DOCKETED

Docket Number:	17-IEPR-04
Project Title:	Natural Gas Outlook
TN #:	222371-1
Document Title:	Appendices, CCST Long-Term Viability of Underground Natural Gas Storage in California
Description:	Appendices, California Council on Science & Technology, an Independent Review of Scientific and Technical Information on the Long-Term Viability of Underground Natural Gas Storage in California
Filer:	Lana Wong
Organization:	California Energy Commission
Submitter Role:	Commission Staff
Submission Date:	1/26/2018 10:34:02 AM
Docketed Date:	1/26/2018

Appendix A

Study Charge

Project: Independent Review of Scientific and Technical Information on Long-Term Viability of Gas Storage

Background

The blowout of well Standard Sesnon 25 in the Aliso Canyon Field resulted in broad impacts that greatly exceeded those envisaged and prepared for both by the site operator and responsible government entities. The incident resulted in the temporary displacement of thousands of residents in the community surrounding the Aliso Canyon field and demonstrated vulnerabilities to the California energy supply chain that placed at risk the energy reliability to 21 million customers in the greater Los Angeles Basin. The broad health and environmental impacts are still being investigated as many of the contaminants released are known to be toxic at high doses but have limited health impact data for long-term chronic exposure. The event substantially increased the amount of methane emitted to the atmosphere for the entire state, and consequently the amount of greenhouse gas pollution emitted due to the state's economic activities.

Proclamation of a State of Emergency (see #14 below for study request)

WHEREAS on October 23, 2015, a natural gas leak was discovered at a well within the Aliso Canyon Natural Gas Storage Facility in Los Angeles County, and Southern California Gas Company's attempts to stop the leak have not yet been successful; and

WHEREAS many residents in the nearby community have reported adverse physical symptoms as a result of the natural gas leak, and the continuing emissions from this leak have resulted in the relocation of thousands of people, including many schoolchildren; and

WHEREAS major amounts of methane, a powerful greenhouse gas, have been emitted into the atmosphere; and

WHEREAS the Department of Conservation, Division of Oil, Gas and Geothermal Resources issued an emergency order on December 10, 2015 prohibiting injection of natural gas into the Aliso Canyon Storage Facility until further authorized; and

WHEREAS seven state agencies are mobilized to protect public health, oversee Southern California Gas Company's actions to stop the leak, track methane emissions, ensure worker safety, safeguard energy reliability, and address any other problems stemming from the leak; and

WHEREAS the California Public Utilities Commission and the Division of Oil, Gas and Geothermal Resources--working closely with federal, state and local authorities including the California Attorney General and the Los Angeles City Attorney--have instituted investigations of this natural gas leak and have ordered an independent, third-party analysis of the cause of the leak; and

NOW, THEREFORE, given the prolonged and continuing duration of this natural gas leak and the request by residents and local officials for a declaration of emergency, I, EDMUND G. BROWN JR., Governor of the State of California, in accordance with the authority vested in me by the State Constitution and statutes, including the California Emergency Services Act, HEREBY PROCLAIM A STATE OF EMERGENCY to exist in Los Angeles County due to this natural gas leak.

IT IS HEREBY ORDERED THAT:

1. All agencies of state government shall utilize all necessary state personnel, equipment, and facilities to ensure a continuous and thorough response to this incident, as directed by the Governor's Office of Emergency Services and the State Emergency Plan.

2. The Governor's Office of Emergency Services, in exercising its responsibility to coordinate relevant state agencies, shall provide frequent and timely updates to residents affected by the natural gas leak and the appropriate local officials, including convening community meetings.

STOPPING THE LEAK

3. The California Public Utilities Commission and the California Energy Commission shall take all actions necessary to ensure that Southern California Gas Company maximizes daily withdrawals of natural gas from the Aliso Canyon Storage Facility for use or storage elsewhere.

4. The Division of Oil, Gas and Geothermal Resources shall direct Southern California Gas Company to take any and all viable and safe actions to capture leaking gas and odorants while relief wells are being completed.

5. The Division of Oil, Gas and Geothermal Resources shall require Southern California Gas Company to identify how it will stop the gas leak if pumping materials through relief wells fails to close the leaking well, or if the existing leak worsens.

6. The Division shall take necessary steps to ensure that the proposals identified by Southern California Gas Company pursuant to Directives 4 and 5 are evaluated by the panel of subject matter experts the Division has convened from the Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories to evaluate Southern California Gas Company's actions.

PROTECTING PUBLIC SAFETY

7. The Division of Oil, Gas, and Geothermal Resources shall continue its prohibition against Southern California Gas Company injecting any gas into the Aliso Canyon Storage Facility until a comprehensive review, utilizing independent experts, of the safety of the storage wells and the air quality of the surrounding community is completed.

8. The California Air Resources Board, in coordination with other agencies, shall expand its real-time monitoring of emissions in the community and continue providing frequent, publicly accessible updates on local air quality.

9. The Office of Environmental Health Hazard Assessment shall convene an independent panel of scientific and medical experts to review public health concerns stemming from the gas leak and evaluate whether additional measures are needed to protect public health beyond those already put in place.

10. The California Public Utilities Commission and the California Energy Commission, in coordination with the California Independent System Operator, shall take all actions necessary to ensure the continued reliability of natural gas and electricity supplies in the coming months during the moratorium on gas injections into the Aliso Canyon Storage Facility.

ENSURING ACCOUNTABILITY

11. The California Public Utilities Commission shall ensure that Southern California Gas Company cover costs related to the natural gas leak and its response, while protecting ratepayers.

12. The California Air Resources Board, in consultation with appropriate state agencies, shall develop a program to fully mitigate the leak's emissions of methane by March 31, 2016. This mitigation program shall be funded by the Southern California Gas Company, be limited to projects in California, and prioritize projects that reduce short-lived climate pollutants.

STRENGTHENING OVERSIGHT OF GAS STORAGE FACILITIES

13. The Division of Oil, Gas and Geothermal Resources shall promulgate emergency regulations requiring gas storage facility operators throughout the state to comply with the following new safety and reliability measures:

    a. Require at least a daily inspection of gas storage well heads, using gas leak detection technology such as infrared imaging.

b. Require ongoing verification of the mechanical integrity of all gas storage wells.

c. Require ongoing measurement of annular gas pressure or annular gas flow within wells.

d. Require regular testing of all safety valves used in wells.

e. Establish minimum and maximum pressure limits for each gas storage facility in the state.

f. Require each storage facility to establish a comprehensive risk management plan that evaluates and prepares for risks at each facility, including corrosion potential of pipes and equipment.

14. The Division of Oil, Gas and Geothermal Resources, the California Public Utilities Commission, the California Air Resources Board and the California Energy Commission shall submit to the Governor's Office a report that assesses the long-term viability of natural gas storage facilities in California. The report should address operational safety and potential health risks, methane emissions, supply reliability for gas and electricity demand in California, and the role of storage facilities and natural gas infrastructure in the State's long-term greenhouse gas reduction strategies. This report shall be submitted within six months after the completion of the investigation of the cause of the natural gas well leak in the Aliso Canyon Storage Facility.

SB 826 Budget Act of 2016

"Of the amount appropriated in Schedule (3) of this item, $2,500,000 shall be allocated for a contract with the California Council on Science and Technology to conduct an independent study. The Public Utilities Commission, in consultation with the State Energy Resources Conservation and Development Commission, the State Air Resources Board, and the Division of Oil, Gas, and Geothermal Resources within the Department of Conservation, shall request the California Council on Science and Technology to undertake a study in accordance with Provision 14 of the Governor's Proclamation of a State Emergency issued on January 6, 2016. The study shall be conducted in a manner following well-established standard protocols of the scientific profession, including, but not limited to, the use of recognized experts, peer review, and publication, and assess the long-term viability of natural gas storage facilities in California. Specifically, the study shall address operational safety and potential health risks, methane emissions, supply reliability for gas and electricity demand in the state, and the role of storage facilities and natural gas infrastructure in the state's long-term greenhouse gas reduction strategies. The study shall be completed by December 31, 2017."

Appendix B

Scope of Work

The CCST study of natural gas storage in California will assess the long-term viability of gas storage facilities in California. The assessment will include an evaluation of the current state of the thirteen gas storage fields in California, a broad review of the potential health risks and community impacts associated with their operation, fugitive gas emissions, and the linkages between gas storage capacity and California's current and future energy needs. Recommendations to public policy makers will be made where appropriate.

Key questions for each of the report sections are identified in this Statement of Work, which will be a living document. The Steering Committee, in consultation with the CPUC, will review, modify and select the key questions from the list below to be addressed at a level of detail commensurate with the available funding for the report.

Objectives and Key Questions

Key Question 1: What risks do California's underground gas storage facilities pose to health, safety, environment, and infrastructure?

1. What are the different gas storage reservoir characteristics (e.g., storage in depleted gas or oil reservoirs, depth, lithology, hydrology, trap configuration, age of wells, etc.) and geographic settings surface characteristics (e.g., topography, elevation, vegetation, proximity to population, etc.) in California?

2. What are the potential failure modes involving gas release (e.g., large and sudden emissions of methane, fires and explosions, high-pressure gas releases)? What do we know about the likelihood of each of these failure modes at CA gas storage facilities and gathering lines today, e.g. based on documented past events? What are the potential emission rates and dispersion patterns of leaked gases? What are the consequences of the failure modes on gas storage infrastructure and consequently on delivery (e.g., wells, gathering lines, compressors, turbines, control equipment, etc.)?

3. What are the expected trends in capacity as storage facilities age, and as wells are taken out of service because of loss of reservoir integrity?

4. For various failure modes, what are the human health risks? What are the inventories of harmful substances available for release? For harmful constituents

found at low concentration in natural gas, including odorants, hydrogen sulfide, and aromatics what is the relationship between well-studied acute exposure impacts and potential longer-term (days to months) exposures to on-site workers and the communities near storage sites? What are the health risks to workers, nearby communities, and vulnerable populations of exposure to harmful substances, and/or to flames and explosions related to gas leakage? What are the health consequences of long-term low-flow rate leakage? What is the overall human health risk of various failure modes given their frequency and consequences?

5. What are the likely impacts of possible leakage, both from large emissions or long-term low-flow rate leakage, on California's greenhouse gas pollution budget? How do gas storage leaks compare to other fugitive emissions not covered by California's Cap and Trade program?

6. How will regulatory changes underway affect the integrity of storage? Are there practices beyond those specified in the new rules that might be useful in protecting the integrity of storage? In particular, can the assessment of a broader range of failure modes and consequences help set priorities for monitoring and intervention practices that will limit the most severe potential impacts? What are the key elements and level of detail required to develop effective risk management plans?

Key Question 2: Does California need underground gas storage to provide for energy reliability through 2020?

1. What is the current role of gas storage in California today? How has storage been designed to operate in different gas utility regions? What kind of and how much gas storage does California need to support its energy system, particularly in winter and summer extreme weather? What gas system benefits are derived from storage? What is the role of gas storage and arbitrage on California's core consumer energy prices?

2. How is the role of gas storage changing with powerful current and near term trends such as cheap gas, drought, decommissioning of nuclear power facilitates, national trends in fuel-switching to gas, increasing renewable portfolio standards, and the possible degradation of capacity of existing storage facilities, especially considering California's position at the "end of the pipeline" nationally?
How might the role and infrastructure of both public and private gas storage change as a result.

3. How have historical storage facility performance problems impacted gas delivery and what have been the consequences for heating, electrical supply and industrial uses including refining?

4. Given the energy mix we will have in the near future, what would be required to replace gas storage facilities while maintaining reliability in supply under normal and extreme conditions? What infrastructure, regulatory and operational changes designed to optimize the use of existing infrastructure (such as balancing rules, nomination cycles and increased use of line pack) would be required? What may be the likely economic impact of these measures and what would the safety tradeoffs be? How do recent gas and electric market rule changes and those currently under consideration affect the role of storage and potential alternative resources to replace it? What are the potential costs and safety implications to implement energy infrastructure to replace gas storage facilities?

5. How are new requirements/regulations designed to improve integrity likely to affect the reliability of gas supply?

Key Question 3: How will implementation of California's climate polices change the need for underground gas storage in the future?

1. How could coordination of gas and electric operations reduce the need for storage? How may regional coordination of electric grid operation and planning change the role of gas/electric coordination and use of infrastructure?

2. What do changes in the energy system and possible changes anticipated to meet California's 2030 and 2050 climate goals imply for future gas usage and the need for gas? How might deployment of new technology impact the need for storage? In particular, what alternatives can feasibly replace or compete with gas storage in the deployment and integration of intermittent renewable energy? What practical economic and environmental impacts might these alternatives incur?

3. What does the assessment of storage that might be required to meet 2050 goals imply about storage in the interim time period?

Appendix C

CCST Steering Committee Members

The Steering Committee oversees the report authors, reaches conclusions based on the findings of the authors, and writes an executive summary. Lead authors and technical experts for each chapter also serve as Ex-Officio Steering Committee members.

Full *curricula vitae* for the Steering Committee members are available upon request. Please contact California Council on Science and Technology (916) 492-0996.

Steering Committee Members

- **Jens T. Birkholzer**, Co-Chair, Lawrence Berkeley National Laboratory
- **Jane C.S. Long**, Co-Chair, Independent Consultant
- **J. Daniel Arthur**, ALL Consulting LLC
- **Riley M. Duren**, NASA Jet Propulsion Laboratory
- **Karen Edson**, retired California Independent System Operator
- **Robert B. Jackson**, Stanford University
- **Michael L.B. Jerrett**, University of California, Los Angeles
- **Najmedin Meshkati**, University of Southern California
- **Scott A. Perfect**, Lawrence Livermore National Laboratory
- **Terence Thorn**, JKM Energy and Environmental Consulting
- **Samuel J. Traina**, University of California, Merced
- **Michael W. Wara**, Stanford Law School

Ex-Officio Members

- **Catherine M. Elder (Technical Expert)**, Aspen Environmental Group
- **Jeffery B. Greenblatt (Lead Author)**, Lawrence Berkeley National Laboratory
- **Curtis M. Oldenburg (Lead Author)**, Lawrence Berkeley National Laboratory

Jens T. Birkholzer, Ph.D., Co-Chair

Director, Earth Sciences Division, Lawrence Berkeley National Laboratory

Dr. Jens Birkholzer is a Senior Scientist at the Lawrence Berkeley National Laboratory (LBNL, Berkeley Lab). As an internationally recognized expert in subsurface energy applications and environmental impact assessment, he currently serves as the Director for the Energy Geosciences Division (EGD) in the Earth and Environmental Sciences Area (EESA). He received his Ph.D. in water resources, hydrology, and soil science from Aachen University of Technology in Germany in 1994. Dr. Birkholzer joined LBNL in 1994, left for a management position in his native Germany in 1999, and eventually returned to LBNL in 2001. He has over 400 scientific publications, about 130 of which are in peer-reviewed journals, in addition to numerous research reports. He serves as the Associate Editor of the International Journal of Greenhouse Gas Control (IJGGC) and is also on the Board of Editorial Policy Advisors for the Journal of Geomechanics for Energy and Environment (GETE). Dr. Birkholzer leads the international DECOVALEX Project as its Chairman, is a Fellow of the Geological Society of America, and serves as a Senior Fellow of the California Council on Science and Technology.

Jane C.S. Long, Ph.D., Co-Chair

Independent Consultant and CCST Council Member

Dr. Long holds a ScB in biomedical engineering from Brown University, an MS and PhD in hydrology from U.C. Berkeley. She formerly was Associate Director for Energy and Environment at Lawrence Livermore National Laboratory, Dean of Mackay School of Mines at the University of Nevada, Reno; and a scientist and department chair in energy and environment for Lawrence Berkeley National Laboratory. Dr. Long is an advisor for the Environmental Defense Fund, on the board of directors for Clean Air Task Force and the Bay Area Air Quality Management District Scientific Advisory Board. She is a fellow of the American Association for the Advancement of Science, an Associate of the National

Academies of Science (NAS) and a Senior Fellow of the California Council on Science and Technology (CCST). She was Alum of the Year in 2012 for the Brown University School of Engineering and Woman of the Year for the California Science Center in 2017.

J. Daniel Arthur, P.E., SPEC

President, Petroleum Engineer, Program Manager, ALL Consulting

Mr. Arthur is a registered professional petroleum engineer specializing in fossil energy, planning/engineering, the entire lifecycle of water, resource development best practices, gas storage, and environmental/regulatory issues. He has 30 years of diverse experience that includes work in industry, government, and consulting. Mr. Arthur is a founding member of ALL Consulting and has served as the company's President and Chief Engineer since its inception in 1999.

Prior to founding ALL Consulting, Mr. Arthur served as a Vice President of a large international consulting engineering firm and was involved with a broad array of work, including supporting the energy industry, various federal agencies, water and wastewater projects (municipal/industrial), environmental projects, various utility related projects, and projects related to the mining industry. Mr. Arthur's experience also includes serving as an enforcement officer and National Expert for the U.S. Environmental Protection Agency (EPA) and a drilling and operations engineer with an independent oil producer, as well as direct work with an oilfield service company in the mid-continent.

In 2016, Mr. Arthur was appointed to serve on a Steering Committee for Natural Gas Storage for the California Council on Science and Technology. Mr. Arthur's role on the Committee is primarily focused on well construction, integrity and testing based on his expertise, but also included overall analysis on issues such as global climate change and other issues (e.g., induced seismicity, gas markets, etc.). In 2010, as the shale boom was heightening, Mr. Arthur was appointed to serve as a Sub-Group Leader for a National Petroleum Council study on North American Resource Development. His Sub-Group focused on technology that is and will be needed to address development (e.g., hydraulic fracturing, horizontal drilling, production, etc.) and environmental challenges through the year 2050. Mr. Arthur was also appointed to a U.S. Department of Energy Federal Advisory Committee on Unconventional Resources. And lastly, Mr. Arthur supported the U.S. Department of Energy through the Annex III Agreement between the United States and China to provide support relative to coal bed methane and shale gas development in China.

Mr. Arthur routinely serves as a testifying and/or consulting expert on a broad variety of issues that range from basic engineering to catastrophic incidents. He has also served to advise management and legal teams on a plethora of issues in an effort to avoid litigation, reach settlements, or develop strategies for future activities. His experience and continued level of activity on such issues has expanded his experience on a variety of issues, while also exposing him to an array of technical and forensic approaches to assess past activities, claims, etc. Mr. Arthur is also a member of the National Association of Forensic Engineers (NAFE).

Mr. Arthur has managed an assortment of projects, including regulatory analysis (e.g., new regulation development process, commenting/strategizing on new proposed regulations, negotiating with regulatory agencies on proposed regulations, analysis of implementation impacts, etc.); engineering design (including roads, well pads, design of various types of wells; completions/fracturing; water and wastewater systems, and oil & gas facilities); life cycle analysis and modeling; resource evaluations; energy development alternatives analysis (e.g., oil, gas, coal, electric utility, etc.); feasibility analyses (including power plants, landfills, injection wells, water treatment systems, mines, oil & gas plays, etc.); remediation and construction; site closure and reclamation site decommissioning; reservoir evaluation; regulatory permitting and environmental work; geophysical well logging; development of new mechanical integrity testing methods, standards, and testing criteria; conduction and interpretation of well tests; restorative maintenance on existing wells and well sites; extensive hydrogeological and geochemical analysis of monitoring and operating data; sophisticated 2-dimensional and 3-dimensional modeling; geochemical modeling; drilling and completion operations; natural resource and environmental planning; natural resource evaluation; governmental and regulatory negotiations; restoration and remediation; environmental planning, design, and operations specific to the energy industry in environmentally sensitive areas; water management planning; alternative analysis for managing produced water; beneficial use of produced water; water treatment analysis and selection; produced water disposal alternatives; facilities engineering for wastewater handling (e.g., disposal wells, injection wells, water treatment, water recycling, water blending, etc.); construction oversight; contract negotiations and management; contract negotiation with wastewater treatment companies accepting produced water; data management related to water and environmental issues; property transfer environmental assessments; and data management of oil and gas producing and related injection well data and information. He maintains experience with the technical and regulatory aspects of oil and gas and underground injection throughout North America. He has given presentations, workshops, and training sessions to groups and organizations on an assortment of related issues and has provided his consulting expertise to hundreds of large and small clients - including several major international energy companies and government agencies.

Specific to unconventional resource development, Mr. Arthur has gained experience in all aspects of planning, development, operations, and closure. Mr. Arthur has supported the evolution of various activities through this process that have included technical issues such as water sourcing, well drilling techniques, cement design, well integrity analysis, fracturing design & analysis, well performance assessment, production operations and facilities, well plugging & abandonment, site closures, and regulatory compliance. Mr. Arthur's experience covers ever major unconventional play in North America and on other continents. Moreover, Mr. Arthur's experience also includes work with horizontal drilling and various types of completions in both conventional and unconventional reservoirs and with various types of unconventional reservoirs (e.g., shales, limestones, coal).

Riley M. Duren

Principal Engineer, Earth Science & Technology Directorate,
NASA Jet Propulsion Laboratory

Mr. Riley Duren is Chief Systems Engineer for the Earth Science and Technology Directorate at NASA's Jet Propulsion Laboratory. He received his BS in electrical engineering from Auburn University in 1992. He has worked at the intersection of engineering and science including seven space missions ranging from earth science to astrophysics. His current portfolio spans JPL's earth system science enterprise as well as applying the discipline of systems engineering to climate change decision-support. His research includes anthropogenic carbon emissions and working with diverse stakeholders to develop policy-relevant monitoring systems. He is Principal Investigator for five projects involving anthropogenic carbon dioxide and methane emissions. He has also co-led studies on geoengineering research, monitoring, and risk assessment. He is a Visiting Researcher at UCLA's Joint Institute for Regional Earth System Science and Engineering and serves on the Advisory Board for NYU's Center for Urban Science and Progress.

Karen Edson

Vice-President of Policy and Client Services,
California Independent System Operator (ISO), Retired

Ms. Karen Edson has nearly 40 years of experience involving state and federal energy issues. Most recently, she served as Vice-President of Policy and Client Services for the California Independent System Operator (ISO) from 2005 until her retirement in 2016. She performed a key role in building and maintaining strategic partnerships with responsibilities that included overseeing the outreach and education needs of a diverse body of stakeholders, state and federal regulators and policy makers. She was also a leader of internal policy development and oversaw internal and external communications. Her work in the energy field began in the seventies as a legislative aide and state agency government affairs director, leading to her appointment to the California Energy Commission by Governor Jerry Brown in 1981. After her term ended, she founded a small consulting firm that represented non-utility interests including geothermal and solar energy providers, industrial firms with combined heat and power, electric vehicle interests, and several trade associations. Ms. Edson holds a Bachelor's degree from the University of California Berkeley.

Catherine M. Elder, M.P.P.

Practice Director, Energy Economics, Aspen Environmental Group

Elder has 30 years of experience working in the natural gas and electric generation business and leads Aspen's Energy Economics practice, specializing in assistance to state energy agencies, public power entities and others. Elder worked on both federal and state-level natural gas industry restructuring as an employee of Pacific Gas and Electric Company beginning in the mid-1980's. She has reviewed fuel plans and advised lenders providing nonrecourse financing to more than 40 different gas-fired power projects across the U.S. and Canada, and has served as the Chief Gas Price Forecaster both for consultancy R.W. Beck and for the State of California's then-record $13 Billion financing of purchased power arising from the 2000-2001 power crisis. She holds a Master in Public Policy from the John F. Kennedy School of Government at Harvard University and an undergraduate degree in Political Economy (with Honors) from the University of California, Berkeley.

In starting her career at PG&E, Elder helped develop the policies and rules that to this day govern the natural gas market and regulatory framework in California. These include the unbundling of gas from transportation, the development of independent gas storage, and efforts to allow larger customers and marketers to bid for pipeline capacity in an auction whose results would have been used to establish priority of service. (The latter was abandoned in favor of a simpler mechanism in settlement.)

Since leaving PG&E in 1991, Elder worked for two years at law firm Brady & Berliner as its internal consultant, working often with Canadian natural gas producers selling natural gas in the U.S. She then joined Morse, Richard, Weisenmiller & Associates as a Senior Project Manager in Oakland, CA. From 1998 to 2003 she was a Principal Executive Consultant at Resource Management, Inc, in Sacramento, which ultimately became Navigant Consulting. At Navigant she performed independent reviews of natural gas markets, gas arrangements and disconnects between electricity and natural gas markets in support of nonrecourse financing by large financial institutions. She also reviewed the gas arrangement included in many of the tolling agreements put in place by the California Department of Water Resources during the 2000-2001 power crisis and developed the natural gas price forecast used by the state to project gas and electricity costs underlying the associated $13 Billion bond financing. In 2003 she joined consultancy RW Beck, as its natural gas market expert and chief price forecaster, and in 2009 joined Aspen Environmental Group. At Aspen, Elder leads the Energy Economics practice. Key clients have included the American Public Power Association, for whom she authored a major report in 2010 entitled "Implications of Greater Reliance on Natural Gas for Electricity Generation," and the California Energy Commission. Elder has served as the independent fuel consultant for lenders to more than 40 natural gas-fired power projects across the U.S. and Canada.

Jeffery B. Greenblatt, Ph.D.

Staff Scientist, Energy Analysis and Environmental Impacts Division,
Lawrence Berkeley National Laboratory

Jeffery Greenblatt has been involved with modeling pathways of low-carbon energy future since 2006. He has published a number of studies including the groundbreaking California's Energy Future study (sponsored California Council on Science and Technology), an analysis of California greenhouse gas policies in Energy Policy, an analysis of US policies in Nature Climate Change, and a review of the future of low-carbon electricity forthcoming in Annual Review of Environment and Resources. He also works on the life-cycle assessment of emerging technologies including artificial photosynthesis and autonomous vehicles, was involved with both DOE's Quadrennial Technology Review and Quadrennial Energy Review efforts, and recently started a consulting company focused on space technologies. He has more than 15 years of experience in climate change and low-carbon energy technology assessment and modeling. Prior to joining LBNL in 2009, Dr. Greenblatt worked at Google on the Renewable Electricity Cheaper than Coal initiative,
at Environmental Defense Fund as an energy scientist, at Princeton University as a research staff member, and at NASA Ames as a National Research Council associate.
He received a Ph.D. in chemistry from UC Berkeley in 1999.

Robert B. Jackson, Ph.D.

Professor and Chair, Earth Sciences Department, Stanford University

Robert B. Jackson is Michelle and Kevin Douglas Provostial Professor and chair of the department of Earth System Science in the School of Earth, Energy & Environmental Sciences. He studies how people affect the earth, including research on the global carbon and water cycles, biosphere/atmosphere interactions, energy use, and climate change.

Jackson has received numerous awards. He is a Fellow in the American Geophysical Union and the Ecological Society of America and was honored at the White House with a Presidential Early Career Award in Science and Engineering. In recent years, he directed the DOE National Institute for Climate Change Research for the southeastern U.S., co-chaired the U.S. Carbon Cycle Science Plan, and is currently CHAIR of the Global Carbon Project (www.globalcarbonproject.org).

