Long-Term Viability of Underground Natural Gas Storage in California

An Independent Review of Scientific and Technical Information

EXECUTIVE SUMMARY

A Commissioned Report prepared by the
California Council on Science and Technology

CCST
CALIFORNIA COUNCIL ON
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Executive Summary

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Long-Term Viability of Underground Natural Gas Storage in California: An Independent Review of Scientific and Technical Information, Executive Summary

About CCST

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Executive Summary

In late 2015, southern California experienced a large natural gas leak that resulted in the displacement of thousands of residents in the surrounding community. An underground storage facility at Aliso Canyon, the second-largest facility of its kind in the United States, began leaking in October, and the Governor proclaimed a state of emergency on January 6, 2016. The leak was contained in February 2016. Approximately 100,000 tonnes of methane were emitted into the atmosphere.

To address part of the Governor's state of emergency proclamation, the State of California sought more information about all of the underground natural gas storage fields in California, and the California Council on Science and Technology (CCST) was asked to provide the State with an up-to-date technical assessment. In consultation with the California Public Utilities Commission (CPUC), the State Energy Resources Conservation Commission, the State Air Resources Board, and the Division of Oil, Gas, and Geothermal Resources, the assessment includes a broad review of the potential health risks and community impacts associated with their operation, fugitive gas emissions, and the linkages between gas storage, California's current and future energy needs, and its greenhouse gas reduction goals. A scope of work was developed that includes three key questions:

- **Key Question 1:** What risks do California's underground gas storage facilities pose to health, safety, environment and infrastructure?
- **Key Question 2:** Does California need underground gas storage to provide for energy reliability through 2020?
- **Key Question 3:** How will implementation of California's climate policies change the need for underground gas storage in the future?

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Study Process

CCST organized and led the study reported on here. Members of the CCST Steering Committee were appointed based on technical expertise and a balance of technical viewpoints. (Appendix C in the Summary Report provides information about CCST's

Steering Committee membership.) All experts who contributed to the study were evaluated for potential conflicts of interest. Under the guidance of the Steering Committee, a team of experts (science team) assembled by CCST developed the findings based on original technical data analyses and a review of the relevant literature. Appendix D in the Summary Report provides information about the science team. In order for the Steering Committee to oversee the work of the science team and develop recommendations and conclusions based on the findings of the science team, it was important for the Steering Committee to interact regularly with the lead science team members. Therefore, Steering Committee lead science team members were included as *ex officio* non-voting Steering Committee members.

The science team studied each of the issues identified in the scope of work, and the science team and the Steering Committee collaborated to develop a series of findings, conclusions, and recommendations defined as follows:

- **Finding:** Facts we have found that could be documented or referenced and that have importance to our study.

- **Conclusion:** A deduction we made based on findings.

- **Recommendation:** A statement that recommends what an entity should consider doing as a result of our findings and conclusions.

The committee process ensured that conclusions were based on findings (facts), and recommendations were based on findings and conclusions. Both the science team and the Steering Committee members proposed draft conclusions and recommendations. These were modified based on peer review and discussion within the Steering Committee, along with continued consultation with the science team. Final responsibility for the conclusions and recommendations in this Executive Summary lies with the Steering Committee. All Steering Committee members have agreed with these conclusions and recommendations. Any Steering Committee member could have written a dissenting opinion, but no one requested to do so. The conclusions and recommendations expressed in this publication are those of the Steering Committee, and do not necessarily reflect the view of the organizations or agencies that provided support for this project.

The full report, including the summary report, has undergone extensive peer review; peer reviewers are listed in Appendix H of the Summary Report, “Expert Oversight and Review.” Fourteen Reviewers were chosen for their relevant technical expertise. More than 1,150 anonymous review comments were provided to the science team and Steering Committee (study team). The study team revised the report in response to peer review comments. A report monitor, appointed by CCST, then reviewed the response to the review comments and when satisfied, approved the report.

