At extremely high penetration of variable sources, wind and solar generation may become unusable due to limited



coincidence between energy supply and demand. Several studies have examined the value of CAES in reducing curtailment and increasing the penetration of variable generation into the U.S. power grid.

Dr. Paul Denholm is a Senior Energy Analyst in the Strategic Energy Analysis Center at the National Renewable Energy Laboratory. His research interests include examining the technical, economic, and environmental benefits and impacts of large-scale deployment of renewable electricity generation, including the role of enabling technologies such as energy storage, plug-in hybrid electric vehicles and long distance transmission. He holds a B.S. in physics from James Madison University, an M.S. in instrumentation physics from the University of Utah, and Ph.D. in Environmental Studies and Energy Analysis from the University of Wisconsin-Madison.

Dr. Easan Drury is an Energy Analyst in the Strategic Energy Analysis Center at the National Renewable Energy Laboratory. His research interests include developing market penetration models for renewable technologies, and examining the technical and economic impacts of large-scale renewable energy deployment. He holds a B.A. in physics from the University of California, Berkeley, and a M.S. and Ph.D. in Engineering Sciences from Harvard University.

**12.30 PM**

**Lunch**

**(The Low Memorial Library –see map in back cover)**

**2:00 PM**

**Renewable and Sustainable Energy Research at the Center for Life Cycle Analysis**

**Vasilis Fthenakis, *Columbia University***

The Center for Life Cycle Analysis (CLCA) was formed in May 2006 with the mission of guiding technology and energy policy decisions with data-based, well balanced and transparent descriptions of the environmental profiles of energy systems.

The CLCA research on renewable and sustainable energy systems includes the following topics: 1) Thin-Film PV Life Cycle Analysis; 2) High-Concentration PV LCA; 3) Nano-material PV LCA; 4) Building Integrated PV LCA; 5) PV and CSP LCA Harmonization; 6) Solar, Nuclear and Fossil-fuel Cycles Comparative LCA; 7) Power Industry Supply Chain Hybrid LCA; 8) Minimizing Large PV Plant Conflicts with Wild-Life; 9) PV Recycling Technologies; 10) PV Recycling Cost Optimization; 11) Modeling the Synergy of PV and Wind; 12) Modeling PV-CAES Plants; 13) GIS-based Models of Wind and Solar Plant Sites; 14) Effects of Clouds in Large Scale PV Production; 15) Modeling Large Scale Storage for Solar and Wind Power.

**2:10 PM**

**GIS-based tools for optimizing site selection for wind and solar power plants**

**Rob van Haaren, Vasilis Fthenakis, *Columbia University***

Site selection is enabled via GIS-based tools and detailed simulations are based on hourly performance and load data for specific regions. The architecture of these models and some preliminary results of applying those in NYS will be presented.

Rob van Haaren finished his BS at the University of Technology in Eindhoven, the Netherlands. After this, he came to Columbia University to pursue his MS in Earth Resources Engineering and wrote his thesis on Life-Cycle Analysis of different composting methods. Van Haaren is now a PhD student at the same department, working under the supervision of Professor Fthenakis at the Center for Life-Cycle Analysis on Energy Storage in the electricity grid. In this research, his aim is to quantify the costs and environmental impact benefits from energy storage methods under high penetration of renewable electricity generation on the grid.

**2:20 PM**

**Modeling co-optimization of wind and solar penetration and integration with CAES systems**

**Thomas Nikolakakis, Vasilis Fthenakis, *Columbia University***

Studies at the Center for Life Cycle Analysis focus on assessing the environmental impacts of solar systems and compare those with the life-cycle impacts of conventional fuel cycles in various renewable energy penetration scenarios. In conjunction, we develop models that enable accurate

determinations of the technically and economically feasible degrees of penetration of solar and wind power generation for satisfying initially peak and subsequently base load demands.

Thomas Nikolakakis is currently a PhD student in the department of Earth and Environmental Engineering and a Junior researcher in the Center of Life Cycle Analysis at Columbia University. He obtained his M.S degree at Columbia University and his BS in Environmental Engineering from the Technical University of Crete, Chania, Greece, where he graduated first in the Class of 2007. In his undergraduate thesis he studied the fate and transport of copper compounds in the ground. His current research interests include: Modeling of performance of Solar and Wind energy systems; Large scale energy storage in the form of CAES; Life Cycle Analysis.

