# Energy for a Carbon-Constrained World

## April 3, 2017

**Andlinger Center for Energy and the Environment**

**Princeton University**

A Public Symposium Honoring

ROBERT H. WILLIAMS

*Senior Research Scientist*

on the occasion of his retirement from Princeton University

Sponsored by the Andlinger Center for Energy and the Environment, the Princeton Environmental Institute, and the School of Engineering and Applied Science

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ENERGY SYSTEMS ANALYSIS GROUP

## Robert H. Williams

**Biosketch**

Robert H. Williams shifted his research in 1970 from theoretical physics to energy systems analysis, with the aim of identifying and articulating energy technologies and strategies that offer promise in addressing the major environmental, security, and other societal challenges posed by conventional energy. He has led the Energy Systems Analysis Group during his 41-year career at Princeton University, and under the University's Carbon Mitigation Initiative, he has led the Carbon Capture Group since 2001.

His research has addressed energy end-use efficiency, industrial cogeneration, nuclear energy (especially proliferation issues), fuel cell vehicles and hydrogen for transportation, renewable energy (especially biomass, wind, and photovoltaic), $CO_2$ capture and storage for electricity generation, synthetic fuels manufacture and hydrogen production—from coal, natural gas and biomass. In recent years, he has given particular attention to $CO_2$ enhanced oil recovery as a market launch strategy for promising $CO_2$ capture technologies, to BECCS (biomass energy with carbon capture and storage), and to fossil-renewable energy synergisms in advancing low-carbon energy (especially coal/biomass with $CO_2$ capture and storage and wind/natural gas). He has also carried out research on energy technological innovation policy and has explored energy strategies from national, global, and developing country (especially China) perspectives.

Williams served on two panels (on Energy Research and Development and on International Cooperation in Energy Research, Development, Demonstration, and Deployment) of the President's Council of Advisors on Science and Technology, the Global Environment Facility's Science and Technology Advisory Panel, the UNFCCC's Intergovernmental Panel on Climate Change, the China Council for International Cooperation on Environment and Development, the Board of Directors (as a founding member) of the International Energy Initiative, and other domestic and international organizations that address energy issues. He made contributions to the World Energy Assessment, the subsequent Global Energy Assessment, the International Energy Agency's World Energy Outlook, the (Chinese) National Institute of Clean and Low Carbon Energy, the (U.S.) National Coal Council, and other domestic and international bodies.

He is a Fellow of the American Physical Society and received its Leo Szilard Award for Physics in the Public Interest (1988) for "applying physics to end-use energy efficiency and educating physicists, members of Congress, and the general public on energy conservation issues." He received the Sadi Carnot Award (1991) from the US Department of Energy for his work on energy efficiency. He received a MacArthur Prize (1993). The National Audubon Society and American Association of Engineering Societies awarded him the Joan Hodges Queneau Palladium Medal for innovative engineering solutions to environmental problems (1995). He shared the 2000 Volvo Environment Prize with Jose Goldemberg (Brazil), Thomas Johansson (Sweden), and Amulya Reddy (India)—awarded for their book *Energy for a Sustainable World*; that book's ideas on sustainability were adopted by the Brundtland Commission's report on sustainable development (*Our Common Future*).

**Education**

BS Physics, Yale University, 1962.
PhD Theoretical Physics, University of California, Berkeley, 1967.

**Professional Positions**

**1978-2017:** Senior Research Scientist, Princeton University, Center for Energy and Environmental Studies **(1978-1999):** Princeton Environmental Institute (1999-2015), and Andlinger Center for Energy and the Environment (2015-2017).
**1975-1978:** Research Scientist, Center for Energy and Environmental Studies, Princeton University.
**1974-1975:** Director of Research, Institute for Public Policy Alternatives, SUNY, Albany.
**1972-1974:** Senior Scientist, Ford Foundation's Energy Policy Project, Washington, DC
**1970-1972:** Assistant Professor, Physics, University of Michigan, Ann Arbor
**1969-1970:** Research Staff Member, Environmental Science Services Admin., Boulder, CO
**1967-1969:** Post-Doctoral Fellow, Environmental Science Services Admin., Boulder, CO

# AGENDA

## Monday, April 3, 2017 • Maeder Hall Auditorium, Andlinger Center

**7:45** **Continental Breakfast**

**8:15** **Welcome and Introductions**

**Yueh-Lin (Lynn) Loo,** Director of the Andlinger Center for Energy and the Environment, Theodora D. '78 and William H. Walton III '74 Professor in Engineering, Professor of Chemical and Biological Engineering, Princeton University

**Eric D. Larson,** Senior Research Engineer, Energy Systems Analysis Group, Andlinger Center for Energy and the Environment, Princeton University

**8:30** **Carbon Mitigation in the Context of Sustainable Development**

**Thomas B. Johansson,** Professor Emeritus, International Institute for Industrial Environmental Economics, Lund University, Sweden

**8:55** **The Past, Present, and Future of Energy Efficiency**

**Howard Geller,** Executive Director, Southwest Energy Efficiency Project, Boulder, Colorado

**9:20** **The Future of Renewable Energy: Challenges and Opportunities**

**Sam Baldwin**, Chief Science Officer, Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington D.C.

**9:45** **Break**

**Fossil Fuels in a Carbon Constrained World**

**10:10** ***Carbon Capture and Storage for a Tolerable Climate Change***

**Stefano Consonni,** Professor of Energy Engineering, Politecnico di Milano, Italy

**10:35** ***Enabling Fossil Fuels to Survive in a Carbon-Constrained World***

**Vello Kuuskraa,** President of Advanced Resources International, Inc., Arlington, Virginia

**11:00** ***Estimation of $CO_2$ Leakage along Old Wells using Numerical Models and Field Measurements***

**Michael Celia,** Theodora Shelton Pitney Professor of Environmental Studies, Professor of Civil and Environmental Engineering, Director of the Program in Environmental Engineering and Water Resources, Princeton University

**11:25** **Nuclear Power: Trapped in a Safety Quagmire**

**Frank von Hippel,** Professor of Public and International Affairs Emeritus and Senior Research Physicist, Woodrow Wilson School of Public and International Affairs, Princeton University

**11:50** **Lunch (see maps at back)**

**1:20** | **Charting a Transition to Sustainable Transportation**

**Joan Ogden,** Professor of Environmental Science and Policy, Director of the Sustainable Transportation Energy Pathway Program, Institute of Transportation Studies, University of California, Davis

**1:45** | **Overcoming Commercial Challenges for Deployment of Large-scale Low-carbon Energy Systems**

**Chris Greig,** Professor and Director of the UQ Energy Initiative and the Dow Center for Sustainable Engineering Innovation, University of Queensland, Australia

**Grid Integration of Intermittent Renewables and $CO_2$ Capture and Storage**

**2:10** | ***Climate Change and Our Future Electricity System - Europe in 2050***

**Wim Turkenburg,** Professor Emeritus of Science, Technology, and Society, Utrecht University, The Netherlands

**2:35** | ***Toward Reduced Costs for $CO_2$ Capture and Storage for Power Grids with High Levels of Intermittent Renewable Electricity***

**Robert H. Williams,** Senior Research Scientist, Energy Systems Analysis Group, Andlinger Center for Energy and the Environment, Princeton University

**3:00** | **Break**

**3:30** | **Panel discussion: Are U.S. Policy Advances to Mitigate Climate Change Possible in the Trump Era?**

**Robert H. Socolow,** Professor Emeritus and Senior Research Scholar, Department of Mechanical and Aerospace Engineering, Princeton University (chair)