An author and photographer, Rob has published a trade book about the environment (The Earth Remains Forever, University of Texas Press) and two books of children's poems, Animal Mischief and Weekend Mischief (Highlights Magazine and Boyds Mills Press). His photographs have appeared in many media outlets, including the NY Times, Washington Post, USA Today, US News and World Report, Nature, and National Geographic.

Michael L.B. Jerrett, Ph.D.

Professor and Chair, Department of Environmental Health Sciences,
University of California, Los Angeles

Dr. Michael Jerrett is an internationally recognized expert in Geographic Information Science for Exposure Assessment and Spatial Epidemiology. He is a full professor and the chair of the Department of Environmental Health Science, and Director of the Center for Occupational and Environmental Health, Fielding School of Public Health, University of California, Los Angeles. Dr. Jerrett is also a professor in-Residence in the Division of Environmental Health Sciences, School of Public Health, University of California, Berkeley. Dr. Jerrett earned his PhD in Geography from the University of Toronto. Over the past 20 years, Dr. Jerrett has researched how to characterize population exposures to air pollution and built environmental variables, the social distribution of these exposures among different groups (e.g., poor vs. wealthy), and how to assess the health effects from environmental exposures. He has worked extensively on how the built environment affects exposures and health, including natural experimental design studies. He has published some of the most widely-cited papers in the fields of Exposure Assessment and Environmental Epidemiology in leading journals, including The New England Journal of Medicine, The Lancet, and Proceedings of the National Academy of Science of the United States of America, and Nature. In 2009, the United States National Academy of Science appointed Dr. Jerrett to the Committee on "Future of Human and Environmental Exposure Science in the 21st Century." The Committee concluded its task with the publication of a report entitled Exposure Science in the 21st Century: A Vision and a Strategy. In 2014 and 2015, he was named to the Thomson-Reuters List of Highly-Cited Researchers, indicating he is in the top 1% of all authors in the fields of Environment/Ecology in terms of citation by other researchers. In 2016, Dr. Jerrett was appointed to the National Academy of Science Standing Committee on Geographical Sciences.

Najmedin Meshkati, Ph.D.

Professor, Department of Civil and Environmental Engineering
Department of Industrial and Systems Engineering, University of Southern California

Dr. Najmedin Meshkati is a (tenured, full) Professor of Civil/Environmental Engineering; Industrial & Systems Engineering; and International Relations at the University of Southern California (USC). He was a Jefferson Science Fellow and a Senior Science and Engineering Advisor, Office of Science and Technology Adviser to the Secretary of State, US State Department, Washington, DC (2009-2010). He is a Commissioner of The Joint Commission (2016-; a not-for-profit organization that accredits and certifies nearly 21,000 healthcare organizations and programs in the United States and operates in 92 countries around the world, http://www.jointcommission.org/) and is on the Board of Directors of the Center for Transforming Healthcare. He has served as a member of the Global Advisory Council of the Civilian Research and Development Foundation (CRDF) Global, chaired by Ambassador Thomas R. Pickering (2013-2016).

For the past 30 years, he has been teaching and conducting research on risk reduction and reliability enhancement of complex technological systems, including nuclear power, aviation, petrochemical and transportation industries. He has been selected by the US National Academy of Sciences (NAS), National Academy of Engineering (NAE) and National Research Council (NRC) for his interdisciplinary expertise concerning human performance and safety culture to serve as member and technical advisor on two national panels in the United States investigating two major recent accidents: The NAS/NRC Committee "Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants" (2012-2014); and the NAE/NRC "Committee on the Analysis of Causes of the Deepwater Horizon Explosion, Fire, and Oil Spill to Identify Measures to Prevent Similar Accidents in the Future" (2010-2011).

Dr. Meshkati has inspected many petrochemical and nuclear power plants around the world, including Chernobyl (1997), Fukushima Daiichi and Daini (2012). He has worked with the U.S. Chemical Safety and Hazard Investigation Board, as an expert on human factors and safety culture, on the investigation of the BP Refinery explosion in Texas City (2005), and served as a member of the National Research Council (NRC) Committee on Human Performance, Organizational Systems and Maritime Safety. He also served as a member of the NRC Marine Board's Subcommittee on Coordinated R&D Strategies for Human Performance to Improve Marine Operations and Safety.

Dr. Meshkati is the only full-time USC faculty member who has continuously been conducting research on human factors and aviation safety-related issues (e.g., cockpit design and automation, crew resource management, safety management system, safety culture, and runway incursions,) and teaching in the USC 63-year old internationally renowned Aviation Safety and Security Program, for the past 25 years. During this period, he has taught in the "Human Factors in Aviation Safety" and "System Safety" short courses. From 1992 to 1999, he also was the Director and had administrative and academic responsibility for the USC Professional Programs, which included Aviation Safety, as well as for the Transportation Safety, and Process Safety Management (which he designed and developed) programs. He has worked with numerous safety professionals from all over the world and has taught safety short courses for private and public sector organizations, including the US Navy, US Air Force, US Forest Service, California OSHA, Celgene, Metrolink, Exelon, the Republic of Singapore Air Force, Singapore Institution of Safety Officers, China National Petrochemical Corporation, Canadian upstream oil and gas industry (Enform), Korea Hydro and Nuclear Power (KHNP), Ministry of Foreign Affairs (Republic of Korea), etc.

Dr. Meshkati is an elected Fellow of the Human Factors and Ergonomics Society (HFES); the 2015 recipient of the HFES highest award, the Arnold M. Small President's Distinguished Service Award, for his "career-long contributions that have brought honor to the profession and the Society"; and the 2007 recipient of the HFES Oliver Keith Hansen Outreach Award for his "scholarly efforts on human factors of complex, large-scale technological systems." He is the inaugural recipient of the Ernest Amory Codman Lectureship and Award (form The Joint Commission for his leadership and efforts in continuously improving the safety and quality of care). He is an AT&T Faculty Fellow in Industrial Ecology, a NASA Faculty Fellow (Jet Propulsion Laboratory, 2003 and 2004), and a recipient of the Presidential Young Investigator Award from the National Science Foundation (NSF) in 1989.

He has received numerous teaching awards at USC, which include the 2013 Steven B. Sample Teaching and Mentoring Award from the USC Parents Association, the 2000 TRW Award for Excellence and Outstanding Achievement in Teaching from the USC Viterbi School of Engineering; the 1996, 2003, 2006, 2007, 2008 and 2016 Professor of Year Award (Excellence in Teaching and Dedication to Students Award) from the Daniel J. Epstein Department of Industrial & Systems Engineering; the Mortar Board's Honored Faculty Award (2007-2008) from the University of Southern California's Chapter of the Mortar Board; and the Outstanding Teaching Award from The Latter-day Saint Student Association at USC (April 11, 2008). He was chosen as a Faculty Fellow by the Center for Excellence in Teaching, USC (2008-2010).

He is the co-editor and a primary author of the book Human Mental Workload, North-Holland, 1988. His articles on public policy; the risk, reliability, and environmental impact of complex, large-scale technological systems; and foreign policy-related issues have been published in several national and international newspapers and magazines such the New York Times, International New York Times (International Herald Tribune), Los Angeles Times, Washington Post, Baltimore Sun, Houston Chronicle, Sacramento Bee, MIT Technology Review, Japan Times, Korea Herald (South Korea), Gulf Today (Sharjah, UAE), Times of India, Hurriyet Daily News (Istanbul, Turkey), Strait Times (Singapore), Iran News (Tehran, Iran), South China Morning Post (Hong Kong), Winnipeg Free Press, Waterloo Region Record, Windsor Star (Canada), Scientific Malaysian, etc.

As chairman of the "group of expects" of the International Ergonomics Association (IEA), Dr. Meshkati coordinated international efforts which culminated in the joint publication of the United Nations' International Labor Office (ILO) and IEA Ergonomic Checkpoints: Practical and Easy-to-Implement Solutions for Improving Safety, Health and Working Conditions book in 1996, for which he received the Ergonomics of Technology Transfer Award from the IEA in 2000. According to the ILO, this book has so far been translated and published into 16 languages including Arabic, Bahasa Indonesia, Bahasa Malaysian, Chinese, Estonian, Farsi, French, Japanese, Korean, Polish, Portuguese, Russian, Spanish, Thai, Turkish, and Vietnamese. The second edition of this book was released by the ILO/IEA in 2010.

Dr. Meshkati simultaneously received a B.S. in Industrial Engineering and a B.A. in Political Science in 1976, from Sharif (Arya-Meher) University of Technology and Shahid Beheshti University (National University of Iran), respectively; a M.S. in Engineering Management in 1978; and a Ph.D. in Industrial and Systems Engineering in 1983 from USC. He is a Certified Professional Ergonomist.

Curtis M. Oldenburg, Ph.D.

Geological Senior Scientist, Energy Geosciences Division,
Lawrence Berkeley National Laboratory

Curtis Oldenburg is a Senior Scientist, Energy Resources Program Domain Lead, Geologic Carbon Sequestration Program Lead, and Editor in Chief of Greenhouse Gases: Science and Technology. Curt's area of expertise is numerical model development and applications for coupled subsurface flow and transport processes. He has worked in geothermal reservoir modeling, vadose zone hydrology, and compressed gas energy storage. Curt's focus for the last fifteen years has been on geologic carbon sequestration with emphasis on CO2 injection for enhanced gas recovery, and near-surface leakage and seepage including monitoring, detection, and risk-based frameworks for site selection and certification. Curt Oldenburg is a co-author of the textbook entitled Introduction to Carbon Capture and Sequestration.

Scott A. Perfect, Ph.D.

Chief Mechanical Engineer, Engineer Directorate,
Lawrence Livermore National Laboratory

Dr. Perfect is the Chief Mechanical Engineer for the Engineering Directorate at Lawrence Livermore National Laboratory (LLNL). In this role, Dr. Perfect provides leadership ensuring the safety and technical quality of mechanical and related engineering activities conducted throughout the 1600-member Engineering Directorate in support of the Laboratory's diverse missions. Along with the Chief Electronics Engineer, he oversees workforce management and employee development activities within the Engineering Directorate.

Dr. Perfect received his B.S. in Civil Engineering and his M.S. and Ph.D. degrees in Theoretical and Applied Mechanics from the University of Illinois, Urbana-Champaign.

Dr. Perfect began his career at LLNL in 1986 as a member of the Experimental Physics Group, designing hardware, conducting experiments, and performing computational simulations in support of the Defense and Nuclear Technologies Program. After three years in that assignment, he joined the Structural and Applied Mechanics Group where he conducted large-scale nonlinear finite element analyses in support of many projects across the LLNL mission space. His prior leadership assignments are Associate Division Leader for the Defense Technologies Engineering Division and Group Leader for the Structural and Applied Mechanics Group. He has published in the areas of vehicle crashworthiness, nuclear material storage and transportation, magnetic fusion energy, biomechanics of human joints, laser crystal stability, single-crystal plasticity, hydrogen storage, and weapon systems.

Terence Thorn

President, JKM Energy and Environmental Consulting

Terence (Terry) Thorn is a 42-year veteran of the domestic and international natural gas industry and has held a wide variety of senior positions beginning his career as Chairman of Mojave Pipeline Company and President and CEO of Transwestern Pipeline Company. He has worked as an international project developer throughout the world.

As a Chief Environmental Officer, Terry supported Greenfield projects in 14 countries to minimize their environmental impact. He wrote and had adopted company wide Environmental Health and Safety Management Standards and implemented the first environmental management plan for pipeline and power plant construction. In attendance at COP 1 and 2, Terry has remained involved in the climate change discussions where he is focusing on international policies and best practices to control methane emissions.

Residing in Houston, Terry is President of JKM Energy and Environmental Consulting and specializes in project development and management, environmental risk assessment and mitigation, business and policy development, and market analysis. He has done considerable work in the areas of pipeline integrity management systems including audit systems for safety and integrity management programs.

He currently serves as Senior Advisor to the President of the International Gas Union where he helps drive the technical, policy and analytical work product for the 13 Committees and Task Forces with their 1000 members from 91 countries. He also serves on the Advisory Boards for the North American Standards Board where he co-chaired the gas electric harmonization task force, and the University of Texas' Bureau of Economic Geology's Center for Energy Economics where he helped found the Electric Power Research Forum. Terry is also on the Board of Air Alliance Houston which focuses on Houston's greatest air pollution challenges in collaboration with universities, regulators, and partner organizations.

Terry has published numerous articles on energy, risk management and corporate governance and was author of the International Energy Agency's 2007 North American Gas Market Review. As advisor to European gas companies and regulators he co-authored The Natural Gas Transmission Business -a Comparison Between the Interstate US-American and European Situations, Environmental Issues Surrounding Shale Gas Production, The U.S. Experience, A Primer. As a participant in the National Petroleum Council Study Prudent Development: Realizing the Potential of North America›s Abundant Natural Gas and Oil Resources (September 2011), Terry wrote in coordination with the subject team the section on electric gas harmonization, co-authored the chapter on electric generation, and advised on the residential commercial chapter. Most recently he has completed market research projects on electricity markets and gas markets including modeling the US gas markets 2015-2050. Gas Shale Environmental Issues and Challenges was just published by Curtin University in 2015. His most recent papers are «The Bridge to Nowhere: Gas in An All Electric World,» «The Paradigms of Reducing Energy Poverty and Meeting Climate Goals,» and «Making Fossil Fuels Great Again: Initial Thoughts on the Trump Energy Policy.»

Samuel J. Traina, Ph.D.

Vice Chancellor of Research and Economic Development,
University of California, Merced

Dr. Samuel Justin Traina joined the University of California, Merced in July 2002 as the founding director of the Sierra Nevada Research Institute. Prior to beginning his UC Merced duties, Dr. Traina was a professor at Ohio State University.

Dr. Traina received his bachelor's degree in soil resource management and his doctorate in soil chemistry from UC Berkeley, where he also served as a graduate research assistant and graduate teaching assistant. Immediately following, he moved to UC Riverside to conduct postdoctoral research and work as an assistant research soil chemist in the Department of Soil and Environmental Sciences.

In July 2007 Dr. Traina became the Vice Chancellor for Research and Graduate Dean.
As of July 1, 2012 Dr. Traina became solely the Vice Chancellor for Research and Economic Development.

Michael W. Wara, J.D., Ph.D.

Associate Professor, Stanford Law School

An expert on energy and environmental law, Michael Wara's research focuses on climate and electricity policy. Professor Wara's current scholarship lies at the intersection between environmental law, energy law, international relations, atmospheric science, and technology policy.

Professor Wara, JD '06, was formerly a geochemist and climate scientist and has published work on the history of the El Niño/La Niña system and its response to changing climates, especially those warmer than today. The results of his scientific research have been published in premier scientific journals, including Science and Nature.

Professor Wara joined Stanford Law in 2007 as a research fellow in environmental law and as a lecturer in law. Previously, he was an associate in Holland & Knight's Government Practice Group, where his practice focused on climate change, land use, and environmental law.

Professor Wara is a research fellow at the Program in Energy and Sustainable Development in Stanford's Freeman Spogli Institute for International Studies, a Faculty Fellow at the Steyer-Taylor Center for Energy Policy and Finance, and a Center Fellow at the Woods Institute for the Environment.

Appendix D

Report Author Biosketches

- **Scott Backhaus**, Los Alamos National Laboratory
- **Giorgia Bettin**, Sandia National Laboratories
- **Robert J. Budnitz**, Scientific Consulting
- **Eliza D. Czolowski**, PSE Healthy Energy
- **Marcus Daniels**, Los Alamos National Laboratory
- **Mary E. Ewers**, Los Alamos National Laboratory
- **Marc L. Fischer**, Lawrence Berkeley National Laboratory
- **S. Katharine Hammond**, University of California, Berkeley
- **Lee Ann Hill**, PSE Healthy Energy
- **Preston D. Jordan**, Lawrence Berkeley National Laboratory
- **Thomas E. McKone**, Lawrence Berkeley National Laboratory
- **Kuldeep R. Prasad**, National Institute of Standards and Technology
- **Seth B. C. Shonkoff**, PSE Healthy Energy
- **Tom Tomastik**, ALL Consulting, LLC
- **Rodney Walker**, Walker & Associates Consultancy
- **Max Wei**, Lawrence Berkeley National Laboratory

SCOTT BACKHAUS

Information Systems and Modeling Group
Los Alamos National Laboratory
MS C933 Los Alamos, NM 87545
Phone: +1 (505) 667-7545, email: backhaus@lanl.gov

EDUCATION

1997	PHD-PHYSICS University of California, Berkeley, CA
1990	BS-ENGINEERING/PHYSICS University of Nebraska, Lincoln, NE

RESEARCH AND PROFESSIONAL EXPERIENCE

Scott Backhaus received his Ph.D. in Physics in 1997 from the University of California at Berkeley in the area of macroscopic quantum behavior of superfluid 3He and 4He. He is currently the principal investigator for several LANL projects funded by the Office of Electricity in the U.S. Department of Energy, is LANL Program Manager for Office of Electricity and for DHS Critical Infrastructure, and leads LANL's component of the DHS National Infrastructure Simulation and Analysis Group.

CURRENT AND PAST POSITIONS

Since 2015	Principal Investigator, National Infrastructure Simulation and Analysis Center, DHS/OCIA Los Alamos National Laboratory, NM
Since 2015	Program Manager, DHS Critical Infrastructure, Emerging Threats Program Office, Global Security, Los Alamos National Laboratory, NM
Since 2012	Program Manager, DOE Office of Electricity, Science Program Office, Applied Energy, Los Alamos National Laboratory
Since 2012	Principal Investigator, Grid Science Projects DOE/OE, Los Alamos National Laboratory, NM
2010	Principal Investigator, Microgrid Projects. Los Alamos National Laboratory, NM
2003-2015	Technical Staff Member, Condensed Matter and Magnet Science Group, Los Alamos National Laboratory, NM

2000-2002	Reines Fellow, Condensed Matter and Thermal Physics Group, Los Alamos National Laboratory, NM
1998-2000	Director's Funded Postdoctoral Fellow, Condensed Matter and Thermal Physics Group, Los Alamos National Laboratory, NM
1992-1997	Graduate Student Researcher, Department of Physics University of California at Berkeley, CA

HONORS AND AWARDS

2011	Best Paper of the Year, "Quarter-wave pulse tube"–Cyrogenics 2003 MIT Technology Review Top 100 Innovators Under 35
2003	New Horizons Idea Award, World Oil Magazine
2000-2003	Reines Fellow, Los Alamos National Laboratory, NM
1999	R&D 100 Award, Thermo Acoustic Stirling Heat Engine, R&D Magazine
1999	Postdoctoral Publication Prize in Experimental Science, "Thermoacoustic- Stirling Heat Engine", Los Alamos National Laboratory, NM
1998-2000	Director Funded Postdoctoral Fellow, Los Alamos National Laboratory, NM
1994-1997	Graduate Student Researcher Fellowship, NASA
1990-1993	National Science Foundation Graduate Fellowship

GIORGIA BETTIN

Sandia National Laboratories
P.O. Box 5800 Albuquerque, NM 87185-0750
Phone: +1 (505) 844-9315, gbettin@sandia.gov

EDUCATION

2007	PHD-MECHANICAL ENGINEERING Massachusetts Institute of Technology, MA
2005	MS-MECHANICAL ENGINEERING Massachusetts Institute of Technology, MA
2002	BS-MECHANICAL ENGINEERING University of California, Berkley, CA

CURRENT AND PAST POSITIONS

Since 2012	Senior Member of Technical Staff, Geoscience Research and Applications Sandia National Laboratories
2007-2010	Research Scientist, Materials and Mechanics group Schlumberger Doll Research
2002-2007	Research Assistant, Institute for Soldier Nanotechnology Massachusetts Institute of Technology

ROBERT J. BUDNITZ

Robert J. Budnitz Scientific Consulting
734 The Alameda, Berkeley, CA 94707
Phone: +1 (510) 529-9775, budnitz@pacbell.net

EDUCATION

1968	PHD-PHYSICS Harvard University, Cambridge, MA
1962	MA-PHYSICS Harvard University, Cambridge, MA
1961	BA-PHYSICS Yale University, New Haven, CT

CURRENT AND PAST POSITIONS

Since 2017	Principle Consultant, Robert J. Budnitz Scientific Consulting
Since 2017	Affiliate (retired), Energy Geosciences Division Lawrence Berkeley National Laboratory, University of California, Berkeley, CA
2007-2017	Staff Scientist, Energy Geosciences Division Lawrence Berkeley National Laboratory, University of California, Berkeley, CA
2004-2007	Leader, Nuclear and Risk Science Group, Energy and Environment Directorate Program Leader for Nuclear Systems Safety and Security, E&E Directorate Lawrence Livermore National Laboratory, University of California, Livermore, CA
2002-2004	Responsible for the Science & Technology Program, DOE Yucca Mountain Project at the US Department of Energy, Washington D.C. Lawrence Livermore National Laboratory, University of California, Livermore, CA
1981-2002	President, Future Resources Associates, Inc., Berkeley, CA
1980-1981	Vice President and Director, Energy and Environmental Technologies Division Teknekron, Inc., Berkeley, CA

1978-1980	Deputy Director and Director, Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission, Washington D.C.
1967-1980	Associate Director of LBL and Head, Energy & Environment Division Program Leader, LBL Environmental Research Program Physicist, LBL Environmental Research Program Post-Doctoral Physicist, LBL High-Energy Physics Program Lawrence Berkeley National Laboratory, University of California, Berkeley, CA

HONORS AND AWARDS

2017	Elected member, U.S. National Academy of Engineering
2007	Elected Fellow, American Association for the Advancement of Science
2006	American Nuclear Society, Standards Service Award
2005	American Nuclear Society, Theos J. Thompson Award for Reactor Safety
2002	Selected National Associate, U.S. National Academy of Sciences
2001	Society for Risk Analysis, "Outstanding Risk Practitioner Award for 2001"
1998	Elected Fellow, American Nuclear Society
1996	Elected Fellow, Society for Risk Analysis
1988	Elected Fellow, American Physical Society
1988	American Nuclear Society, Nuclear Reactor Safety Division "Best Paper Award"
1961	National Science Foundation Graduate Fellowship in Physics

ELIZA D. CZOLOWSKI
PSE Healthy Energy (Physicians, Scientists, and Engineers for Healthy Energy)
950 Danby Rd. Suite 260 Ithaca, NY 14850
Phone: +1 (607) 252-6754, elizac@psehealthyenergy.org

EDUCATION

2013	MS-PROFESSIONAL STUDIES IN ENVIRONMENTAL SCIENCE SUNY College of Environmental Science and Forestry, Syracuse, NY
2009	BS-ENVIRONMENTAL SCIENCE Allegheny College, Meadville, PA

CURRENT AND PAST POSITIONS

Since 2015	Program Associate, Energy-Environment Program PSE Healthy Energy, Ithaca, NY
2012-2015	Scientist 1 / Graphics Area Lead GZA Geoenvironmental Inc., East Syracuse, NY
2011-2012	GIS Specialist The Palmerton Group, LCC, East Syracuse, NY
2009-2010	Research Scientist, accuracy assessment of land use change maps, water quality Geographic Modeling Services, Jamesville, NY

MARCUS DANIELS

Los Alamos National Laboratory, MS C933
Los Alamos, NM 87545
Phone: +1 (505) 216-1182, mdaniels@lanl.gov

EDUCATION

1996	SYSTEM SCIENCE, PSU
1994	PSYCHOLOGY, PSU

CURRENT AND PAST POSITIONS

Since 2015	Molecular Dynamics, Exploratory Research Program Los Alamos National Laboratory, NM
Since 2016	National Infrastructure Simulation and Anlaysis Center Los Alamos National Laboratory, NM
Since 2015	Quantum Computation, Directed Research Program Los Alamos National Laboratory, NM
2013-2014	ASC Verification and Validation Los Alamos National Laboratory, NM
Since 2012	Promoted Scientist 3, ASC Eulerian codes Los Alamos National Laboratory, NM
2010-2012	Promoted Scientist 2, Programming Models Team Los Alamos National Laboratory, NM
2005-2010	Research Technologist 3, Theoretical Biology Los Alamos National Laboratory, NM
2004-2006	Consulting Modeler, US Department of Agriculture
2001-2005	Modeler, Markets Evolution Research Group Santa Fe Institute, NM
1996-1999	Lead Developer Swarm Program, Executive Director Swarm Developer Group Santa Fe Institute, NM

MARY E. EWERS

A-1, Informational Systems and Modeling
Los Alamos National Laboratory, MS C933
Los Alamos, NM 87545
Phone: +1 (505) 500-2306, mewers@lanl.gov

EDUCATION

2004	PHD-ECONOMICS University of New Mexico, Albuquerque, NM
2002	MA-ECONOMICS University of New Mexico, Albuquerque, NM
1987	BA-ECONOMICS University of California, Santa Barbara, CA

CURRENT AND PAST POSITIONS

Since 2004	Scientist 3, 2, 1, National Infrastructure Simulation and Analysis Center (NISAC) PI Global Oil and Natural Gas Capability Development Los Alamos National Laboratory, NM
2001-2004	Teaching and Research Assistant University of New Mexico, NM

HONORS AND AWARDS

2015	LANL Awards Program in recognition of excellent performance and commitment to the NISAC Fast Response Team
2002	J. Raymond Stuart Prize in Economics, University of New Mexico, NM

MARC L. FISCHER

Atmospheric Science Department
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
1 Cyclotron Rd. Berkeley, CA 94720
Phone: +1 (510) 486-5539, mlfischer@lbl.gov

EDUCATION

1991	PHD-PHYSICS University of California, Berkeley, CA
1982	MS-PHYSICS University of Illinois at Urbana-Champaign, IL
1981	BS-PHYSICS Massachusetts Institute of Technology, MA

CURRENT AND PAST POSITIONS

Since 1998	Staff Scientist, Lawrence Berkeley National Laboratory, Berkeley, CA
1995-1997	Assistant Research Scientist, Environmental Science and Policy Program, University of California, Berkeley, CA
1993-1995.	Postdoctoral Fellow, Lawrence Berkeley National Laboratory, Berkeley, CA
1991-1993	Postdoctoral Fellow, Department of Physics, University of California, Berkeley, CA

HONORS AND AWARDS

1987-1990	NASA Graduate Student Research Fellow
1983	Berkeley University Fellow

S. KATHARINE HAMMOND

School of Public Health
University of California, Berkeley
50 University Hall MS 7360
Phone: +1 (510) 643-0289, hammondk@berkeley.edu

EDUCATION

1981	MS-ENVIRONMENTAL HEALTH SCIENCES Harvard School of Public Health, MA
1976	PHD-CHEMSITRY Brandeis University, MA
1971	BA-CHEMISTRY Oberlin College, OH