**2:40 PM**

## **Multi-functional Application of Co-located Wind Power and Adiabatic CAES**

**Daniel Wolf, Annedore Kanngießner, Christian Dötsch, Fraunhofer Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT**

**Roland Span, Ruhr-Universität Bochum, Lehrstuhl für Thermodynamik**

CAES plants are custom made installations that can be adapted to a certain degree to their intended application. For adiabatic CAES plants these degrees of freedom are represented by the heat storage concept and dimensioning as well as by the turbo machinery's general arrangement and part load performance. The presentation gives a detailed analysis of an application of A-CAES plant co-located with a wind farm on a 110 kV grid. It entails determination of the optimal size of a wind farm and A-CAES plant for given project boundary conditions, and the operational regime of an optimized system. A Generic Optimization Model for Energy Storage (GOMES®), a high resolution optimization model has been developed and applied. It was also examined how a multifunctional storage operation can be realized comprising direct wind energy storage as well as spot market and tertiary reserve market participation simultaneously. It is shown that such a multifunctional operation improves the profitability of CAES plants compared to singular operation at only one market.

Daniel Wolf is a research associate at the Fraunhofer Institute UMSICHT in the department Energy-Efficiency-Technologies. He studied mechanical and process engineering at the Technische Universität Darmstadt, Politécnica de Madrid and Technische Universität Berlin. In 2005 he worked as a junior researcher with Prof. Tsatsaronis at the Institute for Energy Engineering at the Technische Universität Berlin on energy systems modeling and optimization. In 2007 he joined the Fraunhofer Institute UMSICHT where his work focuses on thermal design and optimization of CAES.

**3:00 PM**

## **Firming and Shaping Wind Power: Comparison of CAES and Conventional Natural Gas Power Plants within the National Energy Independence Plan**

**James Mason, Cristina Archer, Bill Bailey, NEIP**

The National Energy Independence Plan, NEIP, recognizes that America has about a decade before fossil fuels, starting with oil, become serially unaffordable. Working within this ten-year constraint, the NEIP's interactive models illustrate conversion of U.S. energy sources to lowest cost renewable electricity using wind in the Midwest and PV in the Southwest. Wind and solar intermittency is resolved by coupling wind and PV plants to compressed air energy storage \*(CAES) power plants. Electricity is distributed to local markets nationwide via a national HVDC grid, flat-priced at about current levels. A recent DOE study of wind power supplying 20 % of the nation's electricity states that energy storage power plants are not needed. Instead, the DOE study uses conventional natural gas power plants to address wind's intermittency. This approach will increase U.S. natural gas consumption by 17% at a 20% wind penetration level and will likely create natural gas supply/demand problems in the long-term. In contrast, coupled wind-CAES plants consume 75% less natural gas. Moreover, less than 300 GW of wind capacity coupled to CAES plants can provide DOE's projected need for 100 GW of new base load power plants by 2030.

James Mason is Director of the American Solar Action Plan in Farmingdale, New York. He received a Ph.D. in economic sociology from Cornell University in 1996 and a Master's in environmental sociology from the University of New Orleans in 1991. Mason has published numerous peer-reviewed energy and environmental studies.

Cristina L. Archer is an assistant professor of energy, meteorology, and environmental science in the Department of Geological and Environmental Science of California State University Chico, as well as a consulting assistant professor in the Department of Civil and Environmental Engineering at Stanford University. Her research interests include wind power,



meteorology, air quality, climate change, and numerical modeling. She received her Ph.D. in Civil and Environmental Engineering from Stanford University in 2004.

Bill Bailey is a graduate of West Point with 22 years' service as an Army Officer. His active military experience included traditional Infantry assignments, two tours in Viet Nam, national level intelligence, and academe. Since 1980 he has held positions in academe, business, and in historic structures' real estate development. He currently heads Fiscal Associates, a quantitative market analytic firm. Since early 2008, concerned about the national security implications of fossil fuel use, he has been involved with a group of scientists, engineers, and businessmen in the development of the NEIP, the National Energy Independence Plan.