**Brad Crabtree,** Vice President, Fossil Energy, Great Plains Institute

**Richard Duke,** formerly Special Assistant to President Obama

**Ottmar Edenhofer,** Professor of the Economics of Climate Change, Berlin Institute of Technology, and Deputy Director and Chief Economist, Potsdam Institute for Climate Impact Research, Germany

**José Goldemberg,** President, Fundação de Amparo a Pesquisa do Estado de São Paulo and Professor Emeritus, University of São Paulo, Brazil *(in absentia)*

**David Hawkins,** Director, Climate Program, Natural Resources Defense Council, Washington, D.C.

**John Holdren,** Professor, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, and formerly Science Advisor to President Obama

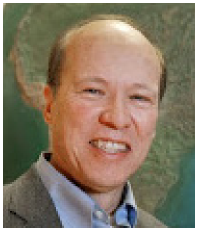
**Henry Kelly,** Senior Scientist, Michigan Institute for Data Science, University of Michigan, Ann Arbor

**5:30** | **Close**

## Yueh-Lin (Lynn) Loo

**Biosketch**

Yueh-Lin (Lynn) Loo is the Theodora D. '78 & William H. Walton III '74 Professor in Engineering and Director of the Andlinger Center for Energy and the Environment at Princeton University. Lynn received her BSE in Chemical Engineering and in Materials Science and Engineering from the University of Pennsylvania in 1996 and her PhD from Princeton University in 2001. She spent a year at Bell Laboratories, Lucent Technologies before joining the faculty in the Chemical Engineering Department at the University of Texas at Austin. She returned to Princeton in 2007. Lynn is interested in the processing and development of materials for low-cost, lightweight and flexible solar cells and circuits, the combination of which is being explored for the creation of "smart" windows to increase building and energy efficiencies. The author of over 140 publications, Lynn has delivered more than 200 invited and plenary lectures globally and she serves on numerous international advisory boards of peer academic institutions, non-governmental organizations, journal publishers and private companies. She is a fellow of the American Physical Society and a Young Global Leader of the World Economic Forum. Her scholarly work has been recognized by numerous other accolades, including Sloan and Beckman Fellowships, the John H. Dillon Medal from the American Physical Society, the Peter and Edith O'Donnell Award in Engineering from the Texas Academy of Medicine, Science and Engineering, and the Alan P. Colburn Award from the American Institute of Chemical Engineers. Learn more about Lynn and her research group at: http://princeton.edu/~loogroup.



## Eric D. Larson

**Biosketch**

Eric Larson is a Senior Research Engineer with the Energy Systems Analysis Group at the Andlinger Center for Energy and the Environment at Princeton. His energy systems analysis research intersects engineering, environmental science, economics, and public policy and has addressed clean and efficient energy supply and use in transportation, industry, buildings, and power generation. His work assesses resource, economic, and environmental implications of prospective technology developments and helps inform public and private decision making toward sustainable, engineering-based solutions to major energy-related problems in the U.S., China, and elsewhere. A recent emphasis in his work has been on the design, simulation, and techno-economic and environmental assessment of processes for converting biomass and fossil fuels into clean transportation fuels and electricity with $CO_2$ capture and storage. He is the co-author of over 230 publications, including co-convening lead author (fossil energy chapter) and a lead author (renewable energy chapter) of the *Global Energy Assessment* (2012).

Larson received a BSE in mechanical engineering from Washington University in St. Louis (1979) and a PhD in mechanical engineering from the University of Minnesota (1983) before joining Princeton to work with Robert Williams. He is an affiliated researcher in Princeton's Science, Technology, and Environmental Policy Program in the Woodrow Wilson School of Public and International Affairs, and he holds an appointment as a Senior Scientist with Climate Central, Inc., a non-profit, non-partisan science and media organization that aims to inform diverse audiences about climate change and potential solutions.

## Thomas B. Johansson

The concept of sustainable development is articulated by the 2015 UN Sustainable Development Goals, of which there are 17, with 230 Indicators. One Goal refers to access to modern forms of energy, another to climate change mitigation. Several others will require interventions in the current ways of addressing energy issues. There are many demands on energy systems for achieving a more sustainable world. Energy services are needed for sustaining growing economies and improving people's well-being. Around a billion people live in poverty. Without affordable access to modern forms of energy they will largely remain so. Pollution of air and water, land use, food supply, peace, and security are additional serious challenges that require changes in energy systems. The task at hand is to evolve energy systems in ways that simultaneously address all energy-related major challenges.

How to do this was the major question addressed in the Global Energy Assessment study in a back casting exercise for 2050. A number of combinations of energy demand and supply measures demonstrated that this is feasible from a resource, technical and economic point of view. They all build on much more efficient use of energy, especially at the point of end-use, and expansion of renewable energy. The study found that nuclear energy is not essential, while carbon capture and storage probably is essential. The exercise found that multiple benefits can result from energy-related actions: increased energy services, jobs and economic development, poverty alleviation, local environmental improvements, climate mitigation, improved health and security, and more. Such multiple benefits represent substantial value for societies, but tend to be absent from corporate decision making, leading to societally suboptimal investments. Pubic policies are needed to correct this. Improved energy efficiency and expanded renewable energy will not easily happen on a scale commensurate with the magnitude and timing of the challenges. Established practices and economic patterns are difficult to change. Vested interests fight back. These are fights for power and money that slow necessary policy action. As widely recognized, "the devil is in the detail", be it in EU Directives, international trade rules, or regulation of competitive markets. The ultimate responsibilities remain in the hands of those making, implementing, and enforcing the rules.

**Biosketch**

Johansson started as a nuclear physicist at the Lund Institute of Technology and got his PhD in 1974 on the creation of Proton-Induced X-ray Emission (PIXE) analysis as a method for analysing very small amounts of elements in very small samples, and its applications. He then turned to energy and joined the Energy Future Study at the Secretariat for Future Studies in the Swedish Prime Minister's office, presenting in 1978 with co-authors the study Solar vs. Nuclear, offering a multidimensional analysis of the two main routes available for future energy supply. This in part led to an invitation to Princeton where the group with Goldemberg, Reddy and Williams was formed, resulting in *Energy for a Sustainable World* (1985), a book that was recognized in the awarding of the Volvo Environment Prize to the authors in 2000. This analysis was taken further in various national and international contexts, including the China Council for International Cooperation on Environment and Development (1992 - 2003) and the work of the Energy Foundation in China (1998 – 2014). From 1994 through 2001 Johansson directed the Energy and Atmosphere Programme at UNDP, where the use of energy as an instrument for socio-economic development was pursued and the World Energy Assessment (2000) was launched. From 1992 to 1996 he was a Convening Lead Author of the IPCC's Second Assessment Report, and thus a co-recipient of the Nobel Peace Prize awarded to the IPCC in 2007. From 2001 through 2009 he directed the International Institute for Industrial Environmental Economics at Lund University. He initiated the Global Energy Assessment in 2006 and served as Co-Chair of its Executive Committee through the completion in 2012. In 2010 he received the European Solar Prize. He served as the Commissioner for fossil free vehicle transport, Ministry of Enterprise, Sweden, with an official Report published at the end of 2013. He is author and co-author of many studies and papers.

## Howard Geller

This presentation will review the role that energy efficiency has played in U.S. energy trends over the past 40 years, and the contribution of key energy efficiency technologies and policies to the dramatic decline in U.S. energy intensity. It will review the status of these technologies and policies today, and the prospects for continued improvements in energy efficiency in the buildings and industrial sectors over the next 10-15 years.