CURRENT AND PAST POSITIONS

Since 2016	Associate Dean for Academic Affairs, School of Public Health, University of California, Berkeley, CA
Since 1994	Professor of Environmental Health Sciences (Associate Professor 1994-2000), School of Public Health, University of California, Berkeley, CA
Since 2013 1994-2001	Director, Industrial Hygiene Program, University of California, Berkeley, CA
2014-2017	Co-Chair, Graduate Group in Environmental Health Sciences, University of California, Berkeley, CA
2006-2012	Chair, Environmental Health Sciences Division, School of Public Health, University of California, Berkeley, CA
1998-2006	Chair, Graduate Group in Environmental Health Sciences, University of California, Berkeley, CA
1985-1994	Associate Professor of Family and Community Medicine and of Pharmacology (Assistant Professor 1985-1989; tenured in April, 1993), University of Massachusetts Medical Center Worcester, MA
1993-1994	Director, Environmental Health Division, Department of Family and Community, Medicine, University of Massachusetts Medical Center Worcester, MA

1985-2003	Visiting Lecturer on Industrial Hygiene; Harvard School of Public Health, Boston, MA
1981-1984	Research Associate, Industrial Hygiene, Harvard School of Public Health, Boston, MA
1976-1980	Assistant Professor of Chemistry, Wheaton College, Norton, MA

HONORS AND AWARDS

2013-2017	School of Public Health Committee on Teaching Excellence Award
2008	Henry F. Smyth Award, Academy of Industrial Hygiene, American Industrial Hygiene Association
2008	Dr. William Cahan Distinguished Professor Award, Flight Attendants Medical Research Institute
2005	Alfred W. Childs Distinguished Service Award, U of CA, Berkeley, School of Public Health
2004	Rachel Carson Environmental Award, American Industrial Hygiene Association
2002	Fellow, American Industrial Hygiene Association
1999	Alice Hamilton Award for Excellence in Occupational Safety and Health, NIOSH

LEE ANN HILL

PSE Healthy Energy (Physicians, Scientists, and Engineers for Healthy Energy)
1440 Broadway, Suite 205
Oakland, CA 94612
Phone: +1 (510) 330-5552, lhill@psehealthyenergy.org

EDUCATION

2016	MS-PUBLIC HEALTH, ENVIRONMENTAL HEALTH SCIENCES University of California, Berkeley, CA
2013	BS-ENVIRONMENTAL SCIENCE Ithaca College, Ithaca, NY

CURRENT AND PAST POSITIONS

Since 2016	Associate, Environmental Health Program PSE Healthy Energy, Oakland, CA
2016	Research Assistant Office of Environmental Health Hazard Assessment, Oakland, CA
2015	Health Intern Natural Resources Defense Council, San Francisco, CA
2014	Environmental Laboratory Intern Ithaca Area Wastewater Treatment Facility, Ithaca, NY
2013	Water Quality Intern City of Ithaca Water Treatment Plant, Ithaca, NY
2013	Environmental Health Intern Tompkins County Health Department, Ithaca, NY

PRESTON D. JORDAN

Energy Geosciences Division
Lawrence Berkeley National Laboratory
1 Cyclotron Rd. Berkeley, CA 94720
Phone: +1 (510) 486-6774, PDJordan@lbl.gov

EDUCATION

1997	MS-GEOTECHNICAL ENGINEERING University of California, Berkeley, CA
1988	BA-GEOLOGY University of California, Berkeley, CA

CURRENT AND PAST POSITIONS

Since 2017	Principal Scientific Engineering Associate, Energy Geosciences Division Lawrence Berkeley National Laboratory, CA
2010-2017	Staff Research Associate, Energy Geosciences Division Lawrence Berkeley National Laboratory, CA
1998-2010	Principal Research Associate, Earth Science Division Lawrence Berkeley National Laboratory, CA
1995-1998	Senior Research Associate, Earth Science Division Lawrence Berkeley National Laboratory, CA
1994-1995	Research Associate, Earth Science Division Lawrence Berkeley National Laboratory, CA
1990-1994	Research Technician, Earth Science Division Lawrence Berkeley National Laboratory, CA
1989-1990	Field Geologist, Consultant to the United States Department of Justice

AWARDS

2016	Societal Impact for the Aliso Canyon natural gas storage well blowout response, Lawrence Berkeley National Laboratory
2015	Spot for the SB4 well stimulation study, Lawrence Berkeley National Laboratory

2014	Spot for the BLM CA hydraulic fracturing study, Lawrence Berkeley National Laboratory
2012	Outstanding Mentor, Lawrence Berkeley National Laboratory
2010	Outstanding Performance for community relations, Lawrence Berkeley National Laboratory

THOMAS E. MCKONE

Lawrence Berkeley National Laboratory
One Cyclotron Road, Berkeley, CA 94720
Phone: +1 (510) 486-6163, temckone@LBL.gov

EDUCATION

1981	PHD-ENGINEERING University of California, Los Angeles, CA
1977	MS-ENGINEERING University of California, Los Angeles, CA
1974	BA-CHEMISTRY St. Thomas College, St. Paul, MN

CURRENT AND PAST POSITIONS

Since 2015	Affiliated Faculty School of Public Health, University of California, Berkeley, CA
Since 2011	Senior Scientist and Deputy for Research Programs Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkeley, CA
2015-2016	Velux Visiting Professor Technical University of Denmark, Lyngby, Denmark
1996-2015	Professor and Research Scientist Step V School of Public Health, University of California, Berkeley, CA
2003-2011	Senior Scientist, Deputy Department Head, Group Leader Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA
2000-2003	Senior Scientist and Group Leader Exposure and Risk Analysis Group, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA
1996-2000	Staff Scientist and Group Leader Exposure and Risk Analysis Group, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA
1983-1995	Staff Scientist Health and Ecological Assessments Division, Lawrence Livermore National Laboratory, CA

1992-1995	Lecturer and Research Engineer Environmental Toxicology Department, University of California, Davis, CA
1987-1988	Visiting Scientist Interdisciplinary Programs in Health, School of Public Health, Harvard University, Boston, MA
1981-1983	Postdoctoral Fellow US Nuclear Regulatory Commission Advisory Committee on Reactor Safeguards (ACRS), Washington, DC
1974-1979	Post Graduate Research Engineer and Teaching Assistant University of California, Los Angeles, CA

HONORS AND AWARDS

2008	Jerome J. Wesolowski Award, International Society of Exposure Science
2003	Constance L. Mehlman Award, International Society of Exposure Science
1981-1983	Fellowship with Advisory Committee on Reactor Safeguards, US Nuclear Regulatory Commission
	Appointment to Scientific Guidance Panel of the California Environmental Contaminant Biomonitoring Program by Governor Arnold Schwarzenegger
	Fellow, Society for Risk Analysis

KULDEEP R. PRASAD

National Institute of Standards and Technology (NIST)
100 Bureau Dr., Gaithersburg, MD 20899

EDUCATION

1991	PHD-AEROSPACE ENGINEERING Georgia Institute of Technology, Atlanta, GA
1987	MS-AEROSPACE ENGINEERING Georgia Institute of Technology, Atlanta, GA
1986	BTech-AERONAUTICAL ENGINEERING Indian Institute of Technology, Kanpur, India

CURRENT AND PAST POSITIONS

Since 2001	Research Engineer, Fire Research Division, National Institute of Standards and Technology, MD
1996-2001	Research Scientist, Computational Physics Naval Research Laboratory, Monterey, CA
1993-1995	Postdoctoral Research Associate, Mechanical Engineering Yale University, New Haven, CT

HONORS AND AWARDS

2007	Special Achievement Award, Department of Commerce
2005	Gold Medal Award for Outstanding Achievement in Science and Engineering

SETH B. C. SHONKOFF
PSE Healthy Energy (Physicians, Scientists, and Engineers for Healthy Energy)
1440 Broadway, Ste. 205, Oakland, CA 94612
Phone: +1 (510) 330-5554, sshonkoff@berkeley.edu

EDUCATION

2012	PHD-ENVIRONMENTAL SCIENCE, POLICY AND MANAGEMENT, University of California, Berkeley, CA
2008	MPH-EPIDEMIOLOGY, University of California, Berkeley, CA
2003	BA-ENVIRONMENTAL STUDIES, Skidmore College, Saratoga Springs, NY

CURRENT AND PAST POSITIONS

Since 2012	Executive Director PSE Healthy Energy, Oakland, CA
Since 2012	Visiting Scholar Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA
Since 2014	Affiliate, Energy Technologies Area Lawrence Berkeley National Laboratory, Berkeley, CA
2011-2014	Contributing Author Intergovernmental Panel on Climate Change (IPCC), University of California, Berkeley, CA
2008-2012	Climate and Health Graduate Student Researcher University of California, Berkeley, CA
2010	Program Associate Berkeley Air Monitoring Group, Berkeley, CA
2007	Health Policy Analyst San Francisco Department of Public Health, San Francisco, CA
2007-2008	Molecular Epidemiology Graduate Student Researcher University of California, Berkeley, CA

2003-2006	Environmental Analyst San Francisco Estuary Institute, Oakland, CA

HONORS AND AWARDS

2017	Pioneer Under 40 in Environmental Public Health, Collaborative on Health and the Environment (CHE)
Since 2014	Emerging Leader, Emerging Leaders Fund, The Claneil Foundation
2012	Outstanding Graduate Student Instructor Award, University of California, Berkeley

TOM TOMASTIK

ALL Consulting, LLC
10811 Keller Pines Court, Galena, OH 43021
Phone: +1 (614) 940-3521, ttomastik@all-llc.com

EDUCATION

1981	MS-GEOLOGY Ohio University, Athens, OH
1979	BS-GEOLOGY Ohio University, Athens, OH

CURRENT AND PAST POSITIONS

Since 2014	Senior Geologist and Regulatory Specialist - ALL Consulting, LLC, Tulsa OK
1988-2014	Senior Geologist -Ohio Department of Natural Resources, Division of Oil and Gas Resources Management, Columbus, OH
1982-1988	Consulting Geologist - Involved in exploration, development, and production of oil and gas wells in Ohio.

HONORS AND AWARDS

2017	Certified Petroleum Geologist # 6354 – American Association of Petroleum Geologists
1988–2017	Mr. Tomastik has authored, coauthored, and presented on various aspects of geology, underground injection, groundwater contamination cases, induced seismicity, stray gas investigations, well integrity, gas storage, petroleum geology, and expert witness testimony.

RODNEY WALKER

Walker & Associates Consultancy
2219 Dorman Court, Katy, TX 77494
Phone: +1 (706) 244-0894, rwalker@rwalkerconsultancy.com

EDUCATION

1985	BS-CIVIL ENGINEERING Clemson University, Clemson, SC

CURRENT AND PAST POSITIONS

Since 2015	CEO and President Walker & Associates Consultancy, Houston, TX
2015-2017	Vice President-Engineering Contanda Terminals (formerly Westway Group), Houston, TX
2011-2015	Director Black and Veatch, Overland Park, KS
2010-2011	Director-Natural Gas Practice Halcrow, London, UK
2006-2010	Principal Consultant R. W. Beck, Inc., Seattle, WA
2002-2006	Executive Vice President-Engineering Diversified Energy Services, Inc., Atlanta, GA
2001-2002	Natural Gas Director City of Toccoa, GA
1999-2001	Public Works Director City of Hartwell, GA
1985-1999	Various Positions (Corporate Engineer, Design Engineer/Drafting Supervisor, Engineering Supervisor, GIS Program Manager, Region Design Engineer) Atlanta Gas Light Company, GA

HONORS AND AWARDS

2012	American Public Gas Association (APGA) Harry M. Cooke Award for Distinguished Service to Natural Gas Industry

MAX WEI

Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, CA 94720
Phone: +1 (510) 486-5220, mwei@lbl.gov

EDUCATION

2009	MBA-HAAS SCHOOL OF BUSINESS University of California, Berkeley, CA
1995	PHD-ELECTRICAL ENGINEERING University of California, Berkeley, CA
1988	BS-ELECTRICAL ENGINEERING University of Michigan, Ann Arbor, MI

CURRENT AND PAST POSITIONS

Since 2012	Program Manager Lawrence Berkeley National Laboratory, CA
2010-2012	Senior Research Associate Lawrence Berkeley National Laboratory, CA
2009-2010	Research Fellow, Renewable and Appropriate Energy Laboratory, Energy and Resources Group University of California, Berkeley, CA
2002-2007	Process Integration Manager Intel Corporation, Santa Clara, CA

Appendix E

Full List of all Report Findings, Conclusions, and Recommendations

Key Question 1

What risks do California's underground gas storage facilities pose to health, safety, environment and infrastructure?

1.1 CHARACTERISTICS OF CALIFORNIA UNDERGROUND GAS STORAGE FACILITIES

Data Quality in DOGGR's Public Datasets

Finding: Information regarding quality control for public datasets relevant to underground gas storage is not available. Aspects of the data suggest quality control processes are not uniformly applied. For instance, well API# 03700722 has high casing and zero tubing pressures at times when its configuration suggests this is not possible. It also has the same casing pressure reported to four significant figures monthly from August 2008 through April 2009. While there appears to be sufficient consistency within the data to provide for accurate characterization of gas storage across the state, the narrower the focus, such as upon a single well, the less accurate the data can be presumed. This can interfere with understanding the risk of events at particular wells and other facilities of interest. As another example of data inconsistencies, some data regarding the same feature varies between publicly available datasets. For instance, well API #03714015 is in the Del Rey Hills area of the Playa del Rey field, which has gas storage, in DOGGR's production and injection database, but is in the Venice area, which does not have gas storage, in DOGGR's AllWells file. The uncertainty created by such inconsistencies has various implications—for instance, whether this well accesses the gas storage reservoir or not affects the LOC risk of that storage. As with the previous finding, though, these inconsistencies do not appear to be sufficiently frequent to preclude accurate characterization of UGS in California.

Conclusion: While DOGGR's public databases provide a wealth of information on underground gas storage wells, this study finds that there are various obvious inconsistencies between and apparent inaccuracies within these databases, which suggests that either quality control processes do not exist or are not uniformly applied. We could not find information regarding quality control for these public data sets relevant to underground gas storage. (See Conclusion 1.21 in the Summary Report.)

Recommendation: The Steering Committee recommends that quality control plans need to be made available if they exist, or need to be created if they do not exist. DOGGR needs to check for consistency between data sets and correct inconsistencies. In the longer-term, DOGGR should develop a unified data source from which all public data products are produced. (See Recommendation 1.21 in the Summary Report.)

<u>Storage in Depleted Oil Versus Gas Reservoirs and Independent Versus Utility Operated</u>

Finding: Storage in depleted gas reservoirs (primarily in northern California) differs from storage in depleted oil reservoirs (only in southern California) in a variety of ways, including:

- Well age and orientation
- Wellhead distribution
- Reservoir depth, initial pressure, and temperature
- Reservoir operating pressure relative to initial pressure
- Compounds in produced gas

Storage by independent operators differs from storage by PG&E, both in depleted gas reservoirs, in a variety of ways, including:

- Well age
- Interconnect length per capacity and gas transferred
- Location of gas handling plant relative to wells

Conclusion: The systematic physical and operational differences between storage in depleted oil and gas reservoirs, independent versus utility operated in depleted gas reservoirs as practiced, may result in significantly different risk profiles between these types of storage fields.

Recommendation: Characterize gas storage risk in depleted oil versus gas reservoirs, and independent versus utility operated in depleted gas reservoirs, to determine if there are generic differences, such as by simulating well blowouts for each. Identification of such differences might lead to different mitigation approaches in each setting, and identify practices that could be transferred between settings.

Age of Storage Wells in Southern California

Finding: Almost two thirds of the wells used for storage in southern California were spudded six to nine decades ago. Two fifths of stored gas was transferred via these wells.

Conclusion: There does not appear to be any limit on the age of well components used for gas storage in the state.

Recommendation: Determine the reasonable life expectancy of a well component given its operation and maintenance, and determine a monitoring and testing schedule that varies based on the temporal failure rate distribution of that type of component.

1.2 FAILURE MODES, LIKELIHOOD, AND CONSEQUENCES

Overall Failure Frequency of UGS

Finding: Gas storage has been carried out in California for over 60 years at around 20 different sites. Several of the facilities have had serious LOC incidents. The most problematic of these sites have been closed and are no longer storing gas. Of the 12 sites open today, seven have incidents recorded in the literature. Although possibly artifacts of reporting or the fact that California's larger facilities are larger than the worldwide average, the failure rate of UGS in California appears to be higher than the worldwide failure frequency, which is about the same or lower than the failure frequency of oil and gas extraction operations.

Conclusion: Analysis of historic failure-rate statistics of California's underground gas storage facilities points to a need for better risk management and improvement in regulations and practices. The Steering Committee views the new regulations proposed by DOGGR as a major step forward to reduce the risk of underground gas storage facilities, provided they are consistently and thoroughly applied and enforced across all storage facilities. In the future, careful re-evaluation of failure statistics, based on ongoing reporting and evaluation of incidents, can help determine whether and to what degree incident reductions have indeed been realized. (See Conclusion 1.1 in the Summary Report).

Recommendation: At regular intervals in the future, DOGGR should assess—by re-analyzing incident reports—whether the frequency of underground gas storage loss-of-containment incidents and other underground gas storage failures in California has actually been reduced. DOGGR should use these statistics to inform auditing processes for regulatory effectiveness. (See Recommendation 1.1 in the Summary Report.)

Focus on Subsurface

Finding: Queries of the database compilations of UGS incidents in California show that well-related leakage is by far the most common failure mode for LOC incidents in this state. In contrast, compilations of UGS failures worldwide suggest that LOC incidents at UGS facilities worldwide are four times more likely to involve above-ground infrastructure (valves, pipes, wellheads, compressors, and other systems) as compared to incidents involving wells. It appears that California's subsurface LOC incidents are substantially higher than the worldwide average.

Conclusion: Although efforts to reduce loss-of-containment incidents should be expended on both surface and subsurface parts of the underground gas storage systems in California, there appears to be a large opportunity to reduce loss-of-containment risk by focusing on reducing subsurface integrity failures, in particular with regard to well integrity issues. Emphasis on subsurface failure modes is consistent with the focus of many of the requirements in DOGGR's interim and draft final regulations. (See Conclusion 1.2 in the Summary Report).

Require Tubing and Packer

Finding: In California, DOGGR regulates UGS wells and until now has not required the use of tubing and packer (two-point failure requirement) in UGS wells. Although this is how most UGS wells are operated in the U.S., it is inconsistent with the U.S. EPA's UIC program, which generally requires injection wells to utilize a tubing and packer configuration. But because UGS is specifically excluded from the UIC program, no such federal requirement exists. The new proposed DOGGR regulations, planned to take effect January 1, 2018, will require a two-point failure configuration for all UGS wells. By the exclusion of UGS from the UIC program, UGS wells have not been required to conform to the two-point failure requirement, resulting in widespread operation of UGS wells that produce and inject fluid through the A-annulus, with the casing serving as the only barrier between high-pressure gas and the environment, including along regions of casing without cement between the outside of casing and the borehole wall. If the SS-25 well at Aliso Canyon had been operated using tubing and packer for production and injection, the hole in the casing, suspected to have been caused by corrosion, would not have caused gas to escape to surface in the 2015 Aliso Canyon incident, because there would have been no reservoir pressure support and gas supply to the A-annulus to feed an ongoing blowout (major LOC incident).

Conclusion: The Steering Committee views the requirement in the new DOGGR regulations of a two-point failure configuration for all underground gas storage wells as an important step in preventing major well blowouts and low-flow-rate loss-of-containment events. (See Conclusion 1.3 in the Summary Report.)

Risk Assessment of Failure Scenarios

Finding: Compilations of UGS incidents worldwide and in California show that loss-of-containment (LOC) of high-pressure natural gas at UGS facilities often occurs by a chain of events that can be described by a failure scenario, which often involves human and organizational factors (HOFs). Queries of the updated database of Evans and Schultz (2017) show that well-related leakage is by far the most common failure mode for LOC incidents in California.

Conclusion: Failure scenarios involving initiating and multiple contributing events are common experience. Risk assessment and analysis methods and capabilities are well-developed and available from the engineering consulting industry to address failure scenarios in terms of understanding linkages between events, finding mitigating actions, and quantifying likelihood and assessing risk quantitatively and semi-quantitatively.

Recommendation: Operators of UGS facilities should utilize long experience and new and existing data to carry out quantitative risk assessment (what is the risk?) and risk analysis (what are the main sources of risk? How can risk be reduced?).

Basis for Failure Frequency Estimates

Finding: Different authors use a different denominator or basis for estimating failure frequency. E.g., some calculate failure rate on a per well basis, while others use per well-yr or per facility-yr.

Conclusion: The number of wells in use at any time over the course of operations of UGS facilities changes. Furthermore, there are abandoned wells that can be an issue for integrity but that are not used for storage. These facts make it difficult to form a meaningful metric for failure frequency using wells as the basis. We prefer to base failure frequencies on a per facility-yr basis. To rank sites and account for the larger number of wells at some sites, we suggest using a working-gas-capacity (Bcf) normalization, whereby the per facility-yr frequency is multiplied by the ratio of the California-average working gas capacity to the particular site working gas capacity. By this approach, one can account indirectly for the expected larger number of wells at larger sites, and normalize failure frequency to the average size site.

Natural Hazards Can Affect Integrity of UGS Facilities

Finding: Some California UGS facilities are located in regions with particular hazards that can affect UGS infrastructure, among which are seismic, landslide, flood, tsunami, and wildfire hazards. The risk arising from these hazards along with monitoring, prevention, and intervention needs, is now being assessed in the risk management plans that DOGGR now requires from each facility. Some natural hazards are more easily evaluated and mitigated than others; e.g., facilities potentially affected by periodic flooding are often protected by dams or placed on elevated land. Earthquake risk, on the other hand, is harder to assess and mitigate. Fault displacement and seismic ground motion can directly affect the surface infrastructure. Fault displacement can also affect wells at depth through shearing of the well casing if the well crosses the plane of the fault. Earthquake risk is a concern in several California facilities, such as Aliso Canyon, Honor Rancho, and Playa del Rey. SoCalGas is currently conducting an in-depth analysis of the risk related to the Santa Susana Fault, including a probabilistic seismic hazard analysis and a probabilistic fault displacement analysis.

Conclusion: Natural hazards can significantly affect the integrity of underground gas storage facilities. (See Conclusion 1.4 in the Summary Report.)

Recommendation: Regulators need to ensure that the risk management plans and risk assessments required as part of the new DOGGR regulations focus on all relevant natural hazards at each facility. In-depth site-specific technical or geological studies may be needed to evaluate potential natural hazards associated with underground gas storage facilities. For some facilities, earthquake risks fall under that category. (See Recommendation 1.4a in the Summary Report.)

Recommendation: Agencies with jurisdiction should ensure that earthquake risks (and other relevant natural hazards) are specifically investigated with in-depth technical or geological studies at all facilities where risk management plans suggest elevated hazard. (See Recommendation 1.4b in the Summary Report.)

Protect UGS from Attack

Finding: By analogy with oil and gas pipelines and wells, which have been the subject of numerous terrorist incidents around the world, UGS facilities in California are vulnerable to similar kinds of attacks.

Conclusion: It is well known that UGS facilities store a highly energetic fuel at high pressure, and that high-pressure pipelines of natural gas are ubiquitous at UGS sites. High-pressure pipelines of natural gas provide a source for explosion and re that may make UGS sites attractive to terrorists or other groups or individuals intent on harm.

Recommendation: UGS sites should carry out a top-to-bottom review of mitigation of the threat of terrorism or other attacks by individuals or groups. Examples of mitigations of this threat include increasing security, decreasing the attractiveness of the facility as a target, maintaining an appropriate degree of confidentiality about operations, improving cyber security to avoid hacking attacks, and locking key valves and controls.

Better Emissions Data and On-site Meteorological Stations

Finding: UGS sites in California are not uniformly equipped with meteorological stations or gas monitoring equipment. Bottom-up approaches that employ empirical emission factors are used to estimate emission inventories. These approaches do not provide the spatially and temporally varying emission data that are critical for estimating downwind consequences of leaks from individual UGS sites.

NOAA's Integrated Surface Database (ISD) provides meteorological data; however, the distances between California UGS sites and the closest stations can range from 2 to 25 km. Many UGS facilities are located in an area of complex topography, which can make the available meteorological data unreliable.

Conclusion: Although a range of practical and sophisticated modeling capabilities is readily available, lack of temporal and spatially varying emission data as well as reliable meteorological data make it difficult to accurately estimate the concentrations and dispersion of gas leakage from UGS facilities.

Recommendation: A practical implementation of continuous emission monitoring technology should be deployed at each UGS facility to provide reliable spatially and temporally varying data for analysis. On-site weather stations should be installed at each UGS facility following National Weather Service (NWS) guidelines. These data could be used to generate accurate estimates of dispersion of leaking gases for risk assessment and emergency response purposes using readily available dispersion models.

Risk to UGS Infrastructure from Fire and Explosions

Finding: Large accidental leaks of natural gas can pose a significant threat to people and property due to thermal radiation from sustained res and collapse of buildings and infrastructure from explosions. Decompression cooling can cause small pipeline leaks to turn into large leaks. Horizontal jet dispersion models that characterize the concentration profile and re models that characterize the radiative heat flux can estimate the ground area (hazard zone) affected by credible failure scenarios. Leak rates and meteorological data can be combined with flammability/explosion-limit estimates to delineate the extent of the hazard zone for risk assessment purposes.

Conclusion: The size of fire and explosion hazard zones can be larger than the footprints of local surface infrastructure, e.g., a compressor pad, gas-processing facility pad, or the clustered wellheads on pads of multiple deviated wells. This is especially true for facilities with gas processing equipment co-located with office/control facilities. LOC failure impacts to UGS infrastructure are potentially very large.

Recommendation: Hazard zones should be delineated for each UGS facility to focus risk mitigation on elimination of leakage and ignition sources to reduce the likelihood of re and explosion, and to design surface infrastructure (e.g., buildings and their layout) to reduce the consequences (loss prevention) of re and explosion if they should occur (safer site-use planning).

Impacts of Leakage on USDW

Finding: Stray gas migration from oil and gas operations into USDW has been well documented across the United States. Leakage of natural gas into USDW from UGS operations can occur and typically is caused by the phenomenon called "annular over pressurization." Most UGS wells are constructed in a manner that results in an open annular space behind the production casing. This annulus is a potential avenue for gas migration from the gas storage reservoir of higher hydrodynamic pressure into formations of lower hydrodynamic pressure, including aquifers.

Conclusion: Storage gas migration into USDW in California has occurred and has been documented in association with the Playa del Rey gas storage field. Other gas storage migration incidents into USDW may go undocumented due to the lack of groundwater monitoring wells or lack of reliance on domestic water wells for private water supplies that would detect the presence of stray gas. Storage gas migration to the surface in a number of California gas storage fields has occurred through leakage through faults and abandoned or improperly plugged oil and gas wells (e.g., Honor Rancho and Montebello).