**3:20 PM Unconventional Gas: A Bridge to the Future?**

**Alfred Cavallo, *Energy Consultant***

In the late 1980s low natural gas prices made renewable energy extremely unattractive economically; storage technologies such as CAES were virtually forgotten. Some portrayed this in a positive sense, claiming that natural gas would be “a bridge to the future”, facilitating a smooth transition to renewable energy systems and technologies. However, nothing of the sort happened. Today, advances in drilling and rock fracturing technologies have allowed a large increase in unconventional natural gas production from low permeability organic-rich shale deposits; a vast new resource appears to be accessible. Once again, natural gas prices are low and once again natural gas is being termed a “bridging fuel” and a “game changer”. US proven gas reserves are now 250 Tcf, the highest they have been in 35 years, and US proven plus potential resources are now given as about 2,000 Tcf, or a 100 year supply at current production rates. However, while gas supplies appear to be abundant, natural gas prices are decoupled from supply over the intermediate and long term and are set by petroleum prices; typically the oil to gas price ratio on a per unit energy basis is about 1.5. Economic development in China and the Far East continues, with sales of automobiles rising rapidly; petroleum demand is expected to be supply constrained by the end of this decade. Crude oil prices will need to increase to bring supply in line with demand (to at least \$150/barrel); this indicates natural gas prices around \$17/million Btu ( $\pm 25\%$ ). Petroleum and natural gas price setting mechanisms will be reviewed and strategies proposed to deal with the current temporary low natural gas price environment.

Dr. Alfred Cavallo did his graduate studies at the University of Wisconsin in plasma physics, and worked for the Max Planck Institute, the French Atomic Energy Commission, and the Princeton Plasma Physics Laboratory in the experimental fusion program. He then moved to the Center for Energy and Environmental Studies at Princeton University, and developed the concept of transforming intermittent wind energy to a reliable power source that is technically and economically competitive with current generators. He has also done research on aerosols and radon risk assessment for the US Department of Energy. His current interests are resource constraints and energy policy.

**3:40 PM Coffee Break**

**RISKS & CHALLENGES IN UNDERGROUND RESERVOIRS**

**SESSION CHAIR: VASILIS FTHENAKIS, COLUMBIA UNIVERSITY AND BROOKHAVEN NATIONAL LABORATORY**

**4:00 PM Potential Risks Associated with Underground CAES**

**S.J. Bauer, T.W. Pfeifle, *Sandia National Laboratories***

Presently, salt caverns represent the only proven underground storage used for CAES, but not in a mode where renewable energy sources are supported. Reservoirs, both depleted natural gas and aquifers represent other potential underground storage vessels for CAES, however, neither has yet to be demonstrated as a functional/operational storage media for compressed air.

Renewable support using CAES implies that the storage “container”, may experience small irregular pressure cycling, subjecting the storage media to repeated stress changes. These repetitive stress changes could degrade the mechanical integrity of salt (cavern storage), as well as sedimentary rock (reservoir storage). Also, air (containing O<sub>2</sub>), may affect the composition and function of the microbial community in subsurface storage (aquifer) reservoirs. The impact will be strongest in reducing environments, particularly if the formation contains pyrite and little carbonate mineral mass. This impact has the potential to negatively affect groundwater quality and the long-term efficiency of the CAES facility. Furthermore, air introduced into a depleted natural gas reservoir presents a situation where ignition/explosion potential in a depleted natural gas reservoir may exist.

We will present the results of initial studies that begin to address these potential underground risks to CAES: experimental deformation of salt in cyclic loading, assessment of biologic growth potential in an aquifer resulting from air cycling, and assessment of ignition/explosion potential in a depleted reservoir from air cycling associated with CAES.

Stephen Bauer of Sandia National Laboratories manages the Geomechanics Lab, where pressures of 150ksi, temperatures of a few hundred degrees C, fluid flow through capabilities, and a 10 order of magnitude strain rate range are used to simulate many in situ earthen conditions. Steve has worked on lab and field testing as well as analyses projects addressing underground storage of natural gas, hydrogen, crude oil, air, and radioactive waste in hard rock, salt and reservoirs (sedimentary rock).