**Biosketch**

Howard Geller is the Executive Director of the Southwest Energy Efficiency Project (SWEEP), a public interest venture he founded in 2001. Based in Boulder, Colorado, SWEEP promotes policies and programs to advance energy efficiency in a six-state region that includes Arizona, Colorado, Nevada, New Mexico, Utah, and Wyoming.

Dr. Geller is the former Executive Director of the American Council for an Energy-Efficient Economy (ACEEE). He established ACEEE's Washington, D.C. office in 1981, stepping down as Executive Director in February 2001. He built ACEEE's reputation and influence through technical and policy assessments, advice to policy makers, development of energy efficiency programs, and services to energy efficiency professionals.

Dr. Geller has advised and conducted energy efficiency studies for utilities, governmental organizations, and international agencies. He has testified before the U.S. Congress on energy issues many times and has influenced key energy legislation, including the National Appliance Energy Conservation Act of 1987 and the Energy Policy Act of 1992. He is author or co author of four books. His most recent book, *Energy Revolution: Policies for a Sustainable Future*, was published in 2003 by Island Press.

In addition to his work in the United States, Dr. Geller has spent significant time working on energy efficiency issues in Brazil. He helped to start Brazil's National Electricity Conservation Program (PROCEL), and helped Brazil develop and implement energy efficiency legislation.

Dr. Geller received the 1998 Leo Szilard Award for Physics in the Public Interest from the American Physical Society in recognition of his contributions to national appliance efficiency standards and more efficient energy use in general. Dr. Geller is a member of the editorial advisory board for the journal *Energy Policy*, and was the associate editor for energy efficiency for the *Macmillan Encyclopedia of Energy*. He served on the Panel on Energy Efficiency Technologies convened by the National Research Council in 2007-08.

Dr. Geller received his PhD in Energy Policy from the University of Sao Paulo in Brazil in 2002. He holds a Masters degree in Mechanical and Aerospace Engineering from Princeton University, class of '79, where his Masters thesis advisor was Bob Williams.

## Sam Baldwin

The cost of renewable power has been rapidly declining, accelerating its penetration into U.S. and global electric power sectors. These advances raise four inter-related issues. First, how much more could the cost of renewable energy decline? Second, what could be the impact of this renewable energy on grid operations and the costs of integrating it into the grid, and what technology advances could be needed to reduce these costs and impacts? Third, how could these renewable energy supplies impact electricity markets? Fourth, after the electricity system, what role could renewables serve in addressing the energy challenges of other sectors—buildings, industry, transportation? The U.S. and the world face significant energy-linked challenges, but renewable energy offers important opportunities to address them.

**Biosketch**

Sam Baldwin is a PhD. physicist and serves as the Chief Scientist for Strategic Programs in the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy (DOE). He most recently served for three years in the Office of the Under Secretary for Science and Energy, leading the Quadrennial Technology Review 2015 on the RDD&D opportunities for the Science and Energy programs at DOE over coming years, coordinating crosscutting R&D teams, conducting portfolio analysis, and many other activities.
In previous positions he has served with the White House Office of Science and Technology Policy (OSTP), the National Renewable Energy Laboratory (NREL), the Congressional Office of Technology Assessment (OTA), Princeton University, the Sahelian Anti-Drought Committee (CILSS) in West Africa, the U.S. Senate, and elsewhere. He is the author or coauthor of more than a dozen books and monographs at DOE, OSTP, OTA, and elsewhere, and more than 30 papers and technical reports on energy technology and policy, physics, and other issues. He was elected as a Fellow of the American Association for the Advancement of Science in 2007.

## Carbon Capture and Storage for a Tolerable Climate Change

### Stefano Consonni

The reduction of greenhouse gas emissions needed to mitigate climate changes poses a formidable challenge. Not only should we reduce carbon emissions very significantly, but we must do it quickly. The idea of Carbon Capture & Storage (CCS) stems from the recognition that we won't be able to reduce the current massive dependence on fossil fuels fast enough. By decoupling the use of fossil fuels from $CO_2$ emissions, CCS can give us the time we need to evolve toward a future where the use of energy does not entail the emission of greenhouse gases. Although CCS is sometimes perceived as an exotic and possibly alarming idea, many of the processes required by carbon capture are well known to the chemical and oil & gas industry. After reviewing basic approaches and technologies, this presentation gives a flavor of some particularly attractive options being pursued for power plants and industrial processes, the hurdles that hamper their introduction and the efforts for their demonstration. Like all new technologies, also CCS is subject to uncertainties and risks. Yet its prospects appear competitive with those of other options now heavily financed by governmental programs.

**Biosketch**

Born in 1958, Prof. Stefano Consonni holds a Degree in Mechanical Engineering from Politecnico di Milano and a Ph.D. in Mechanical and Aerospace Engineering from Princeton University. Since 1990 he has been on the Faculty of the Department of Energy of Politecnico di Milano, becoming full professor of *Energy Systems* in 2001. From 1997 to 2005 he was the Head of the campus of Politecnico in Piacenza. Since 2005 he has been President of Politecnico's LEAP (Laboratory for Energy and Environment, Piacenza), where he also directs the study center MatER (Material and Energy from Refuse).

Prof. Consonni has led or contributed to a number of national and international research programs on gas turbines, combined cycles, cogeneration, gasification, energy from biomass, decarbonization of fossil fuels, energy from waste and residues, and environmental impact of energy systems. He was a visiting Scholar at the Princeton Environmental Institute in 2002-03 and in 2007.

His latest activities focus on carbon capture, energy from waste and biomass, and reduction of greenhouse gas emissions. He is author of over 90 papers published in international journals and conference proceedings.

## Enabling Fossil Fuels to Survive in a Carbon-Constrained World

### Vello A. Kuuskraa

Carbon capture, utilization and storage (CCUS) provides a pathway for the world's abundant storehouse of fossil fuels to survive and even prosper in a carbon-constrained world. However, given the still high costs of $CO_2$ capture, revenues from sale and use of $CO_2$ by the $CO_2$ enhanced oil recovery industry are needed to make CCUS an affordable option.

While supportive of carbon capture and storage (CCS), many in the environmental community oppose the utilization of $CO_2$ for oil recovery ($CO_2$-EOR) and its by-product storage of $CO_2$ (CCUS) stating - - "it will bring more carbon out of the ground." Another often-stated opposition to greater use of $CO_2$-EOR for $CO_2$ storage is that it is a small, niche opportunity.

My talk will address these and other concerns that constrain greater acceptance and use of $CO_2$ enhanced oil recovery for carbon management and how the $CO_2$ sales and tax revenues from domestic $CO_2$-EOR can help make $CO_2$ capture economically viable.

**Biosketch**

Vello A. Kuuskraa is President of Advanced Resources International, a firm internationally recognized for its work on energy economics, supply modeling, and application of new oil and gas recovery technologies. He is the Chairman of the Advisory Board for the $CO_2$ Capture Project (CCP), an industry consortium involving BP, Chevron, Suncor and Petrobras, working to reduce the costs of $CO_2$ capture and enhance the viability of $CO_2$ storage. Mr. Kuuskraa has twice served as a Distinguished Lecturer for the Society of Petroleum Engineers (SPE), first on the topic of "Enhanced Oil Recovery" and more recently on the topic of "Integration of $CO_2$ Enhanced Oil Recovery and $CO_2$ Storage."

Mr. Kuuskraa is a 2001 recipient of the Ellis Island Medal of Honor that recognizes individuals for exceptional professional and patriotic contributions by America's diverse cultural ancestry. He is a member of the National Petroleum Council, the National Coal Council, and the University of Wyoming's Energy Resources Council. He is recently retired from the Board of Directors of Southwestern Energy. Mr. Kuuskraa holds a M.B.A., Highest Distinction from The Wharton Graduate School and a B.S. in Applied Mathematics/Economics from the North Carolina State University.