Overview

The underground natural gas storage system in California today provides essential energy reliability services. California's underground gas storage (UGS) facilities send gas to customers when the State's gas pipelines cannot import gas fast enough to meet consumer demand. These facilities store gas during periods of low demand and make fuel available during periods of high demand, for example for heating on cold winter days or generating electricity for air conditioning on hot summer days. The current configuration of the energy system in California requires essentially all of the State's available underground gas storage capacity, and this complex system works very well from an energy reliability perspective. Currently, underground gas storage facilities regularly obviate the need for California to curtail natural gas delivery during multiday cold winter conditions, provide for storage of natural gas in the summer to meet the total winter season demand, allow for smooth daily operations of electric generators despite intermittent contributions from solar and wind sources, and provide price arbitrage opportunities that can save money for California's consumers.

Although the need for underground gas storage might be reduced in the coming decades in a variety of ways, we found no immediate practical measures that would overcome California's demand for natural gas during peak periods in the winter—a demand that currently exceeds the State's pipeline capacity to import gas. In a post-2020 timeframe, these facilities could be completely replaced with either more pipelines or gas peak-shaving (surface gas storage) units, but not without significant expense (approximately $10-15B capital expenditure), and importantly, not without taking on a new set of incremental risks associated with additional pipelines and associated gas compression systems. To provide some context for this, we note that overall expenditures in California for natural gas are about $10B/year.

In late 2015, the major well blowout at the Aliso Canyon underground gas storage facility illustrated the risks posed by loss-of-containment at underground gas storage facilities (underground gas storage). The Aliso Canyon leak was contained in February 2016, after approximately 100,000 tonnes of methane as well as unknown quantities of other pollutants had leaked into the atmosphere. This loss-of-containment incident caused considerable risks to worker safety and public health.

In the aftermath of the Aliso Canyon well blowout, California moved ahead to develop emergency regulations for all existing underground gas storage facilities in the State. New permanent regulations developed by California's Division of Oil, Gas and Geothermal Resources (DOGGR) will supersede these emergency regulations in January 2018. While many recommendations for further improvement of these regulations are made in this Executive Summary and in Chapter 1 of the report, the emergency regulations now in place and the final ones under development represent a major step forward to reduce the risks to health, safety, environment, and energy infrastructure of underground gas storage facilities, provided these new rules are consistently and thoroughly applied and enforced across all storage facilities. In the future, the effectiveness of the new regulations should be evaluated on a regular basis by an independent peer review or audit program.

Because of the flammability of natural gas and its storage and transport at high pressure, each of the twelve underground gas storage facilities in California presents some non-zero amount of risk to health, safety, the environment, and the underground gas storage infrastructure itself. We have compared the hazards and vulnerabilities of individual facilities based on a set of qualitative risk-related characteristics (Table ES.1-1). For example, facilities that have older repurposed wells (often in former oil reservoirs), have a higher number of reported loss-of-containment incidents, are located in seismic or other natural disaster hazard zones, or are located near large population centers pose relatively greater risks. The Playa del Rey facility, which has a long history of loss-of-containment incidents and is located near a large population center in a very high wildfire hazard zone, stands out as a facility with relatively higher risk to health and safety than the other facilities in California. Aliso Canyon, Honor Rancho, and La Goleta also present higher health and safety risks than other facilities because of their locations near large numbers of people.

The new regulations for underground gas storage require each facility to develop and implement risk management plans comprising two major elements: risk assessment studies as well as intervention and prevention protocols. This requirement allows regulators to thoroughly evaluate how underground gas storage facilities identify and quantify risks and how these insights are translated into appropriate risk management practices. Each facility needs to conduct a robust *quantitative* risk assessment, which should include the key human, organizational, and technological subsystems, and that each facility should start immediately to develop risk targets that will ultimately guide risk-mitigation decision-making. Quantitative risk assessments will also provide further insight into quantitative risk differences between facilities. The State will be able to use this quantitative risk-related information on each facility to assess the tradeoffs between risks associated with individual facilities and their importance in meeting the demands of the natural gas supply.