Recommendation: Implement the proposed DOGGR regulations to improve well integrity and require groundwater monitoring wells at UGS sites to detect possible stray gas migration to USDW aquifers.

Clustered vs. Dispersed Wells

Finding: UGS facilities developed in California depleted oil (DO) reservoirs utilize mostly vertical wells that are widely dispersed across the field. In contrast, UGS facilities developed in California depleted gas (DG) reservoirs are often deviated with closely spaced and centralized wellheads.

Conclusion: There are tradeoffs in risk management of closely spaced versus dispersed wellheads. Maintenance and observation of the wellheads is facilitated by clustering, but failure of a wellhead (e.g., a burning blowout) in close proximity to other wellheads can lead to multiple wellhead failures.

1.3 CAPACITY OF UGS SITES: EFFECTS OF AGE AND STORAGE INTEGRITY

Addressing Formation Damage

Finding: The gas storage reservoir and its ability to deliver gas can be altered due to formation compaction and damage from long-term oil, produced water, and natural gas extraction resulting from grain alteration, changes to reservoir pressure conditions, and changes to the fluid contacts within the underground gas storage field. Formation damage causes reduction in gas storage reservoir permeability which leads to a decrease in deliverability that dramatically impacts the effective capacity of the underground gas storage field.

Conclusion: Because formation damage is more likely in older wells with long histories of production, UGS capacity can be affected by the age of the wells at the UGS facility and its history of operations.

Recommendation: Operators should carry out proactive approaches to identifying, addressing, and properly mitigating formation damage in advance of the reduction in formation permeability to avoid loss of UGS reservoir capacity. Being aware of formation damage implications during drilling, completion, injection, and production operations can help in substantially reducing formation damage and enhancing the ability of a well to inject and withdraw storage gas.

<u>Need for Stronger Regulations to Avoid Loss of Storage Capacity</u>

Finding: Loss of reservoir integrity is a failure of UGS that results in closing of UGS reservoirs, or shutting in of certain wells, or requirement to operate at lower pressure. California UGS has experienced multiple LOC incidents due to reservoir integrity failure, which resulted in storage gas migration through old oil and gas wells back to the surface.

Conclusion: Gas storage reservoir integrity can be defined by the geological and geomechanical conditions that are present within the reservoir that allow for safe operations beyond the wellbore. Likely avenues for gas migration from the reservoir are caused by failure of vertical and/or lateral containment, which can be caused by artificial (well) penetrations, naturally occurring faults or fracture systems that may be transmissive, compromising of the confining zone/caprock sequence due to reservoir overpressurization, and overfilling of the structural or stratigraphic geologic spill points. Fundamentally, UGS reservoir integrity carries two different types of risks: the release of gas from the storage reservoir that reaches aquifers and/ or the surface, or migration of storage gas from the reservoir into overlying or adjacent geologic formations, where it becomes nonrecoverable.

Recommendation: More stringent underground gas storage regulations should be developed to require more technical, geologic, and engineering data to better characterize the gas storage reservoir. By assessing gas-storage-reservoir integrity using a holistic approach (i.e., utilizing multiple approaches such as geophysical logging and pressure testing), the number of incidents associated with gas-storage-reservoir-integrity failure can be dramatically reduced with the added benefit of avoiding loss of storage capacity.

1.4 HUMAN HEALTH HAZARDS, RISKS, AND IMPACTS ASSOCIATED WITH UNDERGROUND GAS STORAGE IN CALIFORNIA

Emissions Inventory Information Gaps and Uncertainty

Finding: There are a number of human health hazards associated with UGS in California that can be predominantly attributable to exposure to toxic air pollutants. These toxic compounds emitted during routine and off-normal emissions scenarios include but are not limited to odorants, compressor combustion emissions, benzene, toluene, and other potentially toxic chemicals extracted from residual oil in depleted oil reservoirs. Given the limited number of compounds monitored for during the 2015 Aliso Canyon incident compared to the number of compounds reported to the California Air Resources Board as emitted from UGS facilities, there is significant uncertainty as to the human health risks and impacts of this large LOC event both over the short- and long-term. Our repeated attempts to acquire useful information about gas composition at each UGS facility in California were unsuccessful. Working with the CPUC, we made formal requests to all operators seeking information on the chemical composition of the stored gas. All responded, but none could provide the detailed information we needed (See Appendix 1.D, in Chapter 1).

Conclusion: Because emissions inventories for underground gas storage facilities lack the temporal, spatial, and technology-specific detail as well as verifiability of emission types and rates, currently available emissions inventories cannot support quantitative human exposure or health risk assessments. There is a need to identify the chemical composition of the gas that is stored, withdrawn, stripped, and delivered to the pipeline, so that associated hazards during routine and off-normal emission scenarios can be assessed. (See Conclusion 1.5 in the Summary Report.)

Recommendation: Agencies with jurisdiction should require that underground gas storage facility operators provide detailed gas composition information at appropriate time intervals. Additionally, these agencies should require the development of a comprehensive chemical inventory of all chemicals stored and used on-site, and the chemical composition of stored, withdrawn, stripped, and compressed gas for each underground gas storage facility. These data should be used to prioritize chemicals to enable site operators and local first responders to set health-based goals for monitoring and risk assessment actions. (See Recommendation 1.5 in the Summary Report.)

Health Symptoms in Communities Near the 2015 Aliso Canyon Incident Were Attributed to the Aliso Canyon UGS Facility

Finding: The majority of households near the Aliso Canyon UGS facility experienced health symptoms during the SS-25 blowout and after the well was sealed, and these symptoms were likely related to the gas leak and/or other emission sources from the Aliso Canyon UGS facility. While many of the symptoms reported by residents match the symptom profile of exposure to mercaptans (gas odorants), other symptoms such as nosebleeds do not, suggesting that air pollutant and other environmental monitoring was not sufficiently inclusive of potential health-damaging pollutants.

Conclusion: Emissions from the 2015 Aliso Canyon incident were likely responsible for widespread health symptoms in the nearby Porter Ranch population. These types of population health impacts should be expected from any large-scale natural gas releases from any underground gas storage facility, especially those located near areas of high population density. However, many of the specific exposures that caused these symptoms remain uncertain, due to incomplete information about the composition of the air pollutant emissions and their downwind concentrations. (See Conclusion 1.6a in the Summary Report.)

Recommendation: Community health risks should be a primary component of risk management plans and best management practices for emission reductions, and measures to avoid (normal and off-normal) gas releases should be immediately implemented at existing underground gas storage facilities. In addition, options for public health surveillance should be considered both during and following major loss-of-containment events to identify adverse health effects in communities. (See Recommendation 1.6a in the Summary Report.)

Population Exposures to Toxic Air Pollutants Increase with Higher Emissions, Closer Community Proximity and Higher Population Density

Finding: Approximately 1.85 million residents live within five miles of UGS facilities in the State of California. In the absence of reliable information on emissions inventories and expected release rates, potential health hazards can be evaluated using normalized source-receptor relationships obtained from atmospheric transport models and best estimates of population distance and density. Both concentration/source and population-intake/source ratios (intake fraction) provide helpful tools to assess the variability of potential exposures and risks among different UGS facilities.

Conclusion: Underground gas storage facilities pose more elevated health risks when located in areas of high population density, such as the Los Angeles Basin, because of the larger numbers of people nearby that can be exposed to toxic air pollutants. Emissions from underground gas storage facilities, especially during large loss-of-containment events, can present health hazards to nearby communities in California. Many of the constituents potentially emitted by underground gas storage facilities can damage health and place disproportionate risks on sensitive populations, including children, pregnant women, the elderly, and those with pre-existing respiratory and cardiovascular conditions. (See Conclusion 1.7 in the Summary Report.)

Recommendation: Regulators need to ensure that the risk management plans required as part of the new DOGGR regulations take into account the population density near and proximity to underground gas storage facilities. One mitigating approach to reduce risks to nearby population centers could be to define minimum health-based and fire-safety-based surface setback distances between facilities and human populations, informed by available science and results from facility-specific risk assessment studies. This may be most feasible for future zoning decisions and new facility or community construction projects. Such setbacks would ensure that people located in and around various classes of buildings such as residences, schools, hospitals, and senior care facilities are located at a safe distance from underground gas storage facilities during normal and off-normal emission events. (See Recommendation 1.7 in the Summary Report.)

<u>Occupational Health and Safety Considerations</u>

Finding: Based on toxic chemicals known to be present on-site, and publicly available emission reporting to air regulators under the Air Toxics Hot Spots Program, we have identified toxic chemicals used at and emitted from UGS facilities. These chemicals include, but are not limited to, hydrogen sulfide, benzene, acrolein, formaldehyde, and 1,3 Butadiene. Currently we have found no available quantitative exposure measurements.

Conclusion: Workers at underground gas storage facilities are likely exposed to toxic chemicals, but the actual extent of those exposures is not known. Without quantitative emission and exposure measurements, we cannot assess the impact of these exposures on workers' health. (See Conclusion 1.8 in the Summary Report.)

Recommendation: Underground gas storage facilities should make quantitative data on emissions of, and worker exposures to, toxic chemicals from facility operations available to the public and to agencies of jurisdiction—e.g., California Occupational Safety and Health Administration (CalOSHA), California Public Utilities Commission (CPUC)—to enable robust risk assessments. It may be advisable to require that underground gas storage facilities be subject to the Process Safety Management of Highly Hazardous Chemicals Standard (29 CFR 1910.119), which contains requirements for the management of hazards associated with processes using highly hazardous chemicals. (See Recommendation 1.8a in the Summary Report.)

Recommendation: The State should require that underground gas storage workplaces conform to requirements of CalOSHA and federal OSHA, and impose additional requirements to protect the health and safety of on-site workers (employees, temporary workers and contractors), whether or not they are legally bound to comply. These requirements include that (1) all training and preparation for incidents and releases be fully concordant with best practices (see Appendix 1.G in Chapter 1); (2) all safety equipment be fully operational and up to date, readily available, and all workers trained in equipment location and proper use; (3) all incident commanders be provided with sufficient, current training; (4) all health and safety standards be observed for all workers on site; and (5) air sampling of workers' exposures be required during routine and off-normal operations to ensure that exposures are within the most health-protective occupational exposure limits. (See Recommendation 1.8b in the Summary Report.)

Continuous Facility Air-Quality Monitoring

Finding: Many UGS facilities emit multiple health-damaging air pollutants during routine operations. Available emissions inventories suggest that the most commonly emitted air pollutants associated with UGS by mass include nitrogen oxides, carbon monoxide, particulate matter, ammonia, and formaldehyde. For instance, Aliso Canyon is the single largest emitter of formaldehyde in the South Coast Air Quality Management District. Gas-powered (as compared to electric-powered) compressor stations are associated with the highest continuous emissions of formaldehyde. CARB regulations for underground gas storage facilities in place since October 1, 2017 require continuous methane concentration monitoring at facility upwind and downwind locations (at least one pair of upwind and downwind locations) but without air sampling.

Conclusion: There is a need to track and if necessary reduce emissions of toxic air pollutants from underground gas storage facilities during routine operations. (See Conclusion 1.9 in the Summary Report.)

Recommendation: Agencies with jurisdiction should require actions to reduce exposure of on-site workers and nearby populations to toxic air pollutants, other health-damaging air pollutants emitted from underground gas storage facilities during routine operations, and ground level ozone, nitrogen oxides, and other ozone precursors. These steps could include (1) the implementation of air monitors within the facilities and at the fence line or other appropriate locations—preferably with continuous methane monitoring with trigger sampling to quickly deploy appropriate off-site air quality monitoring networks during incidents; (2) the increased application and enforcement of emission control technologies to limit air pollutant emissions; (3) the replacement of gas-powered compressors with electric-powered compressors to decrease emissions of formaldehyde; and (4) the implementation of health protective minimum-surface setbacks between underground gas storage facilities and human populations. (See Recommendation 1.9 in the Summary Report.)

Community Symptom-based Environmental Monitoring for High Priority Chemicals

Finding: Symptom reporting and environmental monitoring in Porter Ranch, CA, during and after the 2015 Aliso Canyon incident indicate that chemicals and materials sourced from the SS-25 well entered residences, demonstrating clear indoor and outdoor exposure pathways. However, air pollutant exposures during the SS-25 event are significantly uncertain with respect to characterizing health-relevant exposures, because (1) detection limits for air pollutants such as benzene, mercaptans, and other toxic air pollutants during the SS-25 blowout were often above health and/or odor thresholds; (2) air and other environmental monitoring during much of the time of the SS-25 blowout was non-continuous; and (3) only a small fraction of pollutants known to be associated with UGS facilities was included in the monitoring.

Conclusion: Effective health risk management requires continuous, rapid, reliable, and sensitive (low detection limit) environmental monitoring in both ambient and indoor environments that include chemicals of known concern. (See Conclusion 1.6b in the Summary Report.)

Recommendation: To support a more detailed exposure assessment in communities located near underground gas storage facilities, procedures need to be in place to be able to: (1) rapidly deploy a network of continuous, reliable, and sensitive indoor and outdoor sensors for high priority chemicals, capable of detecting emissions at levels below thresholds for minimum risk levels; and (2) employ real-time atmospheric dispersion modeling to provide information about the dispersion and fate of a large release of stored natural gas to the environment. (See Recommendation 1.6b in the Summary Report.)

Chemical Disclosure for Storage Wells and Associated Aboveground Operations

Finding: While chemicals used in oil and gas production during routine activities (e.g., drilling, routine maintenance, completions, well cleanouts) and well stimulation (e.g., hydraulic fracturing and acid stimulation) are reported for all other wells in the South Coast Air Quality Management District, no such disclosures are made for UGS wells. And this is true for UGS facilities statewide. UGS operators disclose chemical information to the California Environmental Reporting System (CERS) for chemicals stored on-site; however, this information is not publicly available for all facilities, does not include what the chemicals are used for, or the mass or frequency of use on-site, and often lists product names without unique chemical identifiers. As such, it is likely that on-site chemical use occurs, but the composition of those chemicals, the purpose, mass, and frequency of their use, and their associated human health risks during normal and off-normal events at UGS facilities, remain unknown.

Conclusion: To be able to conduct comprehensive hazard and risk assessment of underground gas storage facilities, risk managers, regulators, and researchers need access to detailed information for all chemicals used in storage wells and in associated infrastructure and operations. (See Conclusion 1.22 in the Summary Report.)

Recommendation: The Steering Committee recommends that operators be required to disclose information on all chemicals used during both normal and off-normal events. Each chemical used downhole and on underground gas storage facilities should be publicly disclosed, along with the unique Chemical Abstract Service Registry Number (CASRN), the mass, the purpose, and the location of use. Studies of the community and occupational health risks associated with this chemical use during normal and off-normal events should be undertaken. (See Recommendation 1.22 in the Summary Report.)

Explosion and Flammability Considerations

Finding: During large LOC events, downwind methane concentrations can be higher than flammability or explosion limits. This poses a significant threat to people and property due to sustained fires and collapse of buildings and infrastructure from explosions. For risk assessment purposes, this study compared predicted concentrations from atmospheric dispersion models with methane concentration flammability limits. There are air dispersion conditions and failure scenarios that can present risks of severe harm to workers and nearby communities if a release of flammable gas is ignited due to exposure to high temperatures and associated radiation from a blast. Based on our modeling, the methane concentrations in the close vicinity of the leakage points may exceed the lower flammability limits for typical “off-normal” leakage fluxes. Flammable zones are typically not expected to extend beyond UGS facility boundaries, unless the leak rates are extremely large, i.e., larger than the fluxes experienced in the 2015 Aliso Canyon incident.

Conclusion: Each underground gas storage facility needs an assessment of emitted natural gas combustion potential, and a mapping of the flame and the thermal dispersion associated with this combustion. (See Conclusion 1.10 in the Summary Report.)

Recommendation: Regulators and decision-makers should require the implementation and enforcement of best practices to reduce the likelihood of ignition of flammable gases in and near underground gas storage facilities. Occupational and community hazard zones should be delineated for each underground gas storage facility (possibly based on bounding simulations conducted with atmospheric dispersion models) to focus risk mitigation on elimination of leakage and ignition sources (loss prevention) and safer site-use planning. (See Recommendation 1.10 in the Summary Report.)

1.5 ATMOSPHERIC MONITORING FOR QUALIFICATION OF GHG EMISSIONS AND UGS INTEGRITY ASSESSMENT IN CALIFORNIA

GHG Emission Measurement and Analysis

Finding: Observed methane emissions vary by factors >10× across sites, with three sites (Honor Rancho, McDonald Island, and Aliso Canyon) dominating emissions. Within sites, variations of ~3-5× occur over time. Directly observed emissions are 2-5× higher than the average of emissions reported to CARB. Observations suggest total California UGS emissions are ~9.3 GgCH4/yr (≈ 1% California total methane emissions) which is < 0.1% total California GHG emissions, with compressors and aboveground infrastructure apparently contributing the majority of the emissions.

Conclusion: Though there are discrepancies between directly observed greenhouse gas emissions and those reported to CARB, average methane emissions from underground gas storage facilities are not currently a major concern from a climate perspective compared to other methane and GHG sources, such as dairies and municipal solid waste landfills.

However, average methane emissions from underground gas storage facilities are roughly equivalent to an Aliso Canyon incident every 10 years, and hence worthy of mitigation. (See Conclusion 1.11 in the Summary Report.)

Recommendation: An improved methane monitoring program is needed for better quantitative emissions characterization that allows for direct comparison with reported emissions. The monitoring program could benefit from a combination of persistent on-site measurements and higher accuracy, periodic independent surveys using airborne- and surface-based measurement systems. (See Recommendation 1.11a in the Summary Report.)

Recommendation: Average underground gas storage methane emissions should be monitored primarily for safety and reliability (see Recommendation 1.12 below), since the net GHG effect of underground gas storage facilities is relatively small. However, most of the current GHG leakage detection measurements (e.g., methane concentrations) conducted at underground gas storage facilities point to easily mitigatable sources for aboveground leaks, such as compressors or bypass valves. Thus, with regard to reducing GHG emissions, facilities should maintain and upgrade equipment (particularly compressors and bypass valves) over time, repair leaking equipment (e.g., following the new CARB regulations for natural gas facilities), and reduce leakage and releases (blowdowns) during maintenance operations. (See Recommendation 1.11b in the Summary Report.)

Atmospheric Monitoring for Integrity Assessment

Finding: Natural gas at UGS facilities provides an atmospheric tracer that can enable efforts to monitor integrity of surface and subsurface infrastructure — potentially offering early warning to minimize the impact of leaks and avoid loss-of-containment and other hazardous situations for some failure modes. Methane in particular is both the primary constituent of natural gas and can be measured by a variety of methods to identify, diagnose, and guide responses to integrity issues. Methane also serves as a proxy for other compounds that may be co-emitted, including air toxics such as benzene. There are many methane measurement methods that can be applied to UGS leak detection; however, they have differing capabilities and limitations. Several of these methods have been successfully demonstrated in operational field conditions at Aliso Canyon, Honor Rancho, and other facilities, including several examples that illustrate the potential for coordinated application of multiple synergistic observing system “tiers.” As of October 1st, 2017, regulations of the California Air Resources Board (CARB) went into effect. These regulations require UGS operators to continuously monitor meteorological conditions, including temperature, pressure, humidity, and wind speed and direction, monitor predominantly upwind (background) and downwind methane concentrations in air, and carry out daily gas hydrocarbon concentration measurements at each injection/withdrawal wellhead and attached pipelines. If anomalous concentrations of hydrocarbons persist above certain thresholds for certain periods of time, notification must be made to CARB, DOGGR, and the local air district. It is important to note that the purpose of these monitoring requirements is to detect that leakage is occurring, not to quantify emissions (i.e., leakage rates). Once leaks are detected and located, they can be addressed.

Conclusion: Coordinated application of multiple methane emission measurement methods can address gaps in spatial coverage, sample frequency, latency, precision/uncertainty, and ability to isolate leaks to individual underground gas storage facility components in complex environments and in the presence of confounding sources. A well-designed methane emission and leakage detection monitoring strategy can complement other integrity assessment methods—such as the new mechanical integrity testing, inspections, and pressure monitoring now required by the new DOGGR regulations for storage wells—by providing improved situational awareness of overall facility integrity. In addition to supporting proactive integrity assessments, methane emissions monitoring also helps improve accounting of GHG emissions and timely evaluation of co-emitted toxic compounds in response to potential future incidents. (See Conclusion 1.12 in the Summary Report.)

Recommendation: An optimized methane emission monitoring strategy should be devised to provide low latency, spatially complete, and high-resolution information about methane emissions from underground gas storage facilities and specific components of the gas storage system. A program based on this strategy could benefit from a combination of persistent on-site measurements and higher accuracy, periodic independent surveys using airborne- and surface-based measurement systems. These emissions measurements would complement the on-site wellhead and upwind-downwind concentration-based leakage-detection measurements now required by CARB. The scientific community should be engaged in helping underground gas storage operators and regulators design such a monitoring strategy, and should be serving in an ongoing advisory capacity to ensure that best practices and new developments in monitoring technology can be implemented in the future. (See Recommendation 1.12 in the Summary Report.)

<u>Assessment, Management, and Mitigation Actions in Case of Local Methane Leakage Observations</u>

Finding: At Aliso Canyon, McDonald Island, and Honor Rancho, where total methane emissions have been measured to be above 250 kg/hr in some of the recent airborne measurement campaigns, the sources of these emissions were localized in most cases as originating from above-ground infrastructure such as compressor stations or leaking valves. This is a maintenance or repair issue but not an early warning indicator for large loss-of-containment events. (The 250 kg/hr emissions rate is a limit defined by DOGGR in its order allowing resumption of injection at the Aliso Canyon underground gas storage facility. If this limit is exceeded, the operator must continue weekly airborne emissions measurements until the leaks have been fixed, no new leaks have been found, and emissions are below 250 kg/hr.) But local methane hot spots could also be associated with wellheads or emissions from the ground near gas storage wells, in which case timely assessment and mitigation response can be essential in preventing the evolution of a small leak into a major blowout.

Conclusion: Periodic airborne and surface-based methane monitoring strategies provide the ability for detection of localized leaks within facilities, which in turn allow for early identification, diagnosis, and mitigation response to prevent smaller leaks from becoming a major loss-of-containment incident. (See Conclusion 1.13 in the Summary Report.)

Recommendation: The Steering Committee recommends that DOGGR or CARB develop a protocol for all facilities defining the necessary assessment, management, and mitigation actions for the cases where periodic airborne and surface-based methane surveys identify potential emission hot spots of concern. (See Recommendation 1.13 in the Summary Report.)

<u>Integration, Access, and Sharing of Monitoring/Testing Data</u>

Finding: Since the 2015 Aliso Canyon incident, increasing institutional monitoring requirements, new regulatory monitoring/testing standards, and various measurement and data collection campaigns conducted in academic settings have provided a large amount of information on UGS facilities, in particular with regards to integrity issues and potential loss-of-containment. For example, airborne based measurements of local methane emissions can potentially offer early warning of well integrity concerns, which can then be followed up by detailed well integrity testing and mitigation. Meanwhile, persistent hotspots of gas odorants from environmental monitoring in communities might point to unknown gas leaks in nearby facilities. However, the value of these complementary data types is limited if they are not integrated and maintained in a central database and if access is only given after long delays.

Conclusion: The Steering Committee recognizes the value of coordinated and integrated assessment of complementary types of data on methane emissions and other environmental monitoring to be able to act early and avoid potentially large loss-of-containment incidents. However, the committee is concerned that there is no single data clearing house where (1) the multiple sources of data from required or voluntary reporting/monitoring are collected and maintained; and (2) these data can be easily accessed and evaluated by oversight bodies and the public. (See Conclusion 1.24 in the Summary Report.)

Recommendation: The Committee recommends that these data, particularly on methane concentrations within and near the fence line of the facility and in key locations in adjacent communities, should be posted in real time, informing residents living nearby of potential airborne hazards associated with any loss-of-containment. Data that cannot be posted in real time, because more extensive quality assurance and control is required, should be released at frequent intervals without significant delay from the time of collection, in a standardized digital format. (See Recommendation 1.24a in the Summary Report.)

Recommendation: The Committee further recommends identifying a lead agency in California (e.g., DOGGR, CARB, CPUC) that develops and implements a strategy for the integration, access, quality control, and sharing of all data related to underground gas storage facilities integrity and risk. (See Recommendation 1.24b in the Summary Report.)

1.6 RISK MITIGATION AND MANAGEMENT

Overall Assessment of DOGGR's New Emergency and Proposed Draft Regulations

Finding: The draft DOGGR regulations that will govern subsurface operations at UGS facilities in California contain numerous important provisions that will make UGS safer, and that will also allow for a better understanding of the levels of safety achieved at any specific UGS facility.

Conclusion: The existence of both the emergency DOGGR regulations now in place and the draft permanent regulations still under development represents a major step to reduce risk of loss-of-containment, particularly the requirement for each facility to provide a risk management plan; the requirement of the use of two barriers in wells, e.g., use of tubing and packer; and the requirements for well testing and monitoring. The Steering Committee concludes that the new regulations should profoundly improve well integrity at underground gas storage facilities in California. (See Conclusion 1.14 in the Summary Report.)

Evaluating Risk Management Plans as a Major Element of UGS Integrity

Finding: One of the major and most important elements of both the emergency regulations and the draft permanent regulations is that each UGS facility in California must develop and implement a Risk Management Plan (RMP) with certain specified features as follows: "RMPs shall include a description of the methodology employed to conduct the risk assessment and identify prevention protocols, with references to any third-party guidance followed in developing the methodology. The methodology shall include at least the following: (1) Identification of potential threats and hazards associated with operation of the underground gas storage project; (2) Evaluation of probability of threats, hazards, and consequences related to the events."

Conclusion: Requiring risk management plans and risk assessment studies for each facility is an important step in ensuring underground gas storage integrity, but the draft permanent regulations do not contain enough guidance as to what the risk assessment methodology needs to provide. (See Conclusion 1.15 in the Summary Report.)

Recommendation: The Steering Committee suggests DOGGR make further clarifications and specifications in the risk management plan requirements as follows: (1) the need for each underground gas storage facility to develop a formal quantitative risk assessment, to understand the risks that the facility poses to various risk endpoints (such as worker safety, health of the offsite population, release of methane, property damage, etc.); and

(2) the need to develop a risk target or goal for each risk endpoint that each facility should stay below and that is agreed to by the regulator (DOGGR), rather than written into an enforceable government regulation. These two needs, if satisfied, will provide the basis for rational and defensible risk-management decision-making that would not be possible without results from a formal risk assessment and defined risk targets or goals. The committee also provides guidance on a range of other attributes that a risk management plan must contain, including (1) considerations of human and organizational factors as well as traits of a healthy safety culture; and (2) recommendations regarding intervention and emergency response planning. These detailed suggestions are given in Section 1.6 of the main report. (See Recommendation 1.15 in the Summary Report.)