## Estimation of $CO_2$ Leakage along Old Wells using Numerical Models and Field Measurements

### Michael Celia

Carbon capture and geologic storage involves large-scale injection of captured $CO_2$ into deep geological formations. These geological formations must have sufficient storage capacity while simultaneously having high probability of storage security, with only very small fractions of the injected fluid leaking out of the formation. Old oil and gas wells have been identified as potential leakage pathways, especially in North America where millions of old wells are co-located with the best locations for $CO_2$ storage. Analysis of leakage potential along existing wells requires new computational tools capable of modeling very large spatial domains while resolving small-scale flows along hundreds to thousands of existing wells within the domain. In addition, new data sources are required to quantify hydraulic properties of these old wells. Computational models based on multi-scale semi-analytical algorithms allow for very efficient calculations of leakage amounts. And new measurements of leakage of gases along old wells provide data on effective permeabilities of these wells. When these new data are combined with the leakage models, and applied to a specific field location in Alberta, Canada, quantitative estimates of leakage along old wells can be made. Results show that less than 0.1% of the injected mass of $CO_2$ is expected to leak after 50 years of continuous injection. Even less of the resident brine leaks along these wells. The overall result shows that leakage along old wells appears to be small and should not be a limiting factor in the development of large-scale CCS operations.

**Biosketch**

Professor Michael Celia is the Theodora Shelton Pitney Professor of Environmental Studies and Professor of Civil and Environmental Engineering at Princeton, where he served as Department Chair for the CEE Department from 2005 to 2011. He is currently Director of the Program in Environmental Engineering and Water Resources. Professor Celia's areas of research include ground-water hydrology, multi-phase flow in porous media, numerical modeling, and subsurface energy systems with a focus on geological sequestration of carbon dioxide and shale-gas systems. Ongoing projects include development of new simulation tools to model $CO_2$ injection, migration, and possible leakage associated with carbon capture and geological sequestration (CCS); studies of multi-phase flow and transport in porous media with a focus on multi-scale models, including pore-scale models; modeling of shale-gas systems with a focus on possible $CO_2$ injection into depleted shale-gas reservoirs as well as the fate of fracking fluids; and measurements of methane leakage to the atmosphere along old oil and gas wells. The CCS work is part of a large industry-funded multi-disciplinary effort at Princeton known as the Carbon Mitigation Initiative. Professor Celia served for 10 years as editor of the journal *Advances in Water Resources*. He is a Fellow of the American Geophysical Union (AGU) and the American Association for the Advancement of Science (AAAS) and the recipient of the 2005 AGU Hydrologic Sciences Award (citation: *For fundamental research contributions to subsurface hydrology and numerical methods in water resources, and for providing a model of Academia at its best*). He was the 2008 Darcy Lecturer for the National Ground Water Association, the 2010 Pioneers in Groundwater lecturer for the American Society of Civil Engineers, received the 2012 Hydrology Days Award, and is the recipient of the 2014 Honorary Lifetime Membership Award from the International Society for Porous Media (Interpore). In 2016 Professor Celia was elected to the U.S. National Academy of Engineering (citation: *For contributions to the development of subsurface flow and transport models in groundwater remediation and $CO_2$ sequestration*).

## Frank von Hippel

Globally, the percentage of electric energy produced by fission declined to 11% in 2015 from a peak of 17-18% in the 1990s. Annual new construction coming on line fell from an average of about 20 GWe/yr in the 1970s and 1980s to about 5 GWe/yr after the Chernobyl accident (1989) and about 2 GWe/yr outside China since the Fukushima accident (2011). The average age of nuclear capacity is about 35 years, when many plants begin to require major refurbishments if they are not to be shutdown. Although, a number of major governments still are supportive of nuclear power, the public has become generally skeptical and safety and security requirements multiply while the nuclear workforce ages in most countries.

**Biosketch**

Frank von Hippel is a Senior Research Physicist and Professor of Public and International Affairs emeritus at Princeton where, in 1975, he co-founded and co-chaired for three decades what is now Princeton's Program on Science and Global Security. During 1983-90, von Hippel worked with President Gorbachev's science advisor, Evgenyi Velikhov, to develop a number of successful initiatives to end nuclear testing, end the production of plutonium and highly enriched uranium for weapons, and eliminate excess weapons materials.

During 1993-4, he served as Assistant Director for National Security in the White House Office of Science and Technology Policy and played a major role in developing U.S.- Russian cooperative nuclear initiatives.

In 2006, he co-founded the non-governmental International Panel on Fissile Materials (IPFM) and co-chaired it for its first nine years. He has attempted to inform U.S. Administrations and Congress on nuclear material issues since the Carter Administration.

## Joan Ogden

Achieving deep cuts in carbon emissions from the transportation sector is seen as more difficult and costly than reducing emissions in other sectors, such as electricity. Yet such a transition will be required in a world seeking a 1.5 or 2 degree solution, and energy/economic models suggest that it must begin soon. Transforming to a low carbon transportation system requires success on three fronts: improved energy efficiency, adoption of low net carbon fuels that can be produced from widely available primary sources, and reduced travel demand. There are promising technical options for addressing each of these factors, including adoption of highly efficient alternative fueled vehicles run on biofuels, electricity or hydrogen derived from renewables or fossil sources with CCS. Unlike today's transportation fuel "monoculture", a future low carbon transportation system will likely rely on a portfolio of fuels and vehicle types; light duty vehicles, where electric drive plays a major role, and long haul trucks and aviation where energy-dense liquid fuels would be preferred. (Some of the early work on a portfolio approach was done at Princeton, introducing the concept of "stabilization wedges".) But actual progress towards 2050 goals has been slower than the technical potential suggests, because of an array of complex transition issues. In this talk, I discuss technical options for meeting sustainability goals in the transport sector, and barriers to their implementation. As an example, I consider transition costs for moving the light duty fleet in the United States toward zero emission vehicle (ZEV) technologies such as battery and hydrogen fuel cell vehicles. Making this radical transition involves surmounting many barriers, including the investment costs of bringing new types of vehicles and their fuel infrastructures to cost competitiveness. Even if there is long-term promise for cost competitiveness and large societal benefits, initial investment cost barriers can act as a major disincentive to change. Through a transition cost analysis that accounts for learning and scale up, I estimate that the cost of launching ZEV technologies over the next decade or so would be just a few percent of what we currently spend on light duty vehicles and fuels. Even though a full build-out would take many decades, sufficient scale-up and learning might be accomplished through regional network demonstrations. Finally, I discuss learnings from past energy transitions, including the importance of regional scale network level demonstrations, stakeholder coordination and consistent policy in successful technology adoption.

**Biosketch**

Joan Ogden is Professor of Environmental Science and Policy and founding Director of the Sustainable Transportation Energy Pathways Program at the University of California, Davis. Prior to joining UC Davis in 2003, she was a research scientist at the Princeton University's Environmental Institute. Her primary research interest is techno-economic assessment of low carbon energy technologies, especially alternative fuels, hydrogen, fuel cells and renewable energy. Her recent work centers on hydrogen infrastructure strategies, and applications of fuel cell technology in transportation and stationary power. She has served on high-level committees advising clean energy policies in California, the US and internationally. She is author of two books and numerous technical articles. She holds a BS in mathematics from the University of Illinois and a Ph.D. in theoretical physics from the University of Maryland.