Some sites may pose risks that are difficult to mitigate and large enough to warrant closing the facility. However, in many cases implementing better practices can mitigate the largest risks. For example, in facilities like Aliso Canyon, withdrawal of gas occurred in the past both through a production tube in the well and in the annulus outside of this tubing. This means that a single point of structural failure in the well could lead to a loss-of-containment, as in fact appears to have caused the 2015 Aliso Canyon incident. The new DOGGR well regulations significantly decrease the likelihood of well failure and loss of containment because they require at least two barriers between high-pressure fluids in the well and the surrounding environment. This means that at least two structural elements of the well (either the tubing and the casing or the packer and the casing) would have to fail simultaneously to cause a loss-of-containment rather than just one. If the SS-25 well at Aliso Canyon had been operated with two barriers for containment rather than one, a corrosion hole in the casing would not have caused a major blowout because the packer and the tubing would still contain the high-pressure gas. DOGGR estimates the cost of implementing these new regulations will be about $250M/year.

We emphasize that the State needs to weigh the risks associated with underground gas storage against the benefits, and that the State needs to compare potential alternatives to underground gas storage in a similar risk-benefit framework. The State should evaluate the risks posed and specific benefits provided by each *individual* gas storage facility. If risks cannot be mitigated to an acceptable level, then the State could evaluate other options to retain reliability of gas supply. Options could include building compensating infrastructure (for example, by adding peak-shaving units) or determining through detailed time-of-use assessment and hydraulic modeling of pipeline gas flows whether it is possible to do without the specific facility or use it less. (A preliminary example model of this type was produced for this report and described in Appendix J of the Summary Report.)

In the near term, 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 gas demand.

Looking to the future, California may be able to reduce the need for natural gas, but cannot count on the implementation of its climate policies to fully eliminate the need for gas storage. California plans to increase its renewable energy portfolio to half of all power generation by 2030, while cutting greenhouse gas (GHG) emission by 40% and, per executive order, is also required to reduce emissions to 80% below 1990 levels by 2050. These significant changes raise as yet unanswered questions about how energy system integration and reliability will be accomplished, and what role natural gas, or other gases requiring storage, will play in that endeavor.

By 2030, California will likely use less natural gas overall than today as renewable energy displaces gas-fired electricity generation. However, if that renewable energy supply has similar characteristics to today's portfolio (domestic onshore wind and solar photovoltaic), then the availability of renewable energy will dip significantly in the winter because of reduced solar insolation and slower wind speeds, exactly when the peak need for gas heating occurs, and at other times when the sun is not shining and the wind is not blowing (conditions known as *dunkleflaute* from the German for "dark doldrums"). These conditions could create a need for gas-fired electricity to back up the intermittent renewable energy during cold winter weather, exactly. Thus, absent yet-to-be-identified or deployed seasonal energy storage technologies, electricity reliability will likely require some sort of gas generation and storage function.

The 2050 goals create even more uncertainty about the use of gas. Again, if the renewable energy portfolio looks much as it does today, estimates indicate that California may require nearly as much gas-fired as renewable electricity generation capacity just to ensure electricity reliability. Scenarios that might significantly reduce the need for gas storage would make use of a broader set of energy resources and strategies, such as geothermal, wave-power, imported renewables, a regionalized electricity system, energy storage, renewables curtailment, price responsive demand, or nuclear power. Such resources could provide firm low-greenhouse gas (GHG) electricity, reduce the need for load balancing, and consequently reduce the need for natural gas.

Alternatively, California could meet 2050 goals in ways that increase the need for underground gas storage. For example, gas-fired power plants with carbon capture and storage (CCS)—whereby the carbon dioxide (CO_2) from combustion would be captured and stored underground—may be a cost-effective alternative for meeting emission goals while also meeting energy demand. The CCS approach would likely increase the need for natural gas storage as well as require underground storage of CO_2. Approaches that replace the use of natural gas with lower-GHG alternatives, such as biomethane or hydrogen, would also not reduce the need for underground storage to manage these gases.