Well Integrity Requirements

Finding: The proposed regulations contain various technical requirements for (1) well construction, (2) mechanical integrity testing, (3) monitoring, (4) inspection, testing, and maintenance of wellheads and valves, (5) well decommissioning, and (6) data and reporting. Overall, the Steering Committee finds these requirements a major step forward to improve well integrity in UGS facilities. In terms of the detailed specifications, the committee has several suggestions for revision, e.g., to clarify ambiguous language, provide additional specification, ensure consistency with industry standards, and balance the benefit of frequent testing with the risk to aging wells from installing instrumentation. These detailed suggestions are given in Section 1.6.4 of the report.

Conclusion: The technical requirements for wells provided in the draft DOGGR regulations contain many provisions that are expected to enhance the safety of well operations at the underground gas storage facilities in California. As with any new regulation, application in the practice over time will be an ultimate test, with an “effective” regulatory framework being one that enhances safety to the point that risks are acceptable, while not placing unnecessary burden on operators. (See Conclusion 1.16 in the Summary Report.)

Recommendation: The Steering Committee recommends that DOGGR considers several detailed suggestions made in Section 1.6 of the main report to improve the specific well integrity requirements in the draft regulations. Also, the committee recommends that the finalized regulations be reevaluated after perhaps five years of application (see Recommendation 1.17 below). (See Recommendation 1.16 in the Summary Report.)

Need for Regular Peer Review or Auditing of New DOGGR Regulations

Finding: It is a common practice in many fields to evaluate the effectiveness of regulations, in particular those that may have been newly developed, on a regular basis by peer-review teams or auditing teams. For example, the Groundwater Protection Council (GWPC) organizes peer reviews of the Class II Underground Injection Control Program in certain states to which the U.S. EPA has delegated regulatory authority. (Class II wells are used only to inject fluids associated with oil and natural gas production—not gas storage.) The peer reviews typically include regulators from other states that are involved in those same programs, but may also involve stakeholders from academia and environmental organizations. Although many different approaches have been used and models for organizing them are widespread, one possible suggestion is to use the Interstate Oil and Gas Compact Commission (IOGCC) to help with this review.

Conclusion: Conducting a peer review or audit of the new DOGGR regulations after a few years of implementation would ensure that (1) the latest science, engineering, and policy knowledge is reflected to provide the highest level of safety; (2) these regulations are consistently applied and enforced across all storage facilities and are thoroughly reviewed for compliance; (3) an appropriate safety culture has been fully embraced by operators and regulators; and finally (4) the regulator has the necessary expert knowledge to conduct a rigorous review of the regulatory requirements. (See Conclusion 1.17 in the Summary Report.)

Recommendation: The Governor should ensure that the effectiveness of the DOGGR regulations and the rigor of their application in practice be evaluated by a mandatory, independent, and transparent review program. Reviews should be conducted in regular intervals (i.e., every five years) following a consistent set of audit protocols to be applied across all storage facilities. Review teams would ideally be selected from a broad set of experts and stakeholders, such as regulators from related fields in other states, academia, consultants, and environment groups. Results from the mandatory review should be published in a publicly available report with an opportunity for public comment. Responsibility for the design and executing of the review program should either be with a lead agency designated by the Governor, or alternatively could be assigned to an independent safety review board appointed by the Governor. (See Recommendation 1.17 in the Summary Report.)

Acceptability of the Various Risks: Risk Targets, Risk Goals, Risk Acceptability Criteria

Recommendation: It is recommended that either DOGGR (as part of its regulations or policies) or the industry (perhaps through an industry consortium) determine, for each category of risk, a threshold level of risk, and promulgate these threshold levels as risk targets or goals. There are many possible ways in which a risk target or goal might be formulated, and of course for every risk category, a different target or goal is necessary. An example or two may suffice to provide the general idea.

Risk Management Plans—Methodology for Understanding the Current "Level" of Risk

Recommendation: To complete Element #1 successfully, a facility-specific quantitative risk analysis must be undertaken. The risk analysis must provide a quantified estimate for each analysis "result," including an estimate of the uncertainties in the numbers, and must describe each important contributor in a way that supports later Risk Management Plan Elements (see below), such as comparisons with acceptable risk levels, decisions on further monitoring or analysis, decisions on intervention, and so on. Therefore, it is recommended that the proposed new DOGGR regulations should describe what must be accomplished by an acceptable risk assessment approach and methodology, along with information about how DOGGR will review a given approach and methodology to assure that it is adequate. Although each facility can select its own approach and methodology, this is necessary in the DOGGR regulations to ensure that sufficient rigor and thoroughness are used across all facilities in California. The methodology must address each risk category considered in the Risk Management Plan.

Recommendation: To address the issue raised here, we propose the following draft language capturing the concerns described above:

[proposed for 1726.3(b)] The methodology shall include at least the following:

1. *Identification of the most important potential accident scenarios associated with operation of the underground gas storage project, based on a detailed description of the characteristics of each facility (number of wells, age, operating scheme, etc.);*

2. *Evaluation of the frequency (for example, the annual probability) of each such accident scenario, and the range of consequences associated with it, including estimates of the uncertainties in the numerical values;*

3. *For each important accident scenario, identification of the principal equipment failures, the principal external initiating events if any (earthquakes, flooding, aboveground industrial accidents, etc.), the principal operational errors, and other aspects that contribute to each accident scenario, and for each a description and quantification of its role relative to other contributors in the evolution of the scenario;*

4. *For each scenario leading to an accidental release, identification of the important engineered or natural features that affect the extent of the various end-point consequences, and a quantification of their relative roles, including an estimate of the uncertainties in the quantification.*

Conclusion: The draft DOGGR regulations ignore how human and organizational factors as well as a healthy safety culture drive safety outcomes and performance. (See Conclusion 1.18 in the Summary Report.)

Recommendation: The final DOGGR regulations for underground gas storage facilities should explicitly address the importance and role of human and organizational factors as well as safety culture, commensurate with their impact. DOGGR could follow the State of California's Department of Industrial Relations' (DIR) Occupational Safety and Health Standards Board and at least adopt the two new "Human Factors" and "Safety Culture" elements in the recently revised and updated CalOSHA Process Safety Management for Petroleum Refineries regulation, which became effective on October 1, 2017. In this context, DOGGR should also consider applying other related and applicable elements of the new CalOSHA regulation to underground gas storage safety, such as "Management of Organizational Change." (See Recommendation 1.18 in the Summary Report.)

Risk Management Plan—Routine (or periodic) Monitoring, Data collection, and Analysis

Recommendation: It is recommended that DOGGR require that monitoring, data collection, and analysis must be informed using the insights from a scenario-by-scenario risk analysis to assist decision-makers in determining what to monitor, what data to collect, what to analyze, and why. Especially for scenarios characterized by a low probability of occurrence but a potential for high consequences, only a risk analysis that identifies and characterizes them can reveal the optimal intervention(s) to reduce their potential consequences.

Recommendation: Throughout the new DOGGR draft regulation are requirements for monitoring, data collection, and analysis. Each of these requirements must be linked directly to an underlying risk analysis that can support a determination of the technical basis for deciding, for that activity, (1) how often, (2) with how much detail or accuracy, and (3) how much uncertainty in the measurements is tolerable, and why. An explicit linkage in the language of the requirements to the specific accident scenarios at issue can help provide the technical basis for these decisions.

Risk Management Plan—Intervention Activities

Recommendation: A Risk Management Plan must include a description of the decision-making process including criteria for undertaking interventions of various types. This is needed even though many of the details cannot be provided in the RMP, because each intervention is by its nature highly situation specific.

Recommendation: A change must be made to replace the words "prevention protocols" with "intervention protocols" everywhere in regulatory subsection 1726.3(b).

Risk Management Plan—Emergency Response Plan

Recommendation: A Risk Management Plan must include an emergency response plan that establishes both requirements and expectations, and that is based on a careful understanding of the given facility's risk profile.

Risk Management Plan—Documenting the Results

Recommendation: A Risk Management Plan must include a description of what documentation is required, or desirable, and why. Depending on the circumstances, certain documentation requirements may be specified, and others suggested.

Operating Crew Training

Conclusion: There is no California requirement at today's operating underground gas storage facilities for the regular training of the operating and maintenance crew, nor for the use of written procedures to assist the crew in its response to off-normal conditions and events that might lead to a severe accident. Regular training and written procedures have been demonstrated in other industries to improve safety around off-normal conditions and events. It is likely that underground gas storage could benefit similarly from analogous training and procedures. (See Conclusion 1.19 in the Summary Report.)

Recommendation: The Steering Committee recommends that at each operating underground gas storage facility in California, a requirement be put in place for the regular training of the operating and maintenance crew, using written procedures. This could be either a requirement developed and implemented voluntarily by the industry itself, or a requirement embodied in a government regulation. It is further recommended that the requirement be placed in the Risk Management Plan section of the new DOGGR regulations. (See Recommendation 1.19 in the Summary Report.)

Capability to Predict the Site-specific and Release-specific Transport and Fate of Releases

Conclusion: Although a range of practical and sophisticated models are readily available for predicting the impacts of off-normal LOC events, there is currently no requirement for UGS facilities to possess, or have access to, atmospheric dispersion models that can predict the fate of natural gas emitted from a facility. Also, the lack of temporal and spatially varying emission data from each facility, as well as the past lack of reliable local meteorological data (now addressed by the new CARB regulations for methane emissions from natural gas facilities), make it difficult to accurately simulate the atmospheric dispersion and concentrations of gas leakage from UGS facilities. (See Conclusion 1.20 in the Summary Report.)

Recommendation: Each operating facility in California should arrange to develop a capability to predict the atmospheric dispersion and fate of a large release of natural gas to the environment in near real time, and the impact of such a release on workers, the local population, and the broader environment. The simulation capability should be developed by an independent (ideally single) institution with the technical capacity (i.e., modeling skills) and transparency that meet the public's demand for trust. (See Recommendation 1.20 in the Summary Report.)

Database for Routine Reporting of Off-normal Events Relevant to Safety

Conclusion: Experience from other industries shows that the reporting of minor off-normal events and failures can be very useful when shared and aggregated for the purposes of improving operations and learning from mistakes. (See Conclusion 1.23 in the Summary Report.)

Recommendation: The Steering Committee recommends that a database be developed for the reporting and analysis of all off-normal occurrences (including equipment failures, human errors in operations and maintenance, and modest off-normal events and maintenance problems) at all underground gas storage facilities in California. An example of one kind of input to this database is the required reporting of leak detection and repair required under the new CARB regulations for methane emissions from natural gas facilities. The database should be made publicly available to enable others to derive lessons-learned from it (See Recommendation 1.23 in the Summary Report.)

Underground Gas Storage Project Data Requirements (Section 1726.4)

Recommendation: To maintain consistency in reporting across the industry it is recommended that a definition of a change in the project data be provided. Additionally, a predefined timeframe for reporting such changes should be specified. Furthermore, we recommend a review of all data be done every few years.

Well Construction Requirements (Section 1726.5)

Recommendation: Clarification of what qualifies as a primary barrier is recommended to avoid confusion. Because many of these wells are repurposed, i.e., conversions of existing, old oil and gas wells, we recommend that the evaluation of cement bond integrity be addressed throughout the lifetime of a well and not just at initial casing installation.

Mechanical Integrity Testing (Section 1726.6)

Recommendation: We recommend the following industry standards for logging to demonstrate external mechanical integrity:

> *(A)* Temperature Survey. *A temperature survey performed to satisfy the requirements of external mechanical integrity testing shall adhere to the following:*

1. *The well must be taken off injection at least twenty-four hours but not more than forty-eight hours prior to performing the temperature log, unless an alternate duration has been approved by the DOGGR.*

2. *All casing and all internal annuli must be completely filled with fluid and allowed to stabilize prior to commencement of logging operations.*

3. *The logging tool shall be centralized, and calibrated to the extent feasible.*

4. *The well must be logged from the surface downward, lowering the tool at a rate of no more than thirty feet per minute.*

5. *If the well has not been taken off injection for at least twenty-four hours before the log is run, comparison with either a second log run six hours after the time the log of record is started or a log from another well at the same site showing no anomalies shall be available to demonstrate normal patterns of temperature change.*

6. *The log data shall be provided to the DOGGR electronically in either LAS or ASCII format.*

(B) Noise Log. *A noise log performed to satisfy the requirements shall adhere to the following:*

1. *Noise logging may not be carried out while injection is occurring.*

2. *All casing and all internal annuli must be completely filled with fluid and allowed to stabilize prior to commencement of logging operations.*

3. *Noise measurements must be taken at intervals of 100 feet to create a log on a coarse grid.*

4. *Noise logging shall occur upwards from the bottom of the well to the top of the well.*

5. *If any anomalies are evident on the coarse log, there must be a construction of a finer grid by making noise measurements at intervals of twenty feet within the coarse intervals containing high noise levels.*

6. *Noise measurements must be taken at intervals of ten feet through the first fifty feet above the injection interval and at intervals of twenty feet within the 100-foot intervals containing:*

   a. The base of the lowermost bleed-off zone above the injection interval;

   b. The base of the lowermost USDW; and

   c. In the case of varying water quality within the zone of USDW, the top and base of each interval with significantly different water quality from the next interval.

7. *Additional measurements must be made to pinpoint depths at which noise is produced.*

8. *A vertical scale of one or two inches per 100 feet shall be used.*

(*C*) Cement Evaluation Logging. *A cement evaluation log performed to satisfy the requirements of this section shall adhere to the following:*

1. *Cement evaluation tools shall be calibrated and centralized to the extent feasible.*

2. *Cement evaluation tools shall be run initially under surface pressure and then under pressure of at least 1,500 psi.*

3. *If gas is present within the casing where cement evaluation is being conducted, then a padded cement evaluation tool shall be run in lieu of an acoustic tool.*

(D) Anomalies. *The operator shall take immediate action to investigate any anomalies, as compared to the historic record, encountered during testing as required. If there is any reason to suspect fluid migration, the operator shall take immediate action to prevent damage to public health, safety, and the environment, and shall notify the DOGRR immediately.*

Monitoring Requirements (Section 1726.7)

Recommendation: We recommend the collection and recording of pressure data for all uncemented annuli and injection tubing. Additionally, observation wells should be utilized at all UGS sites, and installation of groundwater monitoring wells to evaluate USDW should be considered.

Inspection, Testing, and Maintenance of Wellheads and Valves (Section 1726.8)

Recommendation: All wellheads and valving should be function-tested and pressure-tested at least annually, and should be rated to withstanding the maximum allowable operational pressures within the UGS field.

Well Leak Reporting (Section 1726.9)

Recommendation: We recommend that a record of mandatory reporting of all integrity issues should be implemented independent of the size of the release. The time line and urgency of the reporting can be varied, depending on the gravity of the release according to the definition in this section of the regulations.

Requirements for Decommissioning (Section 1726.10)

Recommendation: We recommend that the UGS regulations describe an adequate path to wellbore abandonment. Furthermore, DOGGR needs to determine whether the current industry standards are adequate.

1.7 RISK-RELATED CHARACTERISTICS OF UGS SITES IN CALIFORNIA

Site-specific Hazard and Risk Assessment

Finding: The hazards, vulnerabilities, and risk levels are generally different for facilities that store gas in former gas reservoirs versus former oil reservoirs, and also differ qualitatively among individual facilities based on their unique characteristics. Identification of such differences allows the high-level or preliminary assessment of which UGS sites in California may present higher risk to health, safety, and the environment than others, overall or for certain risk categories and scenarios. High-level identification of such risk-related differences can lead to more specialized and effective risk management and mitigation approaches for each setting.

Conclusion: Qualitative assessment of risk-related characteristics of the California underground gas storage facilities points to relatively larger potential risk in facilities that have older repurposed wells often in former oil reservoirs, are located in hazard zones for seismic or other natural disaster risks, may have a higher rate of loss-of-containment incidents, and are located near large populations centers. (See Conclusion 1.25a in the Summary Report.)

Conclusion: Of the currently operating facilities, Playa del Rey stands out as a facility with risk-related characteristics of high concern for health and safety relative to the other facilities in California, followed by Aliso Canyon, Honor Rancho, La Goleta, and Los Medanos. (See Conclusion 1.25b in the Summary Report.)

Recommendation: The State of California should conduct a comparative study of all underground gas storage facilities to better understand the risk of individual facilities relative to others. This comparative study should be based on the risk management plans being developed for each facility and should be commissioned when such risk management plans have matured to the point that they comprise formal risk assessments and mitigation plans (e.g., in five years). The end product would be a table similar to Table ES-1.1 in the Executive Summary, but the revised table would be based on quantitative rather than qualitative information. The quantitative risk-related information on each facility can then be used by decision-makers to examine the tradeoffs between risks associated with individual facilities and their importance in meeting the demands of the natural gas supply. (See Recommendation 1.25 in the Summary Report.)

Key Question 2

Does California need underground gas storage to provide for energy reliability through 2020?

1.1 WHAT IS THE ROLE OF GAS STORAGE IN CALIFORNIA TODAY?

Finding: While forecasts suggest falling total gas demand out through 2030, none of the forecasts break out how much gas might be necessary to firm intermittent renewable generation and the timing of that need, factors which can affect the need for gas storage.

Finding: Nearly every winter has a month with average daily demand that exceeds, or nearly exceeds, pipeline take-away capacity.

Conclusion 2.1: Without gas storage, California would be unable to consistently meet the winter demand for gas.

Conclusion 2.2: If California had no gas storage, the burden of allowing relatively constant gas production to match to seasonally varying demand would shift to production and storage located more than 1,000 miles upstream from California.

Finding: California does not have enough intrastate pipeline take-away capacity to meet forecasted peak winter demand. California's intrastate pipeline capacity (7.5 Bcfd) is insufficient to meet the forecasted 11.8 Bcfd peak load corresponding to a very cold winter day.

Conclusion 2.3: California does not have enough intrastate pipeline take-away capacity to meet forecasted peak winter demand. Currently, winter peak load of 11.8 Bcdf can only be met reliably if storage can deliver 4.3 Bcfd.

Finding: The California utilities, together, have enough storage delivery capacity to meet winter peak day demand based on historic regulatory and operational requirements with about 0.5 Bcfd surplus that can be utilized in case of gas system outages.

Finding: Average daily scheduling of gas delivery generally works because the gas company covers the hourly mismatch between at deliveries and variable usage. Electric generation load causes the change in gas load shown in Figure 11 in hours 12 through 7. Since electric generators have to schedule the same quantity of gas delivery each hour, the incremental supply often comes from storage.

Conclusion 2.4: Gas storage provides crucial hourly balancing for the gas system in all seasons. Without gas storage, California would be unable to accommodate the electricity generation ramping that now occurs nearly every day and that may increase as more renewables are added to the grid.

Finding: Underground gas storage protects California from outages caused by extreme events, notably extreme cold weather that can drastically reduce out-of-state supplies.

Conclusion 2.5: Gas storage could increasingly be called on to provide gas and electric reliability during emergencies caused by extreme weather and wild fires in and beyond California. Both extreme weather and wild fire conditions are expected to increase with climate change. These emergencies can threaten supply when demand simultaneously increases.

Conclusion 2.6: Seasonal price arbitrage can be considered a second-order benefit of utility-owned gas storage. In theory, the utilities could purchase financial contracts to achieve this price benefit. As long as California needs storage to meet winter reliability needs, however, it is prudent to also capture price benefits when they are available. This allows California to avoid the transaction costs that would be associated with using financial contracts to hedge winter prices.

Finding: Natural gas storage in California also enhances market liquidity. It allows marketers a place to store gas for short periods of time (in contrast to the utilities storing gas primarily for winter). This extra degree of freedom helps to manage dis-synchronies between sales contract starts and stops; the timing of new production coming on line; or maintenance periods at a production, gathering or pipeline facility.

Conclusion 2.7: Storage allows access to gas supply in local markets rather than having to wait for it to be transported. In short, storage provides more options to dispose of or to access supply.

Conclusion 2.8: The overarching reason for the utilities' underground gas storage is to meet the winter demand for gas. If storage capacity is sufficient to help meet winter demand, it is then able to perform all the other named functions, including intraday balancing, compensating for production which is not aligned with demand, creating an in-state stockpile for emergencies, and allowing arbitrage and market liquidity.

Recommendation 2.1: In evaluating alternatives that would reduce dependence on underground gas storage and shift norms about controlling interruptibility, the State should obtain detailed analysis of the gas system to ensure that the balancing roles gas storage plays on all timescales can be effectively managed by other means. This analysis should include hydraulic modeling of the gas system. The State should also take into account the role these facilities have had in addressing emergency situations, including extreme weather and wildfires.

1.2 FACTORS THAT MAY BE CAUSING ROLE OF GAS TO CHANGE

Conclusion 2.9: Without gas storage, California would be unable to accommodate the electricity generation ramping that now occurs nearly every day and that may increase as more renewables are added to the grid.

1.4 ALTERNATIVES TO UNDERGROUND GAS STORAGE (TO 2020)

Finding: Based on recent pipeline construction costs, we estimate a total cost of close to $15 billion to add 4.3 Bcfd of large-diameter intrastate pipeline capacity and one new interstate pipeline, should California have no underground gas storage.

Finding: Supplying California's full winter peak day demand completely with gas delivered via pipeline on the day it is needed instead of using gas stored in California pushes the problem of matching supply with demand onto upstream gas pipeline operators and producers.

Conclusion 2.10: Construction of additional pipelines to replace underground gas storage in the 2020 timeframe would cost approximately $15B, would be extremely difficult to get done by 2020, and would shift the risk of supply not meeting demand to upstream, out-of-state supplies.

Finding: California could replace all underground gas storage required today with LNG peak shaving units and meet the 11.8 Bcfd extreme winter peak day demand forecast.

Conclusion 2.11: Replacing all underground gas storage with LNG peak shaving units to meet the 11.8 Bcfd extreme winter peak day demand forecast for 2020 would be extremely difficult to permit and would require about $10B.

Conclusion 2.12: The number of containerized LNG units required to generate each MWh suggest containerized LNG does not appear viable at the scale required to replace California's 4.3 Bcfd winter peak need for underground gas storage use. It may, however, have application in meeting system peaks for a few hours or supporting power plant demands for a few hours. Though, it would require 2,000 containers to support a 50 MW power plant for four hours, and these containers would have to be transported to a power plant, which would incur potential safety issues, increased emissions, and complexity.

Conclusion 2.13: As with the containerized LNG, far too many "CNG In A Box" containers would be needed to replace California's underground storage, but applications such as providing a few hours of gas at a specific location such as a peaking power plant or a refinery could make sense.

Conclusion 2.14: Augmenting gas supply to San Diego with LNG from Sempra's terminal in Mexico would provide a short-term, albeit relatively small (on the order of 300 MMcfd), impact on the need for gas storage in Los Angeles at a small marginal cost, and would not require construction of new facilities.

Finding: In addition to the fact that only small amounts of renewable natural gas are likely to be available by 2020, storing this gas to help meet winter demand and to provide daily ramping would still require use of underground gas storage.

Finding: Gas-fired furnaces overwhelmingly supply building space heating in California and this use results in the winter peak demand for gas. California has no policies specific to electrification of building heat, therefore the source of building heat will not likely switch to electricity for several decades (for more information, see Chapter 3).

Conclusion 2.15: No method of conserving or supplying electricity—including electricity storage (batteries, pumped hydroelectric, compressed air storage, etc.), new transmission, energy efficiency measures, and demand response—can replace the need for gas to meet the winter peak in the 2020 timeframe. The winter peak is caused by the demand for heat, and heat will continue to be provided by gas, not electricity, in that timeframe. Gas storage is likely to remain a requirement for reliably meeting winter peak demand.

Finding: Meeting all of California's 2,830 MMcfd of unmet summer demand via electricity from energy storage would require approximately 420,000 MWh of electricity storage. Cost estimates for energy storage are evolving rapidly. The current cost of a 420,000 MWh electricity storage system capable of offsetting all gas storage for a peak summer day would be approximately $174 billion at the current low end of Lazard's (2016) cost range estimate ($417/kWh). If costs fall an additional 75%, the cost would be $44 billion to offset the summer peak demand for electricity, but this would do little to address the winter peak driven by demand for gas-fired heat.

Finding: Current CPUC storage mandates could offset roughly 8% of the peak gas requirement for electricity in the peak summer month (assuming four hours of storage).

Finding: Energy efficiency measures including the combination of committed savings for natural gas, combined with the reductions expected from AAEE (ignoring the uncertainty in its calculation) and the doubling required under SB 350, appear to total less than 400 MMcfd (assuming all of the electric side savings reduce the need for gas-fired generation). If achieved every day, this could remove the need to meet that same demand with gas from storage, but comes nowhere near offsetting California's 4.3 Bcfd shortage on a winter peak day or any other winter day. The actual impact would depend exactly which measures are adopted, what technologies are affected, and what the hourly use pattern changes are.

Finding: The demand response potential appears large enough to offset a good portion of the withdrawal from storage needed to support intraday load balancing by electricity generators but demand response cannot be called upon routinely enough to fully replace the need to use gas from underground storage.

Conclusion 2.16: We could not identify a technical alternative gas supply system that would meet the 11.8 Bcfd extreme winter peak day demand forecast and allow California to eliminate all underground gas storage by 2020. Two possible longer-range physical solutions are extremely expensive, carry their own risks, and would incur barriers to siting. The potential benefits of other approaches that were examined are either small, cannot be estimated at this time, or have negative impacts such as dramatic increase in air toxins and greenhouse gas emissions. No "silver bullet" can replace underground gas storage in the 2020 timeframe.

Finding: Utilities and pipeline companies already use the line pack they have available. Using line pack beyond the normal operational ranges in use today creates a safety concern because a section of overfilled pipe could lead to over-pressurization and potential release of gas.

Finding: Opportunities to shift to out of area generation on gas-challenged days are limited and not reliable.

Finding: The technical assessments for the Aliso Canyon Reliability Action Plans indicate day ahead limits would be helpful, but not a full solution for the winter peak demand. It cannot, for example, eliminate error in the weather forecast.

Finding: If California had no underground gas storage to support shaped nominations, storage somewhere upstream would be required to support the variation in load. However, this remote storage would be unable to respond to short-notice changes.

Finding: Regulatory and operational changes can help to reduce reliance on underground gas storage, but will not eliminate the need for these services.

Conclusion 2.17: Operational and market alternatives do not eliminate the need for underground gas storage to meet winter demand, which serves to overcome the physical difference between peak winter gas demand and the capacity of pipelines to deliver gas. Nor will these measures have much impact on reducing the need to use storage for daily balancing.

1.5 HOW WILL NEW INTEGRITY AND SAFETY RULES AFFECT NATURAL GAS RELIABILITY?

Conclusion 2.18: In the 2020 timeframe, California's utilities will need to replace some, if not all, of the storage capacity that will be lost by complying with new California regulations to continue to meet peak winter demand. California's independent storage providers will also need to replace some, if not all, of their lost injection and withdrawal capacity, if they want to maintain historic operating levels.