# Overcoming Commercial Challenges for Deployment of Large-scale Low-Carbon Energy Systems

## Chris Greig

Most integrated assessments of the global decarbonization challenge utilize a ‘back-casting’ approach that optimizes the deployment of low-carbon technologies over time to deliver a predetermined $CO_2$ reduction trajectory (e.g. 2DS scenario) at the minimum cost. Such models assume there are no physical supply or execution capacity limits or bottlenecks limiting the introduction and initial deployments of such technologies and instead incorporate technology launch dates and assumed technology learning rates linked to the gross capacity deployed.

This presentation will provide evidence of potential limits to deployment of low carbon technologies and challenge the technology learning curves which are necessary to see material cost reductions in low carbon technologies, especially for low-carbon technologies that involve complex-process megaprojects. The level of risk and uncertainty in delivering such megaprojects is such that government must play a leadership role in collaboration with industry to deliver early mover projects, drive innovation and realize the technical and commercial benefit of learning. The retreat of governments from investments in late-stage commercialization programs poses a major threat to climate mitigation efforts.

**Biosketch**

Professor Chris Greig at the University of Queesnland leads both the UQ Energy Initiative and the Dow Centre for Sustainable Engineering Innovation. He is a Chemical Engineer, having obtained his undergraduate and PhD degrees at the University of Queensland, and is a Fellow of the Australian Academy of Technological Sciences and Engineering. His 25-year industry career commenced as the founder of a successful process technology and contracting company which was later sold to a major international engineering company. Since then, and prior to joining UQ in 2011, he held senior project and executive roles in the mining and energy industries internationally, including CEO of Australia’s ZeroGen project to build a 400 MW advanced-technology coal-fired power plant with $CO_2$ capture and storage. After leading several years of design, engineering, and $CO_2$ storage appraisal efforts, he recommended cancelation of the project to the Australian government. His main interests lie in Energy Transitions, Economics and Policy, Energy for Development, Megaproject Implementation, and $CO_2$ Capture and Storage.

## Climate Change and Our Future Electricity System – Europe in 2050

### Wim C. Turkenburg

Based on the Paris Climate Change Agreement, global emissions of greenhouse gases due to human activities should be reduced to almost zero by 2050 and become negative thereafter. A range of technologies and approaches is needed to achieve this. Major options are a further reduction of the energy intensity of our economic system as well as an accelerated application of wind and solar energy systems. However, this is not enough. Other options are expected to play a major role too, including sustainable use of biomass, Carbon Capture and Storage (CCS) and Negative Emission Technologies (NETs).

Focused on Europe, we developed a model to simulate on an hourly basis the potential demand and supply of electricity in the year 2050. Three scenarios were analyzed in which 40%, 60% or 80% of the electricity is produced from renewable sources, mainly wind and solar. We wanted to know the attractiveness of other options to be applied to achieve a reduction in $CO_2$ emissions of 96% compared to 1990, to supply electricity as reliably as at present, and to have electricity production costs as low as achievable. The results show that in 2050 the preferred option would be natural gas fired power stations combined with CCS. We found no role for nuclear power plants or for coal-fired power plants with CCS.

**Biosketch**

Wim C. Turkenburg (1947) is professor of Science, Technology & Society at Utrecht University, The Netherlands, and owner of a consultancy on energy and environmental issues. He studied physics and mathematics at Leiden University, the University of Amsterdam, and the Institute of Atomic and Molecular Physics in Amsterdam.

In the Netherlands he is a member of the board of the Foundation Preparation Pallas reactor (mainly to produce medical isotopes) as well as a member of advisory and programming committees focusing on e.g. energy policy development, nuclear waste management, bio-based economy, and Negative Emission Technologies. He is also a member of the editorial board of the journal *Energy for Sustainable Development*.

He authored or co-authored hundreds of publications on energy systems analysis, energy technology assessment, renewable energy, Carbon Capture and Storage (CCS), energy efficiency, nuclear energy, energy policies, climate change, and environmental risk assessment. Also, he is the Convening Lead Author of the *World Energy Assessment* (WEA) chapter on Renewable Energy Technologies (2000) and the *Global Energy Assessment* (GEA) chapter on Renewable Energy (2012). He was director of the Copernicus Institute of Sustainable Development of Utrecht University as well as scientific director of the Utrecht Center for Energy research.

He served on a number of international boards and working groups, including the Committee on Energy and Natural Resources for Development of the United Nations, the Working Group on Energy Supply Mitigation Options of the Intergovernmental Panel on Climate Change (IPCC), the Executive Committee of the WEA as well as the GEA, and the Working Group on Renewable Energy of the World Energy Council. In addition he has served on numerous national boards and committees, including the board of the Energy Research Centre of the Netherlands, the Council on Housing, Physical Planning, and Environment of the Netherlands, the General Energy Council of the Netherlands, the Energy Committee of the Social and Economic Council of the Netherlands, the board of the Dutch research program on $CO_2$ Capture, Transport and Storage, the board of the Netherlands Physical Society, the board of the Platform Communication on Climate Change of the Netherlands, and the board of the Netherlands' division of the International Solar Energy Society.

In 1996 he received at MIT the Greenman Award "to honor important contributions toward harnessing technology so that the human race can better live in harmony with the environment" because of his work on CCS. In 2007 he was one of the co-recipients of the Nobel Peace Prize awarded to the IPCC. In 2013 he became 'Knight of the Order of the Netherlands Lion'.

## Toward Reduced Costs for $CO_2$ Capture and Storage for Power on Grids with High Levels of Intermittent Renewable Electricity

**Robert H. Williams**

Spectacular cost reductions for wind and photovoltaic (PV) intermittent renewable electricity supplies (iRES) and various iRES deployment incentives have led to rapid growth of iRES throughout the world. iRES must be complemented by fast-ramping, dispatchable "balancing capacity" (BC—a mix of backup and storage capacity) to ensure a reliable grid electricity supply. In the US, where the shale gas revolution has led to abundant natural gas at low prices, the needed BC has been provided successfully so far mainly by a backup capacity mix of gas turbine combined cycle (GTCC) and combustion turbine (CT) units fired with natural gas.

But, if mid-century carbon-mitigation goals agreed to in Paris are to be met, BC will also have to be decarbonized. Pursuing $CO_2$ capture and storage (CCS) for backup capacity is a major decarbonization option. But CCS is economically challenging for electric grids with a high level of penetration of iRES because capital-intensive CCS backup capacity would have to be operated at a modest fraction of its potential in providing needed power when the wind doesn't blow and the sun doesn't shine. In technical terms, this implies that CCS back-up capacity would typically have to be operated at capacity factors (CFs) of 35-50%—much less than the 80-90% "baseload" capacity factors that are desirable for capital-intensive CCS power systems.

An innovative approach to addressing this "capacity-factor dilemma" is discussed that offers the potential for significantly improving the economics of CCS for an electric grid with high levels of iRES—a so-called hydrogen balancing capacity ($H_2$-BC) approach to ensuring reliable, low-carbon grid electricity. In the $H_2$-BC approach to decarbonization, $H_2$ production and consumption activities are decoupled via buffer underground $H_2$ storage. In the near term, a $H_2$-BC system is likely to be made up of these elements:

- Baseload plants (~ 90% CF) making $H_2$ with CCS from fossil fuel, biomass, or a mix,
- Flexible $H_2$-consuming power plants serving as balancing capacity [some mix of CT and GTCC units and/or compressed air energy storage (CAES)—all fired with $H_2$],
- Buffer underground storage of $H_2$.

What makes this approach to BC plausible is the likelihood that underground buffer $H_2$ storage will be relatively inexpensive.