The current natural gas system works to provide reliable energy for California. However, changes planned to achieve the State's climate goals and actions taken to address problems revealed by the 2015 Aliso Canyon incident have the potential to disrupt this system.
The State needs to closely examine the future of California's energy system as a whole (including tradeoffs among electricity, heat, and transportation demands). California policy makers should develop future scenarios that include detailed information about the time of use of both electricity and natural gas. Scenarios should assess the impact of increasing electrification in all sectors and the possible role for gas with CCS in supplying that electricity generation, incorporate explicit analysis of gas flows, determine the impact of electric regionalization and more dispatchable or firm forms of electricity, and do this on timescales that range from seconds to years. Such analysis would put planning for energy reliability in general, and specifically gas storage, on a much firmer footing.

In summary:

Conclusion ES-1: The risks associated with underground gas storage can be managed and, with appropriate regulation and safety management, may become comparable to risks found acceptable in other parts of the California energy system.

Recommendation ES-1: The State should ensure timely and thorough implementation of the new DOGGR regulations at each underground gas storage facility, emphasizing risk and safety management plans, quantitative risk assessment studies, risk mitigation and prevention, requirements for well integrity testing and monitoring, human and organizational factors, and a robust and healthy safety culture. To evaluate the effectiveness of the new regulations and the rigor of their application in practice, the State should implement an independent and mandatory review program for the new regulations, should publish the review results in publicly available reports, and should provide an opportunity for public comment.

Conclusion ES-2: California's energy system currently needs natural gas and underground gas storage to run reliably. Replacing underground gas storage in the next few decades would require very large investments to store or supply natural gas another way, and such new natural-gas-related infrastructure would bring its own risks. The financial investment would implicitly obligate the State to the use of natural gas for several decades.

Recommendation ES-2: In making decisions about the future of underground natural gas storage, the State should evaluate tradeoffs between the quantified risks of each facility, the cost of mitigating these risks, and the benefits derived from each gas storage facility- as well as the risks, costs, and benefits associated with alternatives to gas storage at that facility.

Conclusion ES-3: Some possible future energy systems that respond to California's climate policies might require underground gas storage—including natural gas, hydrogen, or carbon dioxide—and some potentially would not. California's current energy planning does not include adequate feasibility assessments of the possible future energy system configurations that both meet greenhouse gas emission constraints and achieve reliability criteria on all timescales, from subhourly to peak daily demand to seasonal supply variation.

Recommendation ES-3: The State should develop a more complete and integrated plan for the future of California's energy system, paying attention to reliability on all timescales in order to understand how the role of natural gas might evolve and what kind of gases (e.g., natural gas or other forms of methane, hydrogen, or carbon dioxide) may need to be stored in underground storage facilities in the future.

Please see the Summary Report for discussion of many additional findings, conclusions, and recommendtions.

Table ES-1.1. Selected comparative risk-related characteristics for California underground gas storage facilities (layout of this table is for size 11"x 17" paper). Darker shades generally correspond to larger values or larger expected hazard, while lighter shades correspond to less expected hazard from that attribute.