Finding: PG&E and SoCalGas spent an average of $500,000 per Bcf of cycling capability in 2015 on O&M at their storage facilities. Over time, those expenses appear to have increased at a rate similar to inflation. We could not determine, from information in the public domain, the condition of gas storage facilities or if O&M expense and capital expenditure has been sufficient to maintain the facilities or whether the independent facilities are in better condition and if this might be the case because they are regulated differently or because their owners focus on storage and storage alone.

Recommendation 2.2: DOGGR should conduct detailed facility condition assessments by independent analysts or with stakeholder review, and determine if the level of investment to date is adequate, taking into account the expected cost to implement the new DOGGR rules. This could include an assessment to determine what, if any, impacts occur as a result of different business and regulatory models for utility versus independent storage.

Key Question 3

How will implementation of California's climate policies change the need for underground gas storage in the future?

3.0 INTRODUCTION

Finding: We found no studies that comprehensively assess the volumes of gas needed in the future, i.e., studies that construct complete future possible energy system configurations that meet the climate goals, project the impact of the policies that provide the means to reach these goals, and project the time of use of gas and electricity on every time scale from subhourly to seasonally.

Conclusion 3.1: There are no energy assessment studies that can convincingly inform the future need for underground gas storage in California, because greenhouse gas emissions goals and expectations for energy system reliability remain to be reconciled.

Recommendation 3.1: California should commission or otherwise obtain studies to identify future configurations of energy system technologies for the State that meet emission constraints and achieve reliability criteria on all timescales, from subhourly to peak daily demand to seasonal supply variation. These studies should result in a new hybrid forecasting and resource assessment tool to inform both policy makers and regulators.

3.1 ELEMENTS OF A FUTURE CALIFORNIA ENERGY SYSTEM

Finding: Sub second (frequency regulation) electricity storage can be provided by flywheels or fast-response batteries; response times of minutes to hours and storage capacities of several hours can be provided by thermal storage at the building or power plant, battery storage, and pumped hydroelectric or compressed air energy storage. Flexible load capacity and management of regional transmission capacity are other tools with similar response times to storage that can be called upon for multiple hours at a time.

Conclusion 3.2: Various forms of energy storage could perform intraday balancing, i.e., manage changes in gas demand over a 24-hour period.

Finding: Most forms of energy storage as currently conceived will probably be inadequate for managing daily peak demand that can occur over multiple days and seasonal demand imbalances.

Finding: P2G uses electricity from low-GHG generation technologies to make a substitute chemical fuel. However, similar to natural gas, these chemical fuels require transportation and storage.

Conclusion 3.3: The only currently available means to address multiday or seasonal supply-demand imbalances without using fossil natural gas appears to be low-GHG chemical fuels. These solutions have the same storage challenges as natural gas and may introduce new constraints, such as the need for new, dedicated pipeline and storage infrastructure in the case of hydrogen or CO_2.

Finding: In California (assuming a similar mix of electricity generators as today) climate change could cause a reduction in generating capacity of 2.0-5.2% in summer, with more severe reductions under ten-year drought conditions. Considered altogether, peak demand for electricity generation could increase by 10-15% in 2050.

Conclusion 3.4: Climate change would shift demand for energy from winter to summer, reducing peak gas demand from reserve capacity in winter, but increasing it in summer. Decreases in electric transmission and generation capacity would increase reliance on backup generation and hence underground gas storage, particularly in summer. The net effect would be a stronger reliance on underground gas storage in summer, and possibly increased gas use, than in a scenario without climate change.

3.2 DEMAND FOR UGS IN 2030

Finding: For the scenarios available in the literature, and with some minor exceptions (see below), changes to the energy system from the current state to 2030 are modest. The variation in total annual demand for natural gas in 2030 ranged from between 78% and 100% of current levels in the six GHG-compliant studies we reviewed.

Finding: Among the scenarios included, we found that, by 2030, total non-electricity natural gas demand would decrease by 11-22% relative to today, mainly due to efficiency improvements in the building stock.

Finding: The highest gas use for electricity generation occurs during summer months, roughly July-October (Figure 1). The highest output for both wind and solar also occurs in summer months, peaking in June in both cases (Figure 2). For wind, output declines steadily toward a winter low in December-January, whereas for solar, output remains high through September, after which shorter days and more cloud cover diminish statewide output toward a winter low. Gas use for electricity generation is expected to decline much more in summer than in winter by 2030.

Conclusion 3.5: Although we do not know what the decrease in peak natural gas demand might be, the average reduction in gas use of 600-1200 MMcfd would not be enough to eliminate pipeline capacity deficits that are currently as much as 4.3 Bcfd.

Conclusion 3.6: If California continues to develop renewable power using the same resources the State employs today, these will be at a minimum in the winter, which could create a large demand for gas in the electric sector at the same time that gas demand for heat peaks. Consequently, the winter peak problem that exists today may remain or possibly become more acute. Underground gas storage would then be even more important—unless California deploys complementary strategies, including energy storage, demand response, flexible loads, time-of-use rates, electric vehicle charging, and an expanded or coordinated western grid.

Finding: Based on State policies, CEC projections indicate that overall demand for natural gas will decrease in both summer and winter, allowing for increased flexibility for natural gas injection into storage. However, CEC projects that daily natural gas ramping capability requirements will increase in most months (July through March).

Conclusion 3.7: By 2030, an increase in the need to use gas to supply ramping capability could result in placing greater reliance on underground gas storage.

Finding: January regularly has periods when the combined output of solar and wind is nearly zero, particularly at night when solar is not operating and the wind dies down. In June, average outputs for solar and wind are much higher than January, and a strong anticorrelation between wind and solar keeps the combined output significantly higher than zero in most hours. However, there are still periods where wind output falls to almost zero, sometimes for multiple days at a time, causing dramatic (and sometimes very rapid) drops in total output. In Germany, periods of low solar and wind output are labeled "*dunkelflaute*", which literally translates as "dark doldrums." This variability must be mitigated to ensure reliable electricity. Today the load is balanced mostly with a combination of natural gas turbine generation and hydropower.

Finding: Wind generation capacity (at ~4.9 GW) has not increased since 2014 and is expected to remain constant through 2018. Utility-scale solar PV is expected to more than double, from 4.5 GW in 2014 to 9.1 GW in 2018. The contribution from wind variability will be similar to that shown in Figure 7 and Figure 8 over the next few years, but as solar generation is always zero in the night, the solar variability will continue to grow, exacerbating the total intermittency variation.

Finding: To mitigate expected generation variability, the California Independent System Operator (CAISO) has estimated that almost as much flexible generation capacity as intermittent renewable generation capacity will be needed: for 2018, it estimates that ~16 GW will be needed to balance ~18 GW of intermittent renewables (with this capacity adding some additional intermittent renewables including a portion of behind-the-meter PV generation to the wind and solar capacities mentioned above). This flexible generation capacity varies monthly, with a minimum near ~11 GW in July and a maximum in December.

Finding: Brinkman et al. (2016) explored a model of California's electricity system in 2030 under a 50% GHG reduction scenario, which assumed 56% renewable electricity generation that included 6% customer-sited solar PV. The study found that up to 30 GW of gas generation would be needed to backup these renewables, though half of this capacity would be utilized less than ~25% of the time, making capital investments to insure the availability of such gas generation difficult.

Finding: The ~30 GW of backup natural gas capacity needed in 2030 translates into ~5,000 MMcfd, assuming an average heat rate of ~7,000 Btu/kWh for natural gas turbines (a reasonable assumption based on average heat rates of future California natural gas plants provided from E3). The demand for gas to provide backup for renewable energy comes close to current pipeline import capacity of ~7,500 MMcfd (see Chapter 2).

Conclusion 3.8: Although California's climate policies for 2030 are likely to reduce total gas use in California, they are also likely to require significant ramping in our natural gas generation to maintain reliability. These surges of gas demand for electric generation may require underground gas storage.

Finding: Despite an overall expected decrease in natural gas use in both summer and winter, the use of natural gas for electricity generation may become "peakier" in order to balance the increasingly intermittent output from wind and solar generation, and this potential peakiness could be nearly as large as today on an hourly or seasonal basis. However, these additional demands on UGS are likely to be small compared with the ~1,000 Bcf that is normally injected into and withdrawn from storage every year (see Figure 9 in Chapter 2).

Conclusion 3.9: The total amount of underground gas storage needed is unlikely to change by 2030.

Recommendation 3.2: California should develop a plan for maintaining electricity reliability in the face of more variable electricity generation in the future. The plan should be consistent with both its goals policies and its means policies, notably for 2030 portfolio requirements and beyond, and should account for energy reliability requirements on all timescales. This plan can be used to estimate future gas and underground gas storage needs.

3.3 DEMAND FOR UGS IN 2050

Finding: The maximum rate of deployment of CCS technology exhibited in any scenario is well below the maximum historical rate seen for U.S. expansion of nuclear and natural gas capacities, normalized for California, but the scale-up rates of wind and solar in scenarios which maximize these resources may be close to the historical maximum.

Finding: Meeting seasonal demand peaks and daily balancing, including backing up intermittent renewables are important issues for reliability and these in turn will determine the future need for UGS.

Finding: Future scenarios of the energy system indicate that adding more inflexible and intermittent resources similar to those in use today will challenge reliability and require many fundamental changes to the energy system. Future energy system choices with less intermittent resources will be closer to the current energy system, but will require a wider variety of resources than are currently contemplated in California.

Conclusion 3.10: Future energy systems that include significant amounts of low-carbon, flexible generation might minimize reliability issues that are currently stabilized with natural gas generation.

Recommendation 3.3: California should commit to finding economic technologies able to deliver significantly more flexibility, higher capacity factor, and more dispatchable resources than conventional wind and solar photovoltaic generation technologies without greenhouse gas emissions. These could include biomass, concentrating solar thermal; geothermal; high-altitude wind; marine and hydrokinetic power; nuclear power; out-of-state, high-capacity-factor wind; fossil with carbon capture and storage; or another technology not yet identified.

Conclusion 3.11: Widely varying energy systems might meet the 2050 climate goals. Some of these would involve a form of gas (methane, hydrogen, CO_2) infrastructure including underground storage, and some may not require as much underground gas storage as in use today.

Recommendation 3.4: California should evaluate the relative feasibility of achieving climate goals with various reliable energy portfolios, and determine from this analysis the likely requirements for any type of underground gas storage in California.

Conclusion 3.12: California has not yet targeted a future energy system that would meet California's 2050 climate goals and provide energy reliability in all sectors. California will likely rely on underground gas storage for the next few decades as these complex issues are worked out.

Recommendation 3.5: A commitment to safe underground gas storage should continue until or unless the State can demonstrate that future energy reliability does not require underground gas storage.

Appendix F

Glossary

Abandoned well – a well that is no longer in use and may or may not be plugged.

Accident scenario – see failure scenario. Also sometimes called an “accident sequence.”

Adiabatic CAES – Process by which energy is stored via compressing air and storing it in an underground cavern. In this case, the heat of compression is separately stored via packed rock bed or other thermal storage medium. When the energy is needed, the compressed air is expanded using the stored heat of compression. The expansion drives a turbine and produces electricity.

Aliso Canyon – oil field and natural gas storage facility in the Santa Susana Mountains with 114 active UGS wells owned by SoCalGas. It serves more than 11 million customers and provides fuel to 17 natural gas-fired power plants.

Amalgamates – when a metal combines with mercury to form an alloy, e.g. amalgamated aluminum is a compound containing aluminum and mercury that can form in end use equipment if mercury is not removed from natural gas.

Arbitrage – the practice of purchasing an asset at a lower price and selling it at a higher price in order to profit off of the difference between the prices, i.e. if natural gas can be purchased at a low price, injected into underground storage, and withdrawn and sold when prices are higher.

Baseload electricity generation – minimum amount of electricity created and available at any given time in order to meet demand levels.

Biogas – byproduct of biological anaerobic decay of organic matter found in municipal solid waste, landfills, manure, and wastewater. See Biomethane.

Biogas digesters – large tank to collect organic waste and allow bacteria to convert the waste into biogas through the process of anaerobic digestion.

Biomass – organic material such as agricultural byproducts, urban wood, and forest residues and byproducts that can be combusted to produce power.

Biomethane – final product after CO2 and other contaminants are removed from biogas.

Black start – what operators call bringing the electricity system back from complete blackout with all facilities out.

Blowout – the uncontrolled flow of gas, liquids, or solids (or a mixture thereof) from a well into the aboveground environment.

Boring, borehole – cylindrical hole cut into rock or soil by drilling. Casing, cement, and other well components may be inserted into the boring to construct a well.

Breach blowout – the uncontrolled flow of gas, liquids, or solids (or a mixture thereof) out of fractures or cavities in the ground, the flow of fluid, which originates from well failure.

California Sustainable Freight Action Plan – developed by the California State Transportation Agency, California Environmental Protection Agency, and Natural Resources Agency to lead other relevant State departments in developing an integrated action plan that establishes clear targets to improve freight efficiency, transition to zero-emission technologies, and increase competitiveness of California's freight system.

California's Energy Future – A 2013 CCST Study that examines the potential for biofuels among other energy topics.

Cap and trade – market-based strategy designed to reduce greenhouse gases (GHGs) from multiple sources by setting a firm limit or cap on GHGs and minimizing the compliance costs of achieving GHG emissions reduction goals.

Caprock – laterally extensive and low-permeability and/or high capillary-entry-pressure formation (e.g., clay shale or mudstone) above a storage reservoir capable of impeding upward migration of fluid. Synonymous with seal or confining layer.

Carbon capture and sequestration – family of technologies that capture carbon dioxide (CO2) from fuel combustion or industrial processes and transport the CO2 to a suitable storage site.

Casing – large-diameter pipe (usually steel) inserted within a wellbore to stabilize the hole, isolate the different formations to prevent the flow or crossflow of formation fluid, and to provide a means of maintaining control of formation fluids and pressure as the well is drilled and during injection/withdrawal as a secondary barrier. Casings are normally cemented to the formation (borehole wall).

Chemical energy storage – when energy is stored in the bonds of atoms and molecules.

Citygate – a virtual point at which gas is transferred from the backbone transmission system into the local transmission and distribution system.

Closed-cycle evaporative cooling – system that transfers waste heat to the surrounding air through water evaporation instead of transferring the waste heat to surrounding oceans, rivers, and/or lakes.

Compressed air energy storage (CAES) – ambient air is compressed and stored under pressure in an underground cavern. When the energy is needed, the pressurized air is heated and expanded in an expansion turbine driving a generator for power production.

Condition –measured or observed status, state or property of a system, e.g., the pressure or temperature, the composition of the gas stream, etc.

Confining layer – see caprock

Consequences – quantified negative effect of a failure scenario (e.g., evacuations of people due to a well blowout).

Core Customers – core customers include all residential, regardless of load size, commercial customers with annual loads below 250,000 therms, and those commercial customers with annual loads above 250,000 therms who elect to receive the increased reliability associated with core service.

Cryogenic distillation – the process to purify air into pure oxygen, nitrogen, and argon.

Cushion gas – natural gas in the reservoir or storage field that is not withdrawn (not produced) and that serves to maintain pressure and to drive out working gas on any withdrawal cycle. Also known as base gas.

De-carbonize – to remove carbon from an object or system, i.e. an engine; or to reduce/ replace the supply/demand for fossil fuels in the energy market through the promotion of renewable energy.

Demand response (DR) – changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time.

Depleted reservoir – hydrocarbon reservoir in which the pressure or mass of reserve has been lowered by production, to the point that further production of oil or gas is sub-economic.

Deviated well – a well drilled using directional drilling methods that is not vertical.

Dispatchable fossil backup – a block of fossil power that can be transmitted (dispatched) as a reliable, controllable, and predictable quantity from the generator to the consumer.

Dispatchable generation – any sort of power that can be transmitted (dispatched) as a reliable, controllable, and predictable quantity from the generator to the consumer.

Dispersion – dilution and mixing effects associated with transport, e.g., dispersion of CH_4 occurs as it is transported by wind.

Distributed energy (DE) – physical and virtual assets that are deployed across the distribution grid, typically close to load, and usually behind the meter. The assets can be used individually or in aggregate to provide services to the electric grid.

Diurnal peak 1-in-10 summer day – the planning standard used by SoCalGas for their local transmission and storage systems. Their systems are designed to provide for continuous firm core and noncore service under a hot summer conditions that are likely to occur only one day in ten years.

Diurnal variation – fluctuation of gas use during the day.

Dunkleflaute – German for "dark doldrums" typically used when renewables, such as wind and solar are less available during the day. This is more common in winter.

Electrification – the process of powering by electricity or conversion of a machine or system to the use of electrical power.

Electrochemically – the use of electricity to initiate a chemical reaction, i.e. use electricity to produce methane from carbon dioxide.

Electrolysis – passing a direct electric current through a substance in order to produce a chemical reaction and the separation of materials, e.g. passing an electric current through water produces hydrogen and oxygen gases.

Energy Action Plan – originally prepared jointly by the California Energy Commission, the Public Utilities Commission and the now-defunct Consumer Power and Conservation Financing Authority to establish shared goals and specific actions to ensure that adequate, reliable, and reasonably-priced electrical power and natural gas supplies are achieved and provided through policies, strategies, and actions that are cost-effective and environmentally sound for California's consumers and taxpayers. The plan was last updated in 2008.

Energy Storage Roadmap – strategy document created by the California Independent System Operator, the California Public Utilities Commission, and the California Energy Commission that identifies policy, technology, and process changes to address challenges faced by the storage sector.

Entrain – see Impingement mortality and entrainment.

Event – an occurrence that is relatively short-lived and which can potentially affect the safety or operation of a system. An earthquake, a pipeline rupture, and a breach blowout are all events bearing on UGS safety.

Failure scenario – sequence of events involving a component or system malfunction that results in consequences.

Fault Tree Analysis (FTA) – an approach to estimating likelihood of failure scenarios by breaking the scenario up into multiple contributing events whose likelihoods are easier to estimate.

Features, Events, and Processes (FEPs) – in risk assessment, FEPs comprise all of the elements potentially relevant to failure scenarios. Catalogues of FEPs can be analyzed to aid in generating a complete and accurate set of failure scenarios.

FEP-scenario approach – a method to aid in generating a complete and accurate set of failure scenarios using Features, Events, and Processes (FEPs).

Fines migration – movement of fine particles within the porous medium commonly resulting in partial plugging of the pore space.

Flexible load capacity – the amount of electricity generation that is flexible (i.e., easy to turn on) to balance varying electricity demand and supply in the grid.

Flywheels – store kinetic energy as an angular momentum of a spinning mass.

Form 10-K – a form that companies must file annually with the Securities and Exchange Commission. It provides a comprehensive overview of a company's business and financial condition and includes audited financial statements.

Formation damage – impairment of the permeability of hydrocarbon-bearing formations by various adverse processes, such as compaction, fines migration, etc.

Frac Gradient/Fracture Gradient – the pressure required to induce fractures in rock at a given depth, or variation in fracturing pressure with depth.

Fractional distillation – the separation of a liquid mixture, like crude oil, into its component parts by selective evaporation and condensation.

Gas Transmission Northwest (GTN) – interstate natural gas pipeline system that transports western Canadian sedimentary basin and rocky mountain-source natural gas to third party natural gas pipelines and markets in Washington, Oregon, and California.

Gasification – a set of chemical reactions that uses limited oxygen to convert a carbon-containing material, like coal or biomass, into carbon monoxide and hydrogen. The resulting gas mixture is called syngas or producer gas and is itself a fuel.

General rate case (GRC) – regulatory proceeding in which a utility lays out what it proposes to spend for the next few years and obtains approval to recover those costs in rates.

Geothermal – relating to the internal heat of the Earth. Geothermal energy is power generated from using this heat, e.g., natural steam, hot water springs, etc.

GHG Compliant – a statewide planning scenario is greenhouse gas (GHG) compliant if it meets the standards for greenhouse gas emissions set by the California Air Resources Board (40% reduction below the 1990 level in 2030, and 80% reduction in 2050). It is non-compliant if total GHG emissions are above these caps. Scenarios developed outside of California were considered GHG compliant if their emissions relative to 1990 (or another recent base year) met the same criteria as in California.

Global Warming Solutions Act – a California State Law (AB 32), which passed in 2006, that fights global warming by requiring the California Air Resources Board (CARB) to develop regulations and a cap-and-trade program to reduce greenhouse gas emissions from all sources throughout the state.

Grid scale energy storage – the storing of electrical energy on a large scale when production exceeds consumption so that it can be returned to the electric grid when production falls below consumption. The largest form of grid scale energy storage is pumped storage hydroelectricity.

Hazard – a potential source of harm to humans, other animals, plants, environment, or infrastructure; synonymous with threat.

Heating value – amount of heat produced by the complete combustion of a unit quantity of fuel.

Henry Hub – benchmark measure of U.S. national price, used to forward contracts on NYMEX. The hub is located in Erath, Louisiana, and at one point some 14 different pipelines interconnected with one another at Henry Hub.

HSIP Gold Data – Homeland Security Infrastructure Program infrastructure geospatial data inventory assembled by the National Geospatial–Intelligence Agency (NGA) in partnership with the Department of Homeland Security (DHS).

Hydrocarbon reservoir – a subsurface basin of naturally occurring hydrocarbons, such as crude oil or natural gas, contained in porous or fractured rock formations.

Hydrocarbons – organic compounds consisting entirely of hydrogen and carbon. Most hydrocarbons found on Earth naturally occur in crude oil.

Hydrogen –the first chemical element in the periodic table, which normally exists as a colorless, odorless, tasteless, diatomic gas (H2).

Hydrogen blending – the concept of blending hydrogen in natural gas pipeline networks.

Hydrogen embrittlement – the process by which metals can become brittle and fracture when hydrogen dissolves into the metal.

Hydrokinetic – relating to moving water. Hydrokinetic energy is the energy harnessed from the flowing water, tides and currents in rivers and oceans, typically by using turbines.

Imbalance – difference between a customer's natural gas usage and the gas scheduled for delivery.

Impingement mortality and entrainment – the effects of cooling water withdrawals on aquatic organisms. Impingement is the trapping of large aquatic organisms against the water intake screens. Entrainment is the carrying of small aquatic organisms into the power plant, which effectively kills them via heat, turbulence and/or chemicals.

Incident – an event or occurrence affecting a UGS facility involving any or all of the following: gas release significant enough to warrant reporting, injury/loss of life, damage to property or infrastructure.

Injection – delivery of fluid (liquid or gas) from the ground surface to the reservoir via wells.

Integrated gasification combined cycle (IGCC) – a type of power plant that uses a high-pressure gasifier to turn fuels (typically coal or natural gas) into syngas, which is used as fuel for the gas turbine. The excess steam produced by the syngas coolers is added to the steam cycle to generate more energy. This improves efficiency compared to the normal combined cycle process due to the higher-temperature steam produced by the gasification process.

Interconnection – an electric grid at a regional scale or larger that operates at a synchronized alternating current (AC) frequency, which allows for efficient transmission of power throughout the grid, connecting a large number of electricity generations and consumers and facilitating electricity market trading.

Intermittent renewable electricity – sources of renewable energy, such as wind and solar, that do not produce electricity consistently and cannot be directly controlled.

Interstate – connecting or involving different states.

Intraday balancing – managing changes in gas demand over a 24-hour period.

Intrastate – existing or occurring within the boundaries of a state.

Lateral Pipeline – delivers gas to or from a mainline.

Leakage – gas or related fluid migration or flow out of the storage system into the environment (subsurface or above ground). It is one type of loss of containment.

Levelized cost – the net present value of the unit-cost of electricity over the lifetime of a power-generating facility. This includes the initial capital costs and ongoing operation, fuel and maintenance costs.

Light/medium/heavy duty vehicles – three classifications of vehicles by weight for the purpose of emissions regulations.

Likelihood – probability per unit time (e.g., per year), per component, or quantitative or semi-quantitative chance (or expected frequency) of occurrence of a failure scenario.

Load balancing – the storage of excess electrical power during low demand periods to be released as demand rises.

Load-pocket balancer – a small local facility that stores and delivers natural gas to accommodate the limits on the ability to move large amounts of natural gas back and forth within a system and improve overall system balance.

Load centers – breaker or fuse boxes, which take electricity supplied by the utility or electric company and distribute it throughout the home.

Load serving entities – an industry term for an electric company. They are companies or organizations that supply load (electricity) to consumers.

Load-shifting – a technique of demand-side management, which involves moving the consumption of high wattage loads to different times within an hour or day or week.

Loss of containment (LOC) – unplanned release to the environment (subsurface or above ground) of gas or related fluid. LOC incidents refer to significant losses of containment of stored gas, i.e., significant enough that it warranted reporting.

Low-carbon gas – refers to alternative fuels, such as natural gas, which have lower carbon dioxide emissions when burned (compared to conventional petroleum fuels).

Low-carbon gas scenario – the scenario of GHG emissions reduction in California to meet 2030 and 2050 GHG emissions reduction goals, which relies heavily on low-carbon gas production, e.g. biomethane, SNG and/or hydrogen blended into pipelines.

Measured Depth (MD) – the length of the well. This may be larger than the depth of the well if the well is not vertical.

Methane – a chemical compound with the formula CH4 (one atom of carbon and 4 atoms of hydrogen). It is the main constituent of natural gas and is in a gaseous state under typical conditions for temperature and pressure.

Naphtha – a general term for any of the volatile, highly flammable liquid mixtures of hydrocarbons derived during the refining of crude oil, natural gas, coal tar, etc.

Natural gas – a naturally occurring gas mixture consisting primarily of methane. It is found in deep underground rock formations and formed when layers of decomposing plant and animal matter are exposed to intense heat and pressure under the surface of the Earth over millions of years.

Natural gas combined cycle plant – a power plant that uses a gas and a steam turbine together to produce more electricity from the same fuel. The waste heat from the gas turbine that burns natural gas is routed to make steam for a steam turbine to generate extra power.

Natural gas reforming – a production process that generates hydrogen from natural gas. The most common process is steam-methane reforming, in which high-temperature steam reacts with methane to produce hydrogen and carbon-monoxide.

Natural gas vehicles (NGV) – a vehicle that uses compressed natural gas or liquefied natural gas for energy.

Liquid natural gas (LNG) needle peakers – small local facilities that are built to meet very high demand for natural gas. These facilities typically chill and store the liquid natural gas and regasify it and add it to the pipeline when needed.

Non-Core Customers – include all cogeneration, regardless of load size, and those commercial customers with annual loads above 250,000 therms. 250,000 therms are approximately equal to an annual monthly average usage level of 20,800 therms.

Non-fossil electricity generation – the generation of electric power using non-fossil fuel sources, like hydropower, nuclear, wind, and solar.