For the US, early-mover $H_2$-BC projects are likely to be based on $H_2$ from natural gas, using captured $CO_2$ for enhanced oil recovery, storing $H_2$ underground in salt caverns, and selling decarbonized electricity into markets where a strong carbon-mitigation policy is in place (e.g., California). Because no radical new technologies are required, and supporting public policies are in place or in the offing, there are reasonable prospects for advancing this concept in the near term.

## PANEL DISCUSSION: 3:30

## Are US Policy Advances to Mitigate Climate Change Possible in the Trump Era?

Climate science skepticism and anti-new-tax sentiments in the current White House and Congress suggest that any progress to be made on carbon-mitigation policy in the US in the years immediately ahead will have to be made via venues other than new federal government policy initiatives. The distinguished members of the panel will explore possibilities that such a gloomy outlook for new federal policy in support of carbon-mitigation for energy might not be inevitable. The panel will discuss four policy issues:

(a) Fixing wholesale electricity markets that are breaking down as a result of growth in intermittent renewable electricity and the shale gas revolution.

(b) Technology cost buydown for large-scale, low-carbon energy technologies.

(c) A carbon tax.

(d) Carbon-mitigation policy for developing countries.

### Robert Socolow (Panel Chair)

**Biosketch**

Robert Socolow is professor emeritus and a full-time member of the senior research staff in the Department of Mechanical and Aerospace Engineering at Princeton University. In his research he seeks new conceptual decade-scale frameworks that are useful for climate change policy. With colleagues he introduced “stabilization wedges,” “one billion high emitters,” “committed emissions,” and “destiny studies.” He is engaged with multi-disciplinary efforts to anticipate key issues associated with low-carbon futures, including analyses of energy efficiency in buildings, wind and solar power, nuclear fission and fusion power, $CO_2$ capture and storage from fossil fuels and the air, impacts on the land when biocarbon is priced, and technological “leapfrogging” by developing countries. He is a member of the American Academy of Arts and Sciences, an associate of the National Research Council of the National Academies, a fellow of the American Physical Society, a fellow of the American Association for the Advancement of Science, and the recipient of the Leo Szilard Lectureship Award by the American Physical Society. He earned his Ph.D. from Harvard University in theoretical high energy physics in 1964 and joined the Princeton University faculty in 1971.

# Panelists

## Brad Crabtree

**Biosketch**

Brad joined the Great Plains Institute (GPI) in 2002, and he currently oversees its Fossil Energy Program, managing regional and national projects in power generation, carbon capture and enhanced oil recovery (EOR). He co-directs the National EOR Initiative, a national coalition of energy, industrial and technology companies, labor unions, and environmental and energy policy organizations that advocates for federal incentives to expand the capture of $CO_2$ for use in EOR with geologic storage. He also coordinates the State $CO_2$-EOR Deployment Work Group, a 14 state effort convened by Governors Matt Mead (Wyoming) and Steve Bullock (Montana) and dedicated to advancing policies and commercial deployment of carbon capture and EOR.

Previously at GPI, Brad coordinated energy policy advisory groups for the Midwestern Governors Association and facilitated the Midwestern Greenhouse Gas Reduction Accord Advisory Group for six governors and the Manitoba premier. He also co-directed Powering the Plains, the Institute's original flagship project that developed a comprehensive, 50-year regional blueprint for energy efficiency, renewable energy and advanced coal technologies with carbon capture. Brad has organized multiple overseas energy policy and technology delegations through GPI for public and private-sector leaders from North Dakota, the Midwest and nationally.

Prior to GPI, Brad was with the Consensus Council in Bismarck, ND, directing regional flood mitigation and resource management projects. His background also includes energy and environmental policy and project development work in Washington, DC and Brazil and field research in Borneo.

Brad was appointed by U.S. Secretary of Energy Ernest Moniz and serves on the National Coal Council, which prepares studies and makes recommendations to the Secretary on coal and the coal industry. He ranches with his wife and daughter in North Dakota, where he was a statewide candidate for Public Service Commissioner in 2010 and 2012. A graduate of the Georgetown School of Foreign Service, Brad has an MA in history from Johns Hopkins University.

## Richard Duke

**Biosketch**

During the second term of the Obama administration, Rick Duke worked at the White House, where he helped to craft and implement the Climate Action Plan. His domestic priorities spanned the EPA's Clean Power Plan, the 2015 budget deal to achieve long-term extensions to renewable energy tax credits, DOE's appliance standards program, regulations on non-$CO_2$ gases, and measures to bolster the lands sector carbon sinks and cut agricultural emissions. His international work in support of the Paris Agreement included defining the United States' 2025 emissions reduction target for the November 2014 leader-level joint announcement with China that jumpstarted the Paris negotiations process; bilateral engagement with Mexico and other major economies on their respective Paris Agreement emission reduction targets; and driving development and defense of two successive U.S. Biennial Reports to the UNFCCC. He also served as the White House lead to negotiate the landmark Kigali Amendment to the Montreal Protocol to phase down HFCs as well as a global market-based measure to offset growth in international aviation emissions from 2020 under the International Civil Aviation Organization. Finally, he led the team that authored the U.S. Mid-Century Strategy to achieve deep decarbonization by 2050.

During the first Obama term, he served as Deputy Assistant Secretary for Climate Policy at the U.S. Department of Energy, including helping to launch the Clean Energy Ministerial and contributing to first-term policies such as the social cost of carbon, the mercury and air toxics standard, and the clean energy standard legislative proposal.

Previously, he launched the Center for Market Innovation at NRDC, and as an engagement manager at McKinsey & Company, his projects included managing development of the firm's first global greenhouse gas abatement curve. He holds a Ph.D. from Princeton University, where his doctoral work focused on the economics of public investment in clean energy.

## Ottmar Edenhofer

**Biosketch**

Ottmar Edenhofer is among the world's leading experts on the economics of climate change. He is Deputy Director and Chief Economist at the Potsdam Institute for Climate Impact Research. In 2012 he was appointed director of the newly-founded Mercator Research Institute on Global Commons and Climate Change. He co-chaired the IPCC Working Group III assessment effort from 2008 to 2015, and edited its contribution to the IPCC Fifth Assessment Report "Climate Change 2014: Mitigation of Climate Change". The Fifth Assessment Report provided the scientific basis for the Paris Agreement. Presently, Edenhofer is on the "High-level economic commission on carbon prices" preparing a scientific assessment for World Bank and International Monetary Fund spring 2017 meetings. For the German government he heads the task force "Climate Policy and Finance" preparing scientific policy advice before the G20 summit in Germany (July 2017). Edenhofer's many peer-reviewed publications address the design of instruments for climate and energy policy, questions of growth, technological change and development, distributional effects of climate policy instruments, game theoretic aspects of designing international agreements, long-term scenarios of the climate and energy system, mitigation costs and mitigation strategies, as well as the science-policy interface. His work has been picked up by The New York Times, the Economist, China Daily, Nature, Der Spiegel, and others, and he is a frequent contributor to German popular press, such as DIE ZEIT. He currently supervises 15 PhD students.