		Independents					Pacific Gas and Electric			Southern California Gas			
	Facility[1]	**Gill Ranch Gas**	**Kirby Hill Gas**	**Lodi Gas**	**Princeton Gas**	**Wild Goose Gas**	**Los Medanos Gas**	**McDonald Island Gas**	**Pleasant Creek Gas**	**Aliso Canyon**	**Honor Rancho**	**La Goleta Gas**	**Playa del Rey**
UGS facility characteristics	2015 Capacity (Bcf)	20.0	15.0	17.0	11.0	75.0	17.9	82.0	2.3	86.2	27.0	19.7	2.4
	Average depth (range) of storage reservoir(s) (ft)	5,850 - 6,216	1,550 - 5,400	2,280 - 2,515	2,170	2,400 - 2,900	4,000	5,220	2,800	9,000	10,000	3,950	6,200
	Average annual gas transfer per well per from 2006 to 2015 (million scf)	150	69	511	78	866	255	75	22	197	244	232	13
	Number of open[2] wells connected to storage reservoir in 2015	12	18	26	13	17	21	88	7	115	41	18	54
	Median age of open[2] wells as of 2015 (yrs)	5	7	13	4	7	36	41	41	42	39	63	79
Failure modes, likelihoods, and hazards	Maximum deep-seated landslide susceptibility	0	VII	0	0	0	VI	0	VII	X	X	X	X
	Last fault rupture through or (*) within 500 m of flow line(s) (yrs ago)	None	<130,000	None	None	None	<130,000*	None	None	<15,000*	<15,000*	<130,000*	None
	Hazard of Quaternary fault shearing of well(s) present	No	Yes	No	No	No	Maybe	No	No	Yes	Unlikely	Unlikely	No
	Max. 2% probability of exceeding 0.2-sec spectral acceleration in 50 years (g)	1.45	1.55	1.25	0.95	0.65	2.15	1.25	1.85	2.75	2.45	2.65	1.65
	Earthquake-induced landslide hazard zone	No	?	No	No	No	?	No	No	Yes	Yes	?	Yes
	Tsunami hazard	No	No	No	No	No	No	No	No	No	No	Yes	?
	Flooding hazard	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	No
	Fire hazard severity zones - predominant (maximum, if different)	Not zoned (moderate)	Moderate	Not zoned (moderate)	Not zoned (moderate)	Not zoned (moderate)	Moderate	Not zoned (moderate)	Moderate	Very high	Very high	Not zoned	Very high
	Number of reported distinct LOC incidents in Evans (2008) and in Folga et al. (2016)	0	0	0	0	1	1	2	1	3	1	0	3
Health and safety	Proximity of handling plant (center) to well field (km)	0.0	0.7	6.5	0.9	8.0	0.3	0.0	0.4	0.2	0.0	0.5	0.0
	Population in proximity to UGS	909	401	23,771	848	195	223,069	6,473	8,821	325,330	180,359	101,371	691,757
	Median (max) formaldehyde emissions from 1996 - 2015, predominantly from compressors (lbs/yr)	4 (5)	108 (205)	1,291 (1,291)	not reported	not reported	4,968 (7,204)	11,163 (11,163)	not reported	15,001 (20,640)	18,675 (27,296)	2,197 (3,456)	3,038 (5,772)
GHG emissions	Average observed methane emission rate (kg CH4/hr)	88	37	0	43	35	11	150	16	200[3]	740	36	0
	Extrapolated annual emissions/average annual gas injection (%)	0.8	0.4	0.0	0.4	0.1	0.1	0.2	0.4	0.2[3]	1.2	0.1	0.0

[1] Storage in facilities whose name includes "Gas" is in depleted gas reservoirs; otherwise storage is in depleted oil reservoirs

[2] "open" includes wells with DOGGR status "Active" and "Idle", which are unplugged and have a wellhead

[3] Aliso emissions measured following repair of the 2015 blowout

Concluding Remarks

The California Legislature mandated this study in mid-2016, and CCST conducted the study in a eleven-month period ending December 2017. Effectively, the research was conducted over a very short period of about seven months. CCST could not fully investigate many issues raised by the study because of time constraints. In addition, the study predates the availability of some pertinent information, specifically the results of the root-cause analysis of the 2015 Aliso Canyon incident. Because of the need to publish the report by December 2017, several topics will likely require further exploration.

CCST could not investigate the feasibility and impacts on reliability of closing one or more underground gas storage sites in the State while leaving the others open. For example, the Playa del Rey facility apparently does not store or withdraw a large amount of gas, providing only about 1% of total natural gas storage across California. However, Playa del Rey is close to a densely populated area, and the risk of loss-of-containment at Playa del Rey is higher than most other natural gas storage facilities. Our report questions, but does not answer, the impact of closing this site. The State should commission a cost-benefit analysis including full consideration of risks associated with loss-of-containment from this facility.