NO_x emissions – nitric oxide and nitrogen dioxide gases, which are produced during the consumption of fuels (e.g., in car engines and power plants). These gases contribute to air pollution, specifically the formation of smog and acid rain.

Off-normal – condition characterized by deviation from standard operational or shut-in status, e.g., gas leakage in a system designed to contain gas, plug-in lines that are intended to transport gas, excessively high or low pressure in flowlines, tanks, well tubing or annuli.

Off-peak – refers to lower electrical power demand and generally discounted electricity prices during specific times.

Once-through-cooling (OTC) – a method of cooling power plants, where water is taken from a nearby source (e.g., river or lake) and circulated through pipes to absorb the heat from the steam in the power plant and then discharged back to the local source.

Overhang – amount of gas left at the border that California does not bring into pipelines.

Overpressure – fluid pressure above the hydrostatic pressure, e.g., as caused by injection.

Oxy-combustion – or oxy-fuel combustion, which is the process of burning a fuel using pure oxygen instead of air as the primary oxidant. Since the nitrogen component of air is not heated, fuel consumption is reduced and higher flame temperatures are possible.

Packer – a device inserted into a well that is then expanded (e.g., inflated) to seal the well. E.g., a packer is used to seal the A-Annulus from the reservoir while allowing the tubing to run through it to convey high-pressure fluids (liquids and gases).

Parabolic trough concentration designs – a design for a solar thermal energy collector that is straight in one dimension and curved as a parabola in the other two (like a trough) and lined with a mirror. The sunlight is then focused along the focal line, where there is often a tube, which contains a fluid that is heated to a high temperature to generate electricity.

Peak demand – the time period which represents the highest point of customer consumption of electricity.

Perfs (short for perforations) – holes or slots in well casing, tubing, or liner to connect the well to the reservoir fluids.

Photoelectrochemical – refers to the interaction of light with electrochemical systems. Photoelectrochemical cells (PECs) are solar cells that produce electrical energy or hydrogen in a process similar to water electrolysis.

Pipeline capacity – the quantity (volume) of oil or gas required to maintain a full pipeline.

Plant – in the context of a UGS facility, the plant is the part of the facility with surface infrastructure consisting of any one or all of components such as compressors, gas processing units, electricity generation units, or control room and/or operator office space.

Pool – see Hydrocarbon reservoir

Post-combustion capture – the process of collecting carbon dioxide (CO2) from the exhaust of a combustion process and absorbing it in a suitable solvent.

Power-to-gas (P2G) – load balancing technology that converts excess electricity into hydrogen and/or methane, typically for direct pipeline injection.

Pressure swing adsorption – a technology used to separate certain gas species from a mixture of gases by adsorbing the target gases onto a solid surface under high pressure.

Process – a long-term or slow change in the system relevant to performance. Corrosion of steel, cement degradation, or sand production are some examples of processes relevant to UGS performance.

Production – the primary extraction/delivery of fluid (liquid or gas) from a reservoir to the ground surface via a well for beneficial use (see also Withdrawal).

Pumped hydroelectric storage (PHES) – the storage of energy in the form of water in an upper reservoir, pumped from another reservoir at lower elevation. During periods of high electricity demand, power is generated by releasing the stored water through turbines. During periods of low demand, the upper reservoir is recharged by using lower-cost electricity from the grid to pump the water back to the upper reservoir.

Pure Hydrogen – gas that is made up of only hydrogen with no other impurities.

Ramping requirements – the speed at which backup energy might have to be supplied to the electrical grid.

Rate schedule "FT-H" – the cost per volume for hourly firm transportation service of natural gas.

Receipt point capacity – the amount of gas a utility can take away from the interstate pipelines at the California state line, can also be called take-away capacity.

Risk – likelihood (of failure scenario) multiplied by consequences (of failure scenario).

Risk analysis – process by which risks are assessed and managed including development and evaluation of failure scenarios, accident sequences, fault-trees, bow-tie diagrams, mitigation options and their comparative costs.

Risk assessment – systematic process of identifying, evaluating, and quantifying the risks involved in an activity or undertaking.

Risk endpoint – value (e.g., health, safety, containment, non-degradation) to be protected.

Seal – laterally extensive and low-permeability and/or high capillary-entry-pressure formation (e.g., clay shale or mudstone) above a storage reservoir capable of impeding upward migration of fluid. Synonymous with caprock.

Seismic hazard – likelihood that an earthquake will occur in a given location or along a given fault, within a given window of time, and with ground motion intensity exceeding a given threshold. Although the term hazard is used here, its meaning in this context is different from the standard use of the term hazard in risk assessment (see Hazard).

Seismic risk – risk (seismic hazard multiplied by consequences, e.g., collapse of building(s) in the area) of an earthquake in a given window of time.

Sequestration – the process of injecting carbon dioxide (CO2) captured from an industrial or energy-related source into deep subsurface rock formations for long-term storage.

Short-lived climate pollutants (SLCPs) – powerful climate forcers that have relatively short lifetimes in the atmosphere (a few days to a few decades). They include methane, hydrofluorocarbons (HFCs), and black carbon.

Shrinkage – extra gas that customers deliver to the pipeline to account for gas used to run compressors and gas that is lost to measurement discrepancies.

Skin factor – a measure of the increased resistance to flow in the formation around a well as observed by increased pressure drop in the well during production.

Slow-ramping – describes power plants and electricity generation facilities that take a long time to turn on and start generating power.

Solar thermal – describes a form of technology for harnessing solar energy to generate thermal energy or electrical energy.

Spud – to begin drilling a boring into the ground.

Straight line scenario – the scenario of greenhouse gas (GHG) emission reduction in California where the trajectory of GHG emissions reduction is a straight line between today's GHG levels and the 2030 or 2050 goal. This scenario relies on increased renewable electricity generation and building electrification to meet those goals.

Sub second electricity storage – electrical storage that is provided by flywheels or fast-response batteries for the purpose of frequency regulation in the electric grid.

Subsurface blowout – the uncontrolled flow of gas, liquids, or solids (or a mixture thereof) from a well into the subsurface environment.

Syngas – also called synthesis gas, is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and carbon dioxide. It is used for electricity generation, fuel, and the production of hydrogen, ammonia and synthetic hydrocarbon fuels.

Synthetic natural gas (SNG) – a fuel gas that can be produced from fossil fuels, such as lignite coal, oil shale or biofuels. It can serve as a substitute for natural gas and is suitable for transmission in natural gas pipelines.

Take-away capacity – the amount of gas a utility can take away from the interstate pipelines at the California state line, can also be called take-away capacity.

Tariff – the pricing structure a utility charges a customer for gas or electricity consumption.

Temporal scope – the time period over which likely environmental effects may be experienced due to a proposed project or development.

Thermal gasification – the process of converting biomass into a combustible gas, volatiles, and ash in an enclosed reactor in the presence of an oxidizing agent.

Thermochemically – by means of a chemical reaction where there is the release or absorption of heat energy.

Therms – a unit of heat energy equal to 100,000 Btu. It is approximately the energy equivalent of burning 100 cubic feet (or 1 CCF) of natural gas.

Threat – a potential source of harm to humans, other animals, plants, environment, or infrastructure. Synonymous with hazard.

Title 20 – Appliance Efficiency Regulations, set California standards for energy consumption for both federally and non-federally regulated appliances.

Title 24 – California Building Standards Code, regulations that set standards for constructing buildings in California. Updated every three years.

Total Dissolved Solids (TDS) – the sum of the masses of salts and minerals dissolved in groundwater per unit volume of groundwater, e.g., in milligrams per unit volume of water (mg/L) although it is also often referred to as parts per million (ppm).

Tower concentration designs – a design for a solar thermal energy collector that uses an array of flat mirrors to focus the sun's rays upon a collector tower, where the focused rays are used to heat fluids to generate electricity.

Transmission capacity – the amount of electrical power that can be sent over a transmission line.

Transmissivity – a measure of flow resistance and capacity of a permeable pathway. Transmissivity can be thought of as pathway fluid conductivity multiplied by the minimum pathway dimension perpendicular to flow (i.e., the aperture of a fracture).

Tubing – pipe (typically made of steel as used in oil and gas wells) positioned with casing(s) to allow conveyance of fluids to/from the surface from/to a specific location in the subsurface.

Ultracapacitors – an energy storage technology that offers high power density, instant recharging and very long lifetimes. They play a role in delivering peak power and extending the lifespan of batteries in energy storage systems.

Underground Source of Drinking Water (USDW) – an aquifer or part of an aquifer that supplies any public water system, or contains a sufficient quantity of ground water to supply a public water system, and currently supplies drinking water for human consumption, or contains fewer than 10,000 mg/L of Total Dissolved Solids (TDS).

Utility-scale solar PV – a solar power facility that generates solar power and feeds it into the grid, supplying the utility with energy.

Vehicle-Grid Integration Roadmap – a high-level plan to enable electric vehicles to provide grid services while still meeting consumer driving needs.

Warren Alquist Act – a California state law that created the Energy Commission in 1974 and gave it authority to develop and maintain building energy efficiency standards for new buildings.

Water electrolysis – the separation of water into oxygen and hydrogen gas due to an electric current being passed through the water.

Well Cellar – a dug-out area lined with cement or large-diameter (6 ft/1.8 m) thin-wall pipe within which the well extends out of the ground. The casing spool and casing head reside within the well cellar. The depth of the cellar is such that the master valve of the Christmas tree is easy to reach from ground level (after http://www.glossary.oilfield.slb.com/Terms/c/cellar.aspx (accessed 7/25/17)).

Well workover – repair or stimulation of a well for improving production or injection function.

Western grid – the fragmented electric grid across western United States and parts of Canada and Mexico that is managed by multiple entities, including California ISO.

Wind generation capacity – the maximum electric output that can be produced from wind power generation.

Withdrawal – extraction/delivery of fluid (liquid or gas) from a storage reservoir to the ground surface via wells (see also Production).

Working capacity – quantity of gas that can be injected and withdrawn from the field. Excludes cushion gas.

Working gas – the volume of gas that is injected and withdrawn. The total volume of gas in a reservoir is the sum of the working gas and the cushion gas (base gas).

Appendix G

Review of Information Sources

This study was conducted as a synthesis of existing publically available data including the results of many currently on-going or recently completed relevant studies, protocols and proposed regulations. The quality of the assessment depended on the quality of the information and time available for the study. The study includes ant assessment of data adequacy and limitations posed by time constraints.

Our scientists cited a given reference in the report if it met all three of the following criteria:

1. Fit into one of the seven categories of admissible literature (described in a-g below).

    a. Published, peer-reviewed scientific papers.

    b. Government data and reports including analysis of available data from CPUC, DOGGR, and other publically available sources.

    c. Academic studies that are reviewed through a university process, textbooks, and papers from technical conferences.

    d. Studies generated by non-government organizations that are based on data, and draw traceable conclusions clearly supported by the data.

    e. Voluntary reporting from industry. This data is cited with the caveat that, as voluntary, there is no quality control on the accuracy or completeness of the data.

    f. Other relevant publications including reports and theses. We state the qualifications of the information used in the report.

    g. Additional authoritative sources including the expert opinion of the committee and scientific community.

2. Was relevant to the scope of the report.

3. Added substantive information to the report.

For this report, authors of the report reviewed many sources of public information, including some that are not easily accessible to all citizens, such as fee-based scientific journals. If a member of the public wishes to view a document referenced in the report, they may visit California Council on Science and Technology at 1130 K Street, Suite 280, Sacramento, CA 95814-3965. We cannot duplicate or electronically transmit copyright documents. Please make arrangements in advance by contacting CCST at (916) 492-0996.

Appendix H

California Council on Science and Technology Study Process

California Council on Science and Technology (CCST) studies are viewed as valuable and credible because of the organization's reputation for providing independent, objective, and nonpartisan advice with high standards of scientific and technical quality. Checks and balances are applied at every step in the study process to protect the integrity of the studies and to maintain public confidence in them.

Study Process Overview—Ensuring Independent, Objective Advice

For over 25 years, CCST has been advising California on issues of science and technology by leveraging exceptional talent and expertise.

CCST enlists the state's foremost scientists, engineers, health professionals, and other experts to address the scientific and technical aspects of society's most pressing problems.

CCST studies are funded by state agencies, foundations and other private sponsors. CCST provides independent advice; external sponsors have no control over the conduct of a study once the statement of task and budget are finalized. Authors and the Steering Committee gather information from many sources in public and private meetings but they carry out their deliberations in private in order to avoid political, special interest, and sponsor influence.

Stage 1: Defining the Study

Before the author and Steering Committee selection process begins, CCST staff and members work with sponsors to determine the specific set of questions to be addressed by the study in a formal "statement of task," as well as the duration and cost of the study. The statement of task defines and bounds the scope of the study, and it serves as the basis for determining the expertise and the balance of perspectives needed for the study authors, Steering Committee members, and peer reviewers.

The statement of task, work plan, and budget must be approved by CCST's Project Director in consultation with CCST leadership. This review sometimes results in changes to the proposed task and work plan. On occasion, it results in turning down studies that CCST believes are inappropriately framed or not within its purview.

Stage 2: Study Authors and Steering Committee (SC) Selection and Approval

Selection of appropriate authors and SC members, individually and collectively, is essential for the success of a study. All authors and SC members serve as individual experts, not as representatives of organizations or interest groups. Each expert is expected to contribute to the project on the basis of his or her own expertise and good judgment. The lead author(s) serves as an ex-officio, nonvoting member of the SC to ensure continued communication between the study authors and the SC. CCST sends nominations of experts to the Oversight Committee (made up of two CCST Board Members and an outside expert) for final approval after conducting a thorough balance and conflict of interest (COI) evaluation including an in-person discussion. Any issues raised in that discussion are investigated and addressed. Members of a SC are anonymous until this process is completed.

Careful steps are taken to convene SCs that meet the following criteria:

> **An appropriate range of expertise for the task**. The SC must include experts with the specific expertise and experience needed to address the study's statement of task. A major strength of CCST is the ability to bring together recognized experts from diverse disciplines and backgrounds who might not otherwise collaborate. These diverse groups are encouraged to conceive new ways of thinking about a problem.
>
> **A balance of perspectives**. Having the right expertise is not sufficient for success. It is also essential to evaluate the overall composition of the SC in terms of different experiences and perspectives. The goal is to ensure that the relevant points of view are, in CCST's judgment, reasonably balanced so that the SC can carry out its charge objectively and credibly.
>
> **Screened for conflicts of interest**. All provisional SC members are screened in writing and in a confidential group discussion about possible conflicts of interest. For this purpose, a "conflict of interest" means any financial or other interest which conflicts with the service of the individual because it could significantly impair the individual's objectivity or could create an unfair competitive advantage for any person or organization. The term "conflict of interest" means something more than individual bias. There must be an interest, ordinarily financial, that could be directly affected by the work of the SC. Except for those rare situations in which CCST determines that a conflict of interest is unavoidable and promptly and publicly discloses the conflict of interest, no individual can be appointed to serve (or continue to serve) on a SC used in the development of studies if the individual has a conflict of interest that is relevant to the functions to be performed.
>
> **Point of View is different from Conflict of Interest**. A point of view or bias is not necessarily a conflict of interest. SC members are expected to have points of view, and CCST attempts to balance these points of view in a way deemed appropriate

for the task. SC members are asked to consider respectfully the viewpoints of other members, to reflect their own views rather than be a representative of any organization, and to base their scientific findings and conclusions on the evidence. Each SC member has the right to issue a dissenting opinion to the study if he or she disagrees with the consensus of the other members.

Other considerations. Membership in CCST and previous involvement in CCST studies are taken into account in SC selection. The inclusion of women, minorities, and young professionals are additional considerations.

Specific steps in the SC selection and approval process are as follows:

CCST staff solicit an extensive number of suggestions for potential SC members from a wide range of sources, then recommend a slate of nominees. Nominees are reviewed and approved at several levels within CCST. A provisional slate is then approved by the Oversight Committee. Prior to approval, the provisional SC members complete background information and conflict-of-interest disclosure forms. The SC balance and conflict-of-interest discussion is held at the first SC meeting. Any conflicts of interest or issues of SC balance and expertise are investigated; changes to the SC are proposed and finalized. The Oversight Committee formally approves the SC. SC members continue to be screened for conflict of interest throughout the life of the committee.

CCST uses a similar approach as described above for SC development to identify study authors who have the appropriate expertise and availability to conduct the work necessary to complete the study. In addition to the SC, all authors, peer reviewers, and CCST staff are screened for COI.

Stage 3: Author and Steering Committee Meetings, Information Gathering, Deliberations, and Drafting the Study

Authors and the Steering Committee typically gather information through:

1. meetings;
2. submission of information by outside parties;
3. reviews of the scientific literature; and
4. investigations by the study authors and/or SC members and CCST staff.

In all cases, efforts are made to solicit input from individuals who have been directly involved in, or who have special knowledge of, the problem under consideration.

The authors shall draft the study and the SC shall draft findings and recommendations. The SC deliberates in meetings closed to the public in order to develop draft findings and recommendations free from outside influences. All analyses and drafts of the study remain confidential.

Stage 4: Report Review

As a final check on the quality and objectivity of the study, all CCST reports, whether products of studies, summaries of workshop proceedings, or other documents, must undergo a rigorous, independent external peer review by experts whose comments are provided anonymously to the authors and SC members. CCST recruits independent experts with a range of views and perspectives to review and comment on the draft report prepared by the authors and the SC.

The review process is structured to ensure that each report addresses its approved study charge, that the findings are supported by the scientific evidence and arguments presented, that the exposition and organization are effective, and that the report is impartial and objective.

The authors and the SC must respond to, but need not agree with, reviewer comments in a detailed “response to review” that is examined by one or more independent “report monitor(s)” responsible for ensuring that the report review criteria have been satisfied. After all SC members and appropriate CCST officials have signed off on the final report, it is transmitted to the sponsor of the study and the sponsor can release it to the public. Sponsors are not given an opportunity to suggest changes in reports. All reviewer comments and SC deliberations remain confidential. The names and affiliations of the report reviewers are made public when the report is released.

Appendix I

Expert Oversight and Review

Oversight Committee:

- **Richard C. Flagan**, California Institute of Technology
- **John C. Hemminger**, University of California Irvine
- **Robert F. Sawyer**, University of California, Berkeley

Report Monitor:

- **Robert F. Sawyer**, University of California, Berkeley

Expert Reviewers:

- **Aaron S. Bernstein**, Harvard University
- **Nancy S. Brodsky**, Sandia National Laboratories
- **Linda R. Cohen**, University of California, Irvine
- **Rosa Dominguez-Faus**, University of California, Davis
- **James L. Gooding**, Black & VEATCH
- **William Hoyle**, *former* U.S. Chemical Safety and Hazard Investigation Board
- **Gary B. Hughes**, California Polytechnic State University
- **Lisa M. McKenzie**, University of Colorado Denver
- **Michal C. Moore**, Cornell University
- **Joseph P. Morris**, Lawrence Livermore National Laboratory
- **Phillip G. Nidd**, Dynamic Risk Assessment Systems, Inc.
- **Franklin M. Orr**, Stanford University

- **Snuller Price**, Energy and Environmental Economics, Inc.
- **Kevin Woodruff**, Woodruff Expert Services

Appendix J

Unit Conversion Table

1	Oil Barrel (42 gallons)	=	0.158987	Cubic Meters (m^3)
1	Cubic Foot (cf)	=	0.02831685	Cubic Meters (m^3)
1	Cubic Foot per Day (cfd)	=	0.02831685	Cubic Meters per Day (cmd)
1	British Thermal Unit (Btu)	=	1055	Joules (J)
1	MMBtu	=	1000000	British Thermal Units (Btu)
1	Mcf	=	1000	Cubic Feet (cf)
1	MMcf	=	1000000	Cubic Feet (cf)
1	MMcfd	=	1000000	Cubic Feet per Day (cfd)
1	MMscf	=	1000000	Standard Cubic Feet (scf)
1	Therm (th)	=	100000	British Thermal Units (Btu)
1	Dekatherm (dth)	=	1000000	British Thermal Units (Btu)
1	Watt (W)	=	1	Joule per second (J/s)
1	Kilowatt (kW)	=	1000	Watts (W)
1	Megawatt (MW)	=	1000000	Watts (W)
1	Gigawatt (GW)	=	1×10^9	Watts (W)
1	Kilowatt hour (kWh)	=	3.6×10^6	Joules (J)
1	Megawatt hour (MWh)	=	1000	Kilowatt hours (kWh)
1	Pound (lb)	=	0.45359237	Kilogram (kg)
1	Foot (ft)	=	0.3048	Meters (m)
1	Standard Cubic Foot (scf)[1]	=	1020	British Thermal Units (Btu)
1	Pound per Square Inch (psi)	=	6894.76	Pascals (Pa)
1	US Ton	=	907.185	Kilograms (kg)

1 A standard cubic foot (scf) corresponds to 1 cubic foot of gas at 60 °F (15.6 °C) and 14.73 pounds per square inch absolute (psia)

Appendix K

Southern California Natural Gas Infrastructure Model

1. Problem Statement

As part of the CCST study of natural gas storage in California, Los Alamos National Laboratory (LANL) was tasked with creating a dynamic physics based model of the Southern California Natural Gas system infrastructure. GRAIL was used to examine how gas storage facility performance problems impact gas delivery and the consequences for electricity supply. Although GRAIL is still in development stages, GRAIL was used to simulate a scenario in which the Aliso Canyon storage facility was inoperative.

The simulation results show the system had minimal load shedding at natural gas fired generators and pressures remained within operating norms. This is just one scenario that looks at the role gas storage plays in gas supply reliability and in meeting the gas demand for electricity supply. Many more scenarios should be run to further understand the relationship between gas storage and electricity supply. With further research and funding, GRAIL can be used to examine other storage scenarios to identify operational changes that could optimize gas delivery to natural gas fired electric generation facilities. Along with this study, additional studies will be needed to further asses the viability of underground natural gas storage in California.

2. Gas Reliability Analysis Integrated Library (GRAIL)

LANL has developed a preliminary physics-based model to address several pipeline analysis challenges through the development of the Gas Reliability Analysis Integrated Library (GRAIL). Within GRAIL, LANL has made several recent advances to optimization techniques and control system modeling to provide computationally tractable yet accurate and scalable methods for steady-state optimization (Misra, et al., 2015) (Rios-Mercado & Borraz-Sanchez, 2015), dynamic simulation (Zlotnik, Dyachenko, Backhaus, & Chertkov, 2015) (Dyachenko, Zlotnik, Chertkov, & Korotkevich), and predictive optimal control (Mak, Van Hentenryck, Zlotnik, Bent, & Hijazi, Efficient Dynamic Compressor Optimization in Natural Gas Transmission Systems, 2016) (Zlotnik, Chertkov, & Backhaus, Optimal Control of Transient Flow in Natural Gas Networks, 2015) of gas transport under uncertainty. These advances enable efficient computational methods to model decision processes and physical evolution of large-scale pipelines subject to engineering constraints. GRAIL algorithms can be extended to model pipeline flow scheduling, component-level actions, and corrections by automatic supervisory controls and human operators in reaction to disruptions. GRAIL employs Minimum Load Shedding (MLS) optimization to predict selected aspects of the natural gas infrastructure system state, specifically relating to operations during capacity operations.

LANL is developing the GRAIL algorithms for scalable gas flow modeling and optimization for the Department of Homeland Security and for industry practitioners via the Advanced Research Projects Agency-Energy. This set of algorithms consists of three components that perform (i) steady-state optimization, (ii) dynamic simulation, and (iii) dynamic optimization of large-scale natural gas transmission pipeline flows. Each component requires a static network model that describes the structure of the network and engineering constraints on pressure and compressor horsepower. Component (i) has inputs of maximum and minimum supplies and loads (constant scalars) at all network nodes and a prioritization (by numerical values) of importance of the loads. Component (i) output is the steady-state flow on each pipe that delivers gas to loads according to importance by node. Component (ii) requires given flow in or out of each node as time-series over the simulation horizon. Component (ii) output is a time-series of flows and pressures throughout the pipeline system that result from the given time-varying loads. Component (iii) requires the maximum and minimum supplies and loads at all network nodes and a prioritization of the loads (as time-series over the optimization horizon, e.g. 24 hours). Component (iii) output is a time-series of flows and pressures throughout the pipeline system that allocates gas to loads dynamically according to importance by node and time. Component (ii) can be used to simulate the second-order effects of network damage, and components (i) and (iii) can be used to approximate system operator behavior to compensate for network damage.

The GRAIL software is implemented in Julia (Julia, 2017), a free and open-source programming language for scientific computing with capabilities similar to Matlab. Through Julia, GRAIL is utilizes the free an open-source solver Interior Point Optimizer (IPOPT) (Github-coin-or, n.d.), a state-of-the-art code for solving large-scale nonlinear optimization problems. A key advantage of building GRAIL exclusively on open-source software is that there are no license restrictions. This allows GRAIL to be easily packaged as a containerized executable (e.g. via Docker, Kubernetes), which can be run locally or deployed in a scalable High-Performance Cloud environment. Combining containerization of open-source codes with infrastructure as a service (IaaS) (e.g. Amazon Web Services) enables a nearly endless number of GRAIL analyses to be done in parallel at minimal computational cost.

A scenario identical to the scenario in the Aliso Canyon Summer 2017 Assessment was created, the simulation was run for a 24-hour period, and yielded a feasible solution for all network points. The feasible solution, a time series for every network point and edge, had minimal load shedding (0 to 0.6 MMcfd) and pressures within a normal range of 475 to 675 psig. These results are a step in the right direction towards validating the GRAIL model against actual conditions in the natural gas system. For full validation, the hourly pressure and flow data for all metered points in the system are needed but CCST does not have access to that data. Additionally, now with line 4000 outage, it would be interesting to input this new scenario (with specific mitigations detailed by SoCalGas) to see if GRAIL can find a feasible solution and to look at the geospatial pressure differentials in the system. As GRAIL matures and the visualization becomes more sophisticated in near real time, the benefits will become more clear.

2.1. Data

The GRAIL capability uses inputs from three different sources:

Homeland Security Infrastructure Program (HSIP) Gold 2015 (Homeland Security Infrastructure Program, n.d.) is a geospatial database inventory of infrastructure assets assembled by NGA in partnership with the Department of Homeland Security (DHS). The database is subject to the handling and distribution rules for “Unclassified For Official Use Only” due to licensing and sharing restrictions set forth by the data source entities. HSIP Gold provides geolocations for nodes (compressor stations, interconnects, natural gas fueled generators, receipt/delivery points) and edges (pipelines). Geolocation is important in determining the distance between nodes in the pipeline.

The Federal Energy Regulatory Commission (FERC) 567 data provides pressure information for interconnects, compressor stations, receipt/delivery points as well as average daily delivery amounts at each meter station. The FERC 567 data is considered Critical Energy Infrastructure Information (CEII) and is protected from disclosure with “non-disclosure agreements” (NDA).