## José Goldemberg
*(in absentia)*

**Biosketch**

José Goldemberg earned his Ph.D. in Physical Sciences from the University of São Paulo in 1954, where he held the position of Full Professor in the Engineering School's Physics Department. He was Rector of the University from 1986 to 1990. A Member of the Brazilian Academy of Sciences, he has served as the President of the Brazilian Association for the Advancement of Science and President of the Energy Company of the State of São Paulo (CESP). Between 1990 and 1993, he was Brazil's Secretary of State for Science and Technology and Minister of State for Education. Over the years, he did research at the University of Illinois, Stanford, University of Paris (Orsay), and Princeton University. From 1998 to 2000, he served as Co-chair of the World Energy Assessment. More recently, between 2002 and 2006, he was Secretary for the Environment of the State of São Paulo. He has authored many technical papers and books on Nuclear Physics, Sustainable Development, and Energy. In 2007 Time Magazine honoured him as one of its "Heroes of the Environment". In 2008 he was awarded the Blue Planet Prize 2008 of the Asahi Glass Foundation (Japan). In 2010 he received the "Trieste Science Prize" of the Third World Academy of Sciences and in 2013 the "Lifetime Achievement Award" of the Zayed Future Energy Prize. Since 2015 he has been President of FAPESP, São Paulo Research Foundation, and he is Professor Emeritus at the University of São Paulo.

# Panelists

## David G. Hawkins

**Biosketch**

David Hawkins began his work in "public interest" law upon graduation from Columbia University Law School in 1970. He joined the Natural Resources Defense Council's (NRDC) Washington, DC office in 1971 as one of the organization's first staff members. In 1977, he was appointed by President Carter to be Assistant Administrator for Air, Noise, and Radiation at the Environmental Protection Agency. During his time at EPA, he was responsible for initiating major new programs under the 1977 Amendments to the Clean Air Act. With President Reagan's election in 1981, Mr. Hawkins returned to NRDC to co-direct NRDC's Clean Air Program. In 1990, he became Director of NRDC's Air and Energy Program, and in 2000 he became the Director of NRDC's Climate Center. NRDC's climate work focuses on advancing policies and programs to reduce the pollution responsible for global warming. Mr. Hawkins has worked with Congress, the Executive Branch, and various members of the business community to design policies that will slow, stop and reduce the emissions of global warming pollution. Mr. Hawkins is recognized as an expert on advanced coal technologies and carbon dioxide capture and storage. He assumed his current position as Director, NRDC Climate Programs, in 2011. He currently serves on the boards of the Woods Hole Research Center, Resources for the Future, and the Center for Clean Air Policy. He has previously served on the Board on Environmental and Energy Systems of the National Academy of Sciences and the U.S. Department of Energy's Climate Change Science Program Product Development Advisory Committee. Mr. Hawkins participated in the Intergovernmental Panel on Climate Change's Special Report on Carbon Dioxide Capture and Storage and in the IPCC's Fourth Assessment Report on climate change. Mr. Hawkins is married with three children and lives in Connecticut.

## John Holdren

**Biosketch**

John Holdren is the Teresa and John Heinz Professor of Environmental Policy at the Kennedy School of Government and Professor of Environmental Science and Policy in the Department of Earth and Planetary Sciences at Harvard University. He is also Senior Advisor to the Director at the independent, nonprofit Woods Hole Research Center. From January 2009 to January 2017, he was President Obama's Science Advisor and the Senate confirmed Director of the White House Office of Science and Technology Policy (OSTP), becoming the longest-serving Science Advisor to the President in the history of the position (dating back to World War II). His responsibilities in that role included advising the President on all science and technology issues bearing on the President's agenda, coordinating R&D strategy and budgets across the Executive Branch departments and agencies; overseeing interagency S&T programs, including the U.S. Global Change Research Program; developing initiatives in STEM education; advancing scientific integrity and openness in government; and representing the U.S. government in interactions with the U.S. and global science and engineering communities.

Dr. Holdren earned S.B. and S.M. degrees from M.I.T. and a Ph.D. from Stanford in aerospace engineering and theoretical plasma physics. He is a member of the U.S. National Academy of Sciences, the U.S. National Academy of Engineering, the American Philosophical Society, the American Academy of Arts and Sciences, and the Council on Foreign Relations. He is also a foreign member of both the Royal Society of London and the Indian National Academy of Engineering and a former President of the American Association for the Advancement of Science. His other honors include one of the first MacArthur Prizes (1981), the Volvo International Environment Prize (1993), the Tyler Prize for Environment (2000), and the Heinz Prize for Public Policy

(2001). In 1995 he gave the acceptance speech for the Nobel Peace Prize on behalf of the Pugwash Conferences on Science and World Affairs, an international organization of scientists and public figures in which he served in leadership positions from 1982 to 1997.

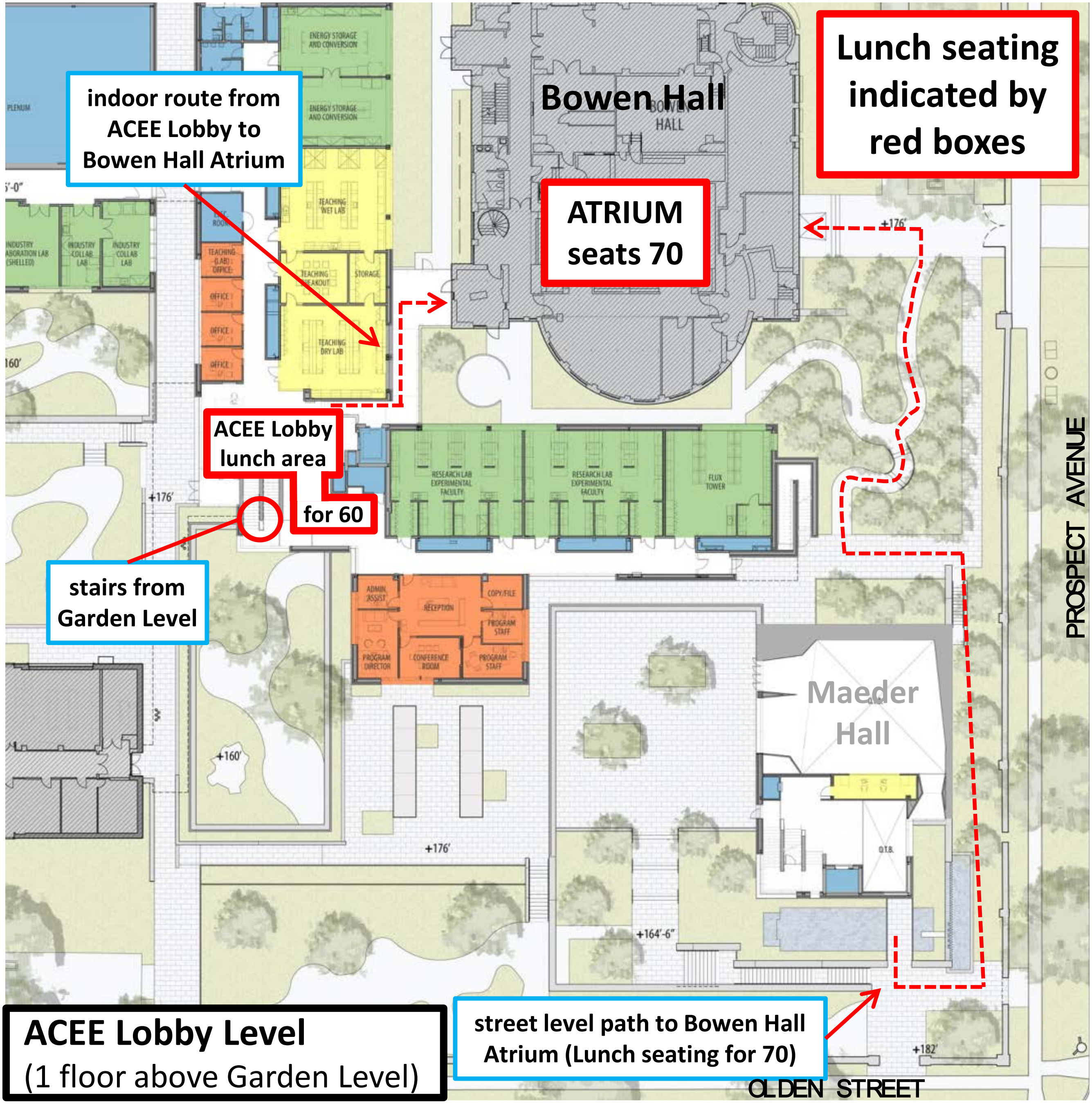
Prior to joining the Obama administration, Dr. Holdren was a professor in both the Kennedy School of Government and the Department of Earth and Planetary Sciences at Harvard University, as well as CEO of the independent, non-profit Woods Hole Research Center. From 1973 to 1996, he was on the faculty of the University of California, Berkeley, where he co-founded and co-led the interdisciplinary graduate-degree program in energy and resources.