**4:20 PM**

### **On the Use of Large-scale Multi-physics Modeling to Address Potential Vulnerabilities Associated with Air/Gas Mixtures in CAES**

**Nick Simos**, *Brookhaven National Laboratory*

We present an overview of modeling for addressing the CAES vulnerability in natural gas/air systems and discuss the results of complex simulations of extreme scenarios in CAES systems. By relying on advanced capabilities in analyzing large-scale complex systems which involve gas mixtures enclosed in a multitude of rock formations and the ability to simulate explosion- and/or detonation-type events through the use of multi-physics formulation, the resilience of the overall CAES system to intense but extremely rare events will be assessed. In particular, through a detailed representation of the air/gas mixture volume and the surrounding rock in the finite element space and the use of arbitrary Lagrangian-Eulerian formulation which enables the mechanics at their interface different scenarios are analyzed to assess the consequences on the cavern walls. Given the great variability in rock properties that exist between different sites of CAES systems, the rock failure potential as a function of the type is assessed. Realistic scenarios which do not involve the potential combustion or even explosion within the gas/air mixture such as the sudden drop of pressure in the reservoir as a result of uncontrolled or unplanned release, which will constitute a dynamic event, are also being evaluated.

Dr. Simos joined the Nuclear Energy Department at Brookhaven National Laboratory in 1989 and promoted to scientist in 1993 studying seismic safety of nuclear installations. In 1996 he moved to Los Alamos and the accelerator for tritium production. In 1999 he joined the Spallation Neutron Source project in charge of beam collimation. He is a member of the Neutrino Factory collaboration and the Long Baseline Neutrino Experiment leading the experimental effort on high-power accelerator targets. He has been principal investigator on vulnerability of critical infrastructure for DHS. He currently holds a joint appointment with the Photon Science Directorate.

**4:40- 5 PM**

### **Use of Carbon Dioxide as a Cushion Gas for CAES**

**Curtis M. Oldenburg**, *Lehua Pan*, *Lawrence Berkeley National Laboratory*

We are investigating the advantages of using carbon dioxide (CO<sub>2</sub>) as the cushion gas for CAES. Carbon dioxide compresses non-linearly and acts like a super-cushion when the reservoir is operated around the critical pressure and near the critical temperature. This behavior allows the storage of more air (working gas) for a given reservoir size. Furthermore, an operator could receive payments for sequestering CO<sub>2</sub> under the various cap-and-trade or carbon tax policies under consideration that are aimed at lowering CO<sub>2</sub> emissions from fossil-fuel power plants and other industrial facilities. To provide the foundation for future studies of the use of CO<sub>2</sub> as a cushion gas, we have modeled the coupled hydrologic and two-phase flow aspects of standard aquifer CAES

including coupled reservoir and wellbore flow. We simulated the initial fill with air of a two-dimensional radial CAES reservoir to create the working and cushion gas bubble. Subsequently we modeled the physical processes in the reservoir and wellbore of the operation of the system using the same operational parameters as an existing cavern system. Results to date show the reservoir-wellbore system limits deliverability unless relatively large-diameter wells are used. Liquid saturation changes very little during production and injection cycles, but there is slow bleed-off of pressure as the bubble expands against the infinite aquifer over time

Curt is a Staff Scientist and Geologic Carbon Sequestration Program Lead in the Earth Sciences Division at Lawrence Berkeley National Laboratory. His area of expertise is numerical model development and applications for coupled subsurface flow and transport processes. He has worked at LBNL for 20 years in the areas of geothermal reservoir modeling, and vadose zone hydrology. For the last ten years, Curt has worked in three main areas of geologic CO<sub>2</sub> storage, (1) CO<sub>2</sub> injection for enhanced gas recovery, (2) near-surface leakage and seepage processes, and (3) CO<sub>2</sub> leakage risk assessment.

**6:00 PM**

**Conference Reception and Dinner**

**(Garden Room, 1<sup>st</sup> floor of Faculty House –see map in back cover)**

**THURSDAY, OCTOBER 21<sup>ST</sup>, 2010**

**ROUND TABLE DISCUSSION (Limited seating: Speakers and by Invitation)**

**Trustees Room, the Low Memorial Library**

<b>8:30 AM</b>	<b>Breakfast</b>
<b>9:00 AM</b>	<b>CAES R&amp;D Needs</b>
<b>10:30 AM</b>	<b>Coffee Break</b>
<b>10:45 AM</b>	<b>Business Opportunities</b>
<b>12:00 PM</b>	<b>End of Round Table Discussion</b>