Electronic Bulletin Boards (EBB), such as the SoCalGas ENVOY Informational Postings website (Sempra - SoCalGas ENVOY, n.d.), provide open source data on operating capacities and scheduled deliveries for each receipt/delivery point.

Combining data from several sources with varying quality requires a detailed roadmap. The following section and table provides that roadmap.

2.1.1 Inputs

Table 1 shows the data inputs mapped to the GRAIL model variables.

Table 1. Data Inputs Mapped to GRAIL Model Variables

System Component	Network Variable Type	Attribute Required from Source	Mapped GRAIL Model Variable	Units	Source
Compressor	Node connecting elements	Latitude, Longitude	Latitude, Longitude	Decimal Degrees	HSIP Gold 2015
	Node connecting elements	Design Suction Pressure	Cmin (minimum compressor ratio)	Psig	FERC 567
	Node connecting elements	Design Discharge Pressure	Cmax (maximum compressor ratio)	Psig	FERC 567
	Node connecting elements	Rated Horsepower	Hpmax (max horsepower)	HP	FERC 567
Pipeline	Edge	Latitude, Longitude	From Node	Decimal Degrees	HSIP Gold 2015
	Edge	Latitude, Longitude	To Node	Decimal Degrees	HSIP Gold 2015
	Edge	Length	Length	Miles	HSIP Gold 2015
	Edge	Diameter	Diameter	Inches	HSIP Gold 2015
	Edge	MAOP (maximum allowable operating pressure)	Pmax (maximum pressure for nodes and pipelines)	Psig	FERC 567
	Edge	Friction Factor	Friction Factor	Dimensionless	Diameter from HSIP Gold 2015 used in Friction Factor formula Assumed values if missing
Receipt/Delivery Points	Nodes	Latitude, Longitude	Latitude, Longitude	Decimal Degrees	HSIP Gold 2015
	Nodes	Maximum Daily Delivery	Qmax (maximum volume)	MDth/day	FERC 567
	Nodes	Operating Capacity	Qmax (maximum volume)	MMBtu=~Mcf	EBB Nominations
	Nodes	Scheduled Flow	Q (volume)	MMBtu=~Mcf	EBB Nominations
Interconnects	Nodes	Latitude, Longitude	Latitude, Longitude	Decimal Degrees	HSIP Gold 2015
	Nodes	Normal Pressure	P (pressure)	Psig	FERC 567
	Nodes	Scheduled Flow	Q (volume)	MMBtu=~Mcf	EBB Nominations
Natural Gas Fueled Generators	Nodes	Latitude, Longitude	Latitude, Longitude	Decimal Degrees	HSIP Gold 2015

2.1.2. Outputs

Given a Java Script Object Notation (JSON) gas network data file and 24 hours of injection and withdrawal data, and an arbitrary change to the network, the GRAIL model can be used to estimate the minimum reduction of withdrawal (load shed) to ensure gas flow feasibility while adhering to standard operating constraints of pressure and compressor limits. Outputs for the GRAIL model are: mass flux, density, nominations, desired withdrawal, achieved withdrawal, amount shed and compressor ratios at given nodes in the network.

3. Specific formulation of the scenario for the CCST Southern California Natural Gas Infrastructure Model

Given a gas network data file (JSON based network format) and 24 hours of injection and withdrawal data, and an arbitrary damage to the network, GRAIL can determine the minimum reduction of withdrawal (load shed) to ensure gas flow feasibility while adhering to standard operating constraints of pressure and compressor limits. The following sections describe the inputs into the GRAIL model.

3.3.1. Characterization of the Southern California Natural Gas Infrastructure Model for Core Deliveries, Generator Deliveries, Receipt Points (Pipeline), Receipt Points (Storage Withdrawals)

Each natural gas delivery point in the GRAIL model must be coded as sheddable or non-sheddable load. For the Southern California Natural Gas Infrastructure model the natural gas fired electric generators are the only sheddable load points. Core delivery is a term used to define natural gas deliveries to residential and commercial customers and is not allowed to be interrupted in the GRAIL model.

3.3.1.1. Core Deliveries

Natural gas deliveries to receipt points in the Southern California Natural Gas Infrastructure Model were categorized as either: Core Delivery (residential, commercial) or Generator Delivery (for Natural Gas fired generators). Core Delivery was further delineated into LA Basin Core delivery and San Diego Core delivery with the values based on population. Total core gas load was approximately 1437 MMcfd from the Aliso Canyon Risk Assessment Technical Report. 73% of total core delivery was sent to the LA Basin and 26% of the total core delivery was sent to the San Diego area. A flat 24 hour delivery profile was used due to the absence of actual core delivery hourly profile data.

3.3.1.2. Gas deliveries to Natural Gas fired generators

Generator natural gas delivery hourly profiles were estimated for the following generators based on their capacities found in the HSIP 2015 database and the U.S. Energy Information Administration (EIA) 860 database of Operable Generating Units in the United States by State and Energy Source (U.S. Energy Information Administration, n.d.). The hourly generator demand profiles were interpolated using the total hourly electric generation demand profile from the Aliso Canyon Risk Assessment Technical Report, Summer 2017 Assessment (Commission, 2017). Table 2 lists the natural gas electric generators used in the GRAIL simulation of the Southern California natural gas infrastructure model along with their estimated peak hour gas usage and megawatt capacity. The peak hour gas demand represents the 4:00pm value in the hourly profile. This list is based on data available from sources listed in Table 1 and may not include all natural gas fired generators in the Southern California area. Figure 1 shows the hourly demand profiles of each generator in MMcfd.

Table 2. Estimated electric generator demand for natural gas interpolated using the total hourly electric generation demand profile from the aliso canyon risk assessment technical report, summer 2017 assessment. peak hour mmcfd represents the 4:00pm value in the interpolated hourly profile.

Generator	Peak hour MMcfd	MW
AES Alamitos LLC	362	1970
Haynes 1	317	1724
Ormond Beach 1	296	1612
Redondo Beach 5	247	1343
Mountainview CC 3a	204	1108
Encina	174	871
CPV Sentinel Energy Project	156	850
Inland Empire Energy 1	150	819
Scattergood CC	147	803
Otay Mesa	129	686
Elk Hills	114	623
Sunrise Power Co LLC	111	605
Etiwanda 3	122	600
Mandalay 1	105	574
Valley (CA) 1A	105	573
Palomar	101	559
El Segundo 5a	96	526
Walnut Creek Egy 1	92	500
Harbor CC 2	85	466
Huntington Beach 2	83	452
Watson Cogen 1a	74	405
El Centro 4	64	350
Magnolia Repower 1	60	328
Kern River Cogeneration	55	300
Sycamore Cogeneration	55	300

Generator	Peak hour MMcfd	MW
Grayson 4	53	288
Long Beach Generatio GT1	47	260
Midway Sunset Cogeneration Co	43	234
Glenarm GT 1	37	203
Canyon Power Project	36	200
Riverside Energy Res 1	36	196
Chevron El Segundo Refinery	33	183
Indigo Energy 1	27	149
Olive 1	25	139
Malburg 1a	25	138
Niland GT1	22	121
Harbor CGCC 1	19	107

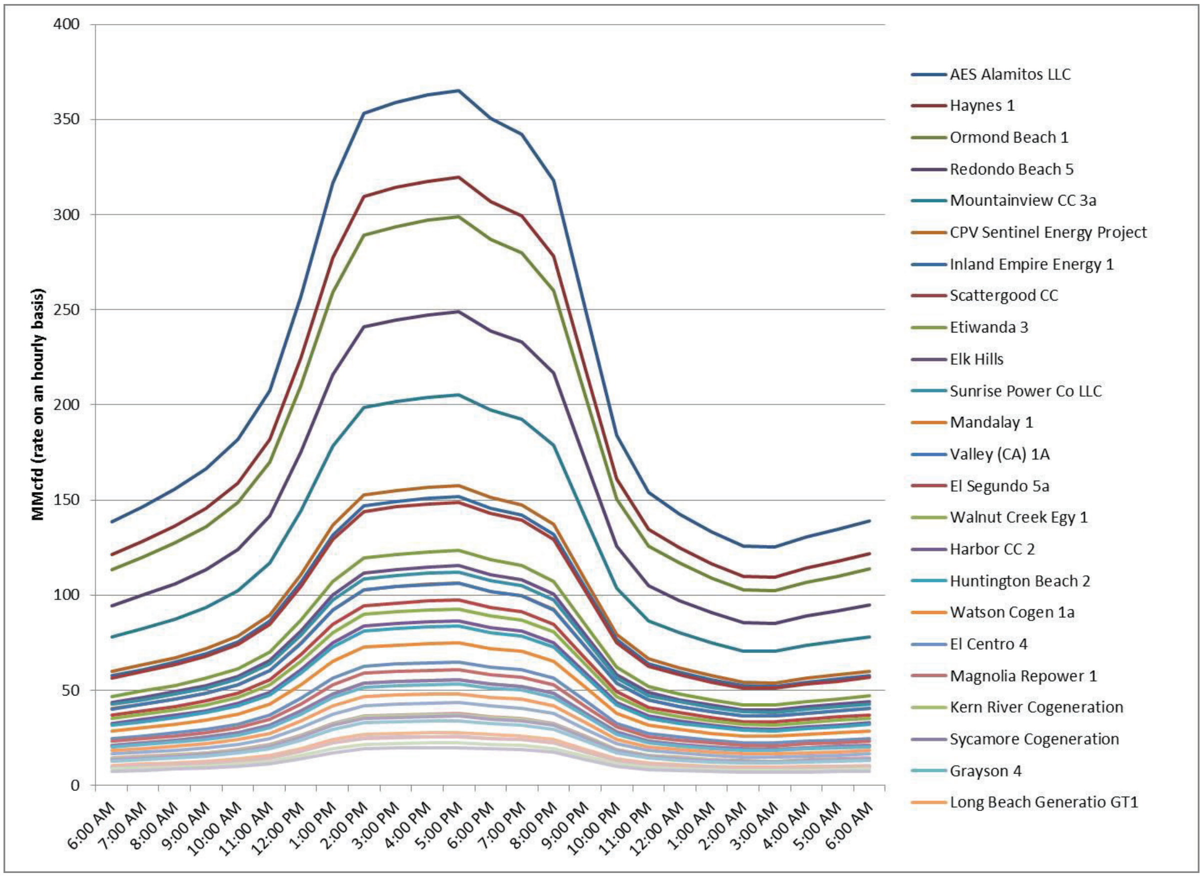

Figure 1. Hourly natural gas consumption profiles for LA basin and San Diego generators interpolated using the total hourly electric generation demand profile from the aliso canyon risk assessment technical report, summer 2017 assessment.

3.3.1.3. Receipt points (pipeline)

Natural gas deliveries to major receipt points were fixed in the GRAIL model using the values in Table 3. Hourly data for the receipt points was not available on the ENVOY website. A flat delivery profile was used for each receipt point. The values of incoming gas supplies were taken from the Aliso Canyon Risk Assessment Technical Report, Summer 2017 Assessment. Total flowing supplies are 3185 MMcfd.

Table 3. Receipt points (MMcfd)

Receipt Point	MMcfd
Line 85	60
Kramer Junction	550
Topock	0 (Line 3000 outage)
El Paso – Ehrenberg1	505
El Paso – Ehrenberg2	505
SoCalGas North Needles	800
Wheeler Ridge	765

3.3.1.4. Receipt points (storage withdrawals)

LANL modeled storage withdrawals from Aliso Canyon, Playa Del Rey, La Goleta and Honor Rancho as specified in the Aliso Canyon Risk Assessment Technical Report, Summer 2017 Assessment. Figure 2 shows the withdrawal profiles for each storage field. Aliso Canyon is modeled with zero withdrawals while the remaining 3 fields have various positive withdrawals during the course of the day.

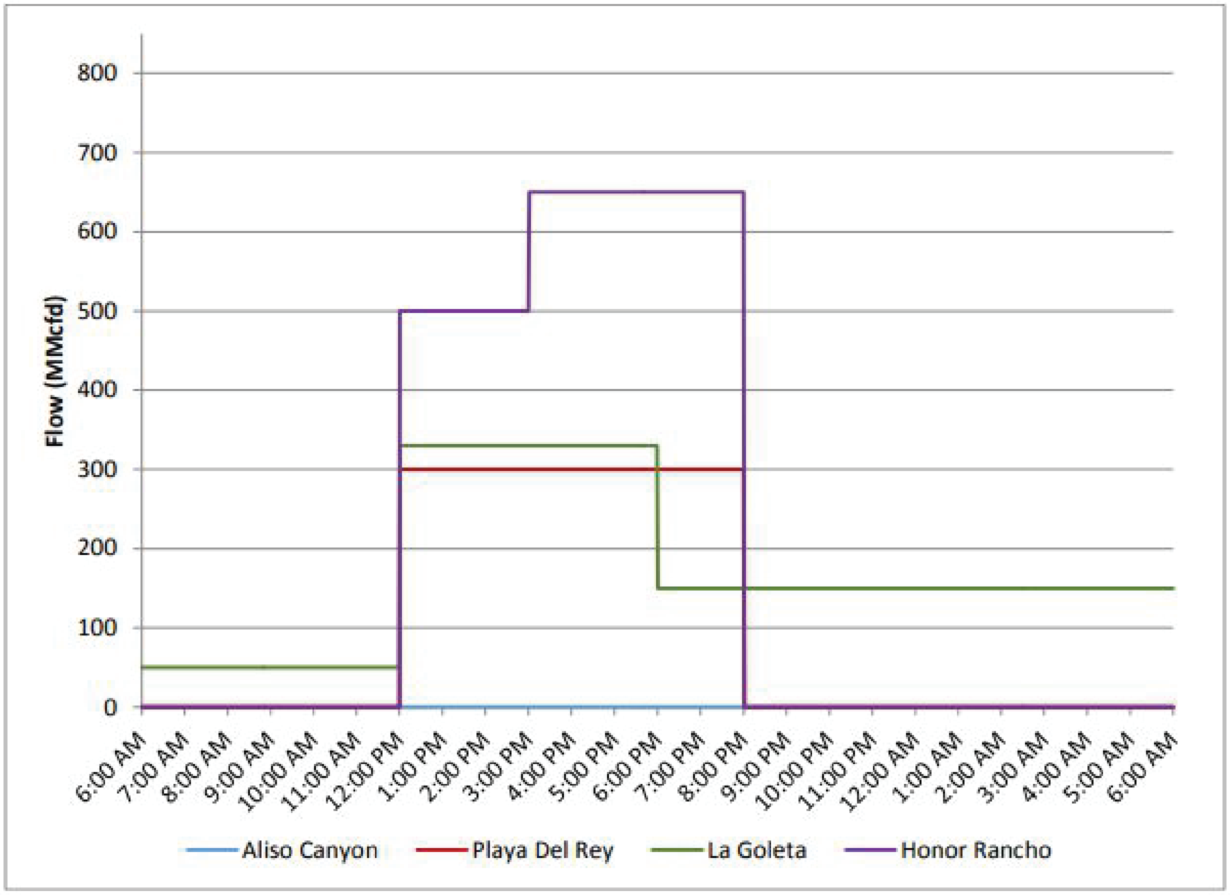

Figure 2. Storage withdrawal hourly profiles

3.3.2. Formulation for scenario inputs to the GRAIL model

The following defines how the core delivery inputs and the electric generator delivery inputs in the GRAIL model were calculated. The following are not the hydraulic modeling equations for GRAIL but rather the equations for calculating the scenario inputs.

Let D_i^c denote the Core delivery of natural gas in MMcfh for all i, and let D_i^{gen} denote the generator I delivery of natural gas in MMcfh. The total consumption of natural gas for electric generation can be written as $D_0^{gen} = \sum D_i^{gen}$ and assuming proportional consumption of natural gas based on MW capacity of each generator (assuming an equal heat rating for all generators) the individual generator consumption of natural gas can be calculated as (1.1).

$$D_i^{gen}(t) = \frac{P_i^{gen}}{\sum P_i^{gen}} * D_0^{gen}(t)$$

Letting $S^{PDR}(t), S^G(t), S^{HR}(t), S^{AC}(t)$ denote the storage withdrawals from Playa del Rey, Goleta, Honor Rancho, and Aliso Canyon and also allowing α_{LA} to represent the proportion of core load attributed to the LA Basin and $(1-\alpha_{LA})$ the core load attributed to the San Diego area, the Total LA Basin Load can be calculated as (1.2).

$$D^{LA}(t) = \sum_{i \in LA} D_i^{gen}(t) + \alpha_{LA} D_0^c(t) - S^{PDR}(t)$$

Where S^{PDR} are injections to Playa del Rey. And equivalently the Total Load in San Diego as (1.3).

$$D^{SD}(t) = \sum_{i \in SD} D_i^{gen}(t) + (1-\alpha_{LA}) D_0^c$$

Each delivery point is coded in the GRAIL model as either sheddable load or non-sheddable load. The model allows for load shedding only at the generator delivery points.

3.3.3. Results

Given the above scenario inputs for all receipt/delivery points in the Southern California Natural Gas Infrastructure Model, the GRAIL simulation was run with the following range of outputs in Table 4.

Table 4. Results for the southern california natural gas infrastructure model

Output Variable	**Range of Values Estimated: Limit Case with 3 Slack nodes**
Density (kg/s-1 m-2)	24-32
Nominations (MMcfd)	0-800 (hourly)
Desired Withdrawals (MMcfd)	0-800 (hourly)
Achieved Withdrawals (MMcfd)	0-800 (hourly)
Amount Load Shed (MMcfd)	0-0.6 (hourly)
Mass Flux (kg/s*m^2)	-4000 to +4000
Pipe Pressures (psig)	475-675
Compressor Ratios	1.0 – 1.35

Modeled pressures in the LA Basin ranged from 475-550 psig; pressures outside of the basin were higher ranging from 550-700 psig. The amount of load shed required to solve the model was small and ranged from 0-0.6 MMcfd on an hourly basis.

3.3.4. Visualization

LANL created a Leaflet (Leaflet - a JavaScript library for interactive maps, n.d.) application for viewing the Southern California Natural Gas Infrastructure Model results from the GRAIL code. Figure 3 displays a sample user interface to the model. The user can investigate mass flux, density, nominations, desired withdrawal, achieved withdrawal, amount shed and compressor ratios at given nodes in the network.

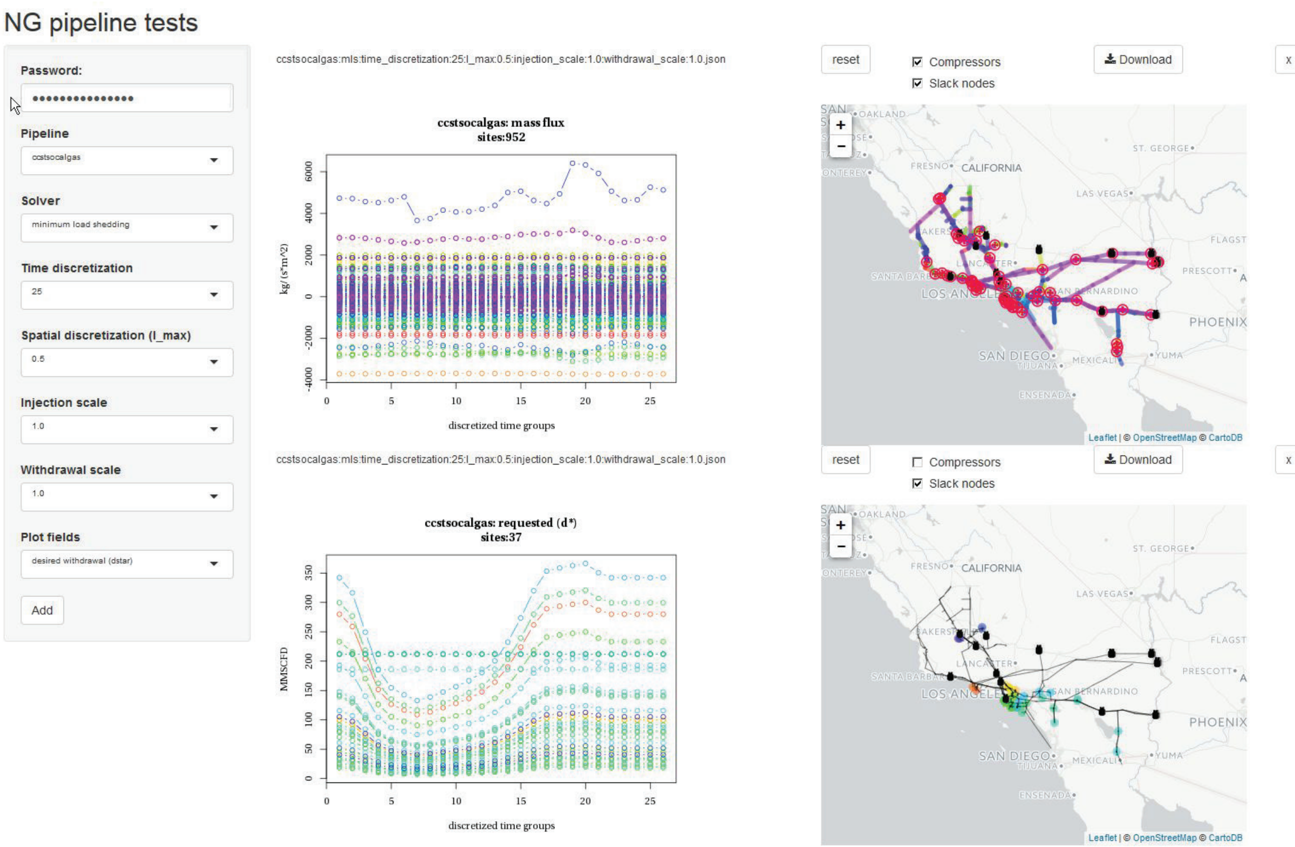

Figure 3. Sample user interface for the southern california Natural gas infrastructure model

4. References

Chertkov, M., Backhaus, S., & Lebedev, V. (2015). Cascading of fluctuations in interdependent energy infrastructures: Gas-grid coupling. *Applied Energy, 160*, 541-551.

Chertkov, M., Fisher, M., Backhaus, S., Bent, R., & Misra, S. (2015). Pressure Fluctuations in Natural Gas Networks caused by Gas-Electric Coupling. *48th Hawaii International Conference on System Sciences*. Honolulu.

Commission, C. P. (2017, May 19). *Aliso Canyon Risk Assessment Technical Report, Summer 2017 Assessment*. Retrieved September 20, 2017, from , http://docketpublic.energy.ca.gov/PublicDocuments/17-IEPR-11/TN217639_20170519T104800_Aliso_Canyon_Risk_Assessment_Technical_Report_Summer_2017_Asses.pdf

Dyachenko, S., Zlotnik, A., Chertkov, M., & Korotkevich, A. (n.d.). Operator Splitting Method For Simulation of Dynamic Flows in Natural Gas Pipeline Networks. arXiv: 1611.10008.

Github-coin-or. (n.d.). Retrieved November 3, 2017, from Github, Inc [US]: https://github.com/coin-or/ipopt

Homeland Security Infrastructure Program. (n.d.). Retrieved November 3, 2017, from https://gii.dhs.gov/HIFLD/hsip-guest

Julia. (2017, November). Retrieved November 3, 2017, from https://julia.com

Leaflet - a JavaScript library for interactive maps. (n.d.). Retrieved November 3, 2017, from https://leafletjs.com

Mak, T., Van Hentenryck, P., Zlotnik, A., & Bent, R. (2017). Dynamic Compressor Optimization in Natural Gas Pipeline Dynamics. *In review at INFORMS Journal on Computing*.

Mak, T., Van Hentenryck, P., Zlotnik, A., Bent, R., & Hijazi, H. (2016). Efficient Dynamic Compressor Optimization in Natural Gas Transmission Systems. *IEEE American Control Conference (pp 7484-7491)*. Boston.

Misra, S., Fisher, M.W., Backhaus, S., Bent, R., Chertkov, M., & Pan,, F. (2015). Optimal Compression in Natural Gas Networks: A Geometric Programming Approach. *IEEE Transactions on Control of Network Systems*, 2, 47-56.

Rios-Mercado, R., & Borraz-Sanchez, C. (2015). Optimization problems in natural gas transportation systems: A state-of-the-art review. *Applied Energy, 147*, 536-555.

Sempra - SoCalGas ENVOY. (n.d.). Retrieved November 3, 2017, from Sempra Energy [US]: https://scgenvoy.sempra.com

U.S. Energy Information Administration. (n.d.). Retrieved November 3, 2017, from https://www.eia.gov

Zlotnik, A., Chertkov, M., & Backhaus, S. (2015). Optimal Control of Transient Flow in Natural Gas Networks. *54th IEEE Conference on Decision and Control*. Osaka.

Zlotnik, A., Dyachenko, S., Backhaus, S., & Chertkov, M. (2015). Model Reduction and Optimization of Natural Gas Pipeline Dynamics. *ASME Dynamic Systems and Control Conference*. Columbus.

Appendix L

Acknowledgements

The steering committee and authors of the report would like to acknowledge the support and hard work of many individuals who were essential to the success of this report.

Dr. Amber Mace, CCST project director, oversaw the development and implementation of the study. Dr. Sarah Brady, CCST project manager extraordinaire, coordinated all of the experts, contracts and project details as well as the day to day activities to deliver the project on time and under budget. Puneet Bhullar, CCST project assistant, provided exceptional organizational support at every stage. Donna King, CCST accountant, oversaw the financial aspects of the contract. Other staff at CCST and LBNL were also invaluable: in particular Dr. Christine Casey, Dr. Susan Hackwood, Ben Landis, Christy Shay, Dr. Brie Lindsey, and Annie Morgan at CCST, and Sahar Iranipour, Mateja Pitako, Helen Prieto, and Cynthia Tilton at LBNL.

Staff and appointees of the California Executive Branch provided vital information and support for the project. Our contacts at the California Public Utilities Commission (CPUC) were essential to the inception and contract management of the project, particularly Eugene Cadenasso, Franz Cheng, Jamie Ormond, and Carlos Velasquez. Many diligent government employees and appointees from the California Energy Commission and the CPUC furnished essential data used in this report.

A number of organizations and individuals acted as hosts on our field trips to both Wild Goose and McDonald Island underground storage facilities: Pacific Gas and Electric Company and Rockpoint Gas Storage.

We also wish to acknowledge the oversight committee for their guidance in assembling and appointing the steering committee: Richard Flagan, John Hemminger, and Bob Sawyer. Bob Sawyer also served as the report monitor. We thank the peer reviewers who provided insightful comments on the draft report: Aaron Bernstein, Nancy Brodsky, Linda Cohen, Rosa Dominguez-Faus, James Gooding, William Hoyle, Gary Hughes, Lisa McKenzie, Michal Moore, Joseph Morris, Phillip Nidd, Franklin Orr, Snuller Price, and Kevin Woodruff.

Without the contributions of these individuals and many more, this report would not have been possible.