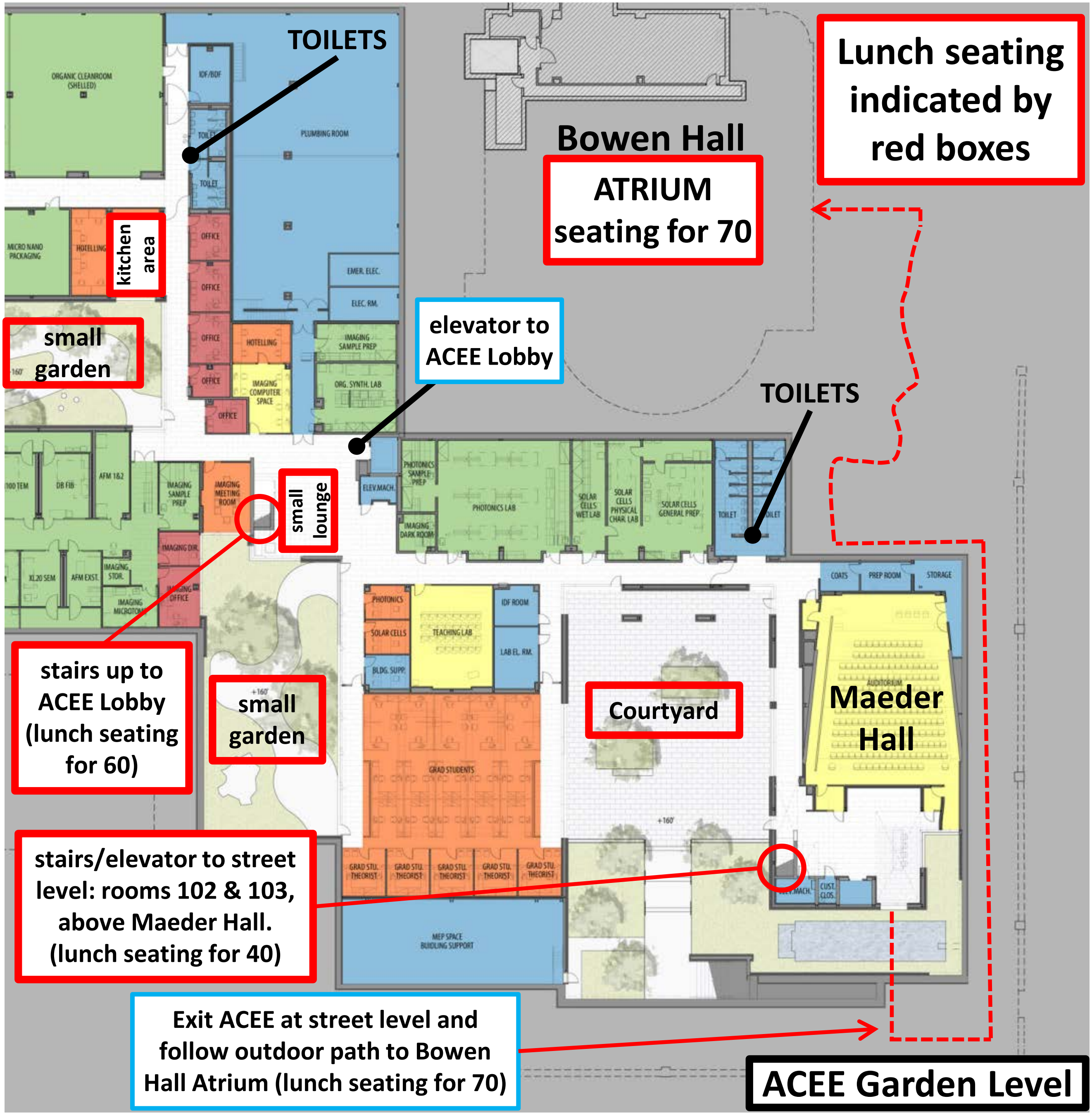
Dr. Holdren has been married since 1966 to Dr. Cheryl E. Holdren, a biologist. They have a son, a daughter, and five grandchildren. John and Cheryl currently live on Cape Cod.

## Henry Kelly

**Biosketch**

Henry Kelly is a Senior Scientist in the University of Michigan's Michigan Institute for Data Science. He has held a number of positions in the federal government, including the US Arms Control and Disarmament Agency, the Congressional Office of Technology Assessment, The US Department of Energy (Principle Deputy Assistant Secretary for Energy Efficiency and Renewable Energy), the White House Office of Science and Technology Policy (Associate Director for Technology, Principal Assistant Director for Environment and Energy and Senior Advisor to the Director). He has also served as the Assistant Director of the Solar Energy Research Institute (now the National Renewable Energy Laboratory), and President of the Federation of American Scientists. He is an elected fellow of the AAAS and APS and is a member of the Advisory Board for the Energy and Environment Directorate of the Pacific Northwest National Laboratory. He has a PhD in physics from Harvard University and a BA in physics from Cornell University.


Lunch seating indicated by red boxes
indoor route from ACEE Lobby to Bowen Hall Atrium
Bowen Hall
ATRIUM seats 70
ACEE Lobby lunch area for 60
stairs from Garden Level
Maeder Hall
PROSPECT AVENUE
OLDEN STREET
street level path to Bowen Hall Atrium (Lunch seating for 70)
ACEE Lobby Level
(1 floor above Garden Level)


Lunch seating indicated by red boxes
Bowen Hall
ATRIUM seating for 70
TOILETS
kitchen area
small garden
elevator to ACEE Lobby
TOILETS
small lounge
stairs up to ACEE Lobby (lunch seating for 60)
small garden
Courtyard
Maeder Hall
stairs/elevator to street level: rooms 102 & 103, above Maeder Hall. (lunch seating for 40)
Exit ACEE at street level and follow outdoor path to Bowen Hall Atrium (lunch seating for 70)
ACEE Garden Level
ORGANIC CLEANROOM (SHELLED)
PLUMBING ROOM
MICRO NANO PACKAGING
HOTELLING
OFFICE
EMER. ELEC.
ELEC. RM.
IMAGING SAMPLE PREP
ORG. SYNTH. LAB
IMAGING COMPUTER SPACE
PHOTONICS LAB
SOLAR CELLS GENERAL PREP
IMAGING MEETING ROOM
TEACHING LAB
GRAD STUDENTS
GRAD STU. THEORIST
MEP SPACE BUILDING SUPPORT
AUDITORIUM
COATS
PREP ROOM
STORAGE
IDF ROOM
LAB EL. RM.
BLDG. SUPP.
SOLAR CELLS
PHOTONICS
IMAGING DIR.
AFM 182
DB FIB
TOILET
ELEV. MACH.
CUST. CLOS.
+160'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