**Shapiro Center**  
**CAES Meeting and Breakfast**



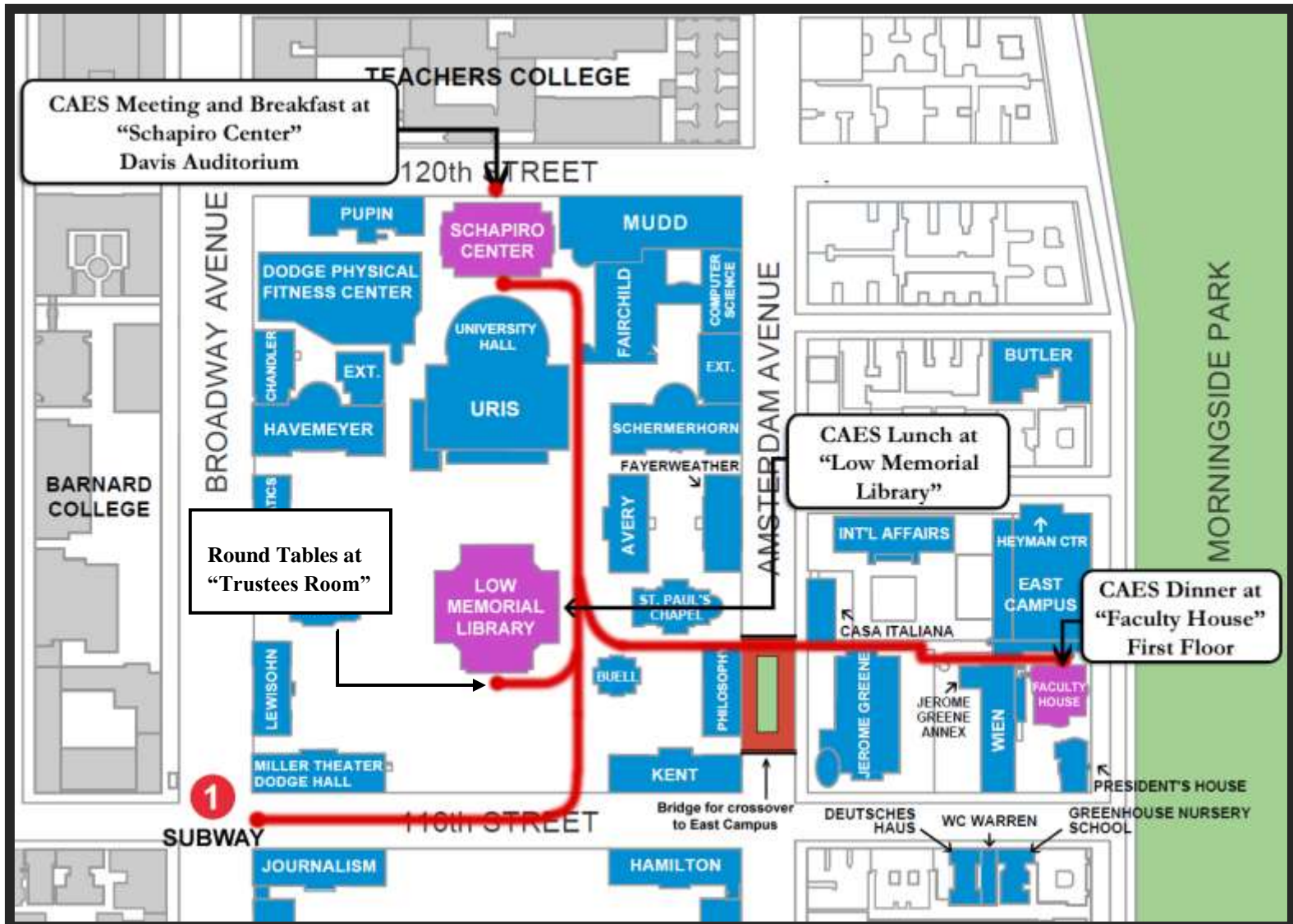
**Faculty House**  
**CAES Dinner**



**Low Memorial Library**  
**CAES Lunch & Round Tables**



## Map of Columbia University's Morningside Campus



**Directions:** Take the 1-Subway to 116<sup>th</sup> and Broadway (Columbia University Main entrance). Then follow the red line: enter the Columbia Campus and walk up the steps of Alma Mater. Pass the Low Memorial Library on the right side and walk straight ahead. Finally, take a left before the Mudd building. You will see signs outside Schapiro that point you to the entrance. Call 917-742-0095 if you need help.