We also recommend a detailed research study of how California’s natural gas system functioned during the several-month shutdown of Aliso Canyon. Researchers should document where the natural gas came from (e.g., other storage facilities, pipelines, etc.) that otherwise would have been supplied by Aliso Canyon, and what the weather conditions were during this interval that impacted demand in both cold and hot weather, and supply from renewable sources. The conditions over the last two years should be compared to historical conditions and the specific conditions required for reliability planning. Such a study would provide important insight about the utility of Aliso Canyon and data for stakeholders about whether Aliso Canyon should remain open.

The State deserves an assessment of these storage facilities based on the best available data and should strive to improve data transparency and availability for follow-on studies. The Steering Committee and investigators made several requests for data in the course of this assessment. The report findings reflect data we were able to obtain. In a number of cases we requested data and did not receive them. For example, daily injection and withdrawal data would help to assess hazards related to loss of well integrity, but DOGGR has these data available only on a monthly basis. The team also requested facility-specific data on withdrawn gas composition, or in the case of the 2015 Aliso Canyon incident, the composition of the gas escaping from the (SS-25) well blowout. An assessment of human health hazards for populations exposed to gas emitted from underground gas storage facilities requires knowing the composition of the gas (including specific trace chemicals: benzene, hydrogen sulfide and others listed in Appendix 1.E of Chapter 1), but the team could not obtain this detailed information. Apparently, operators do not collect these data as discussed in Appendix 1.E. of Chapter 1.

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Acronyms and Abbreviations

API	American Petroleum Institute
bcf	billion cubic feet
Bcfd	billion cubic feet per day
Btu	British thermal unit
CAISO	California Independent System Operator
CalOSHA	California Occupational Safety and Health Administration
CARB	California Air Resources Board
CASRN	Chemical Abstract Service Registry Numbers
CCS	carbon capture and sequestration
CCST	California Council on Science and Technology
CEC	California Energy Commission
CERS	California Environmental Reporting System
CNG	compressed natural gas
CO2	carbon dioxide
CPUC	California Public Utilities Commission
DOGGR	Division of Oil, Gas and Geothermal Resources
DR	demand response
EE	energy efficiency
EG	electric generation
EIA	Energy Information Administration
GHG	greenhouse gas
GW	gigawatt
IFR	interim final rule
kg	kilogram
kwh	kilowatt hour
LNG	liquefied natural gas
LOC	loss of containment
MMBtu	million British thermal units
MMcfd	million cubic feet per day
MW	megawatt
MWh	megawatt hours
O&M	operating and maintenance
OSHA	Occupational Safety and Health Administration
PG&E	Pacific Gas and Electric Company
PHMSA	Pipeline and Hazardous Materials Safety Administration (USDOT)
psi	pounds per square inch
PV	photovoltaic
QRA	quantitative risk assessment
RETI 2.0	Renewable Energy Transmission Initiative 2.0
RMP	risk management plan
SDG&E	San Diego Gas and Electric

Introduction

In late 2015, southern California experienced a large natural gas leak that resulted in the displacement of thousands of residents in the surrounding community. An underground storage facility at Aliso Canyon, the second-largest facility of its kind in the United States, began leaking in October, and the Governor proclaimed a state of emergency on January 6, 2016. The leak was contained in February 2016. Approximately 100,000 tonnes of methane were emitted into the atmosphere.

To address part of the Governor's state of emergency proclamation, the State of California sought more information about all of the underground natural gas storage fields in California, and the California Council on Science and Technology (CCST) was asked to provide the State with an up-to-date technical assessment. In consultation with the California Public Utilities Commission (CPUC), the State Energy Resources Conservation Commission, the State Air Resources Board, and the Division of Oil, Gas, and Geothermal Resources, the assessment includes a broad review of the potential health risks and community impacts associated with their operation, fugitive gas emissions, and the linkages between gas storage, California's current and future energy needs, and its greenhouse gas reduction goals. A scope of work was developed that includes three key questions:

- **Key Question 1:** What risks do California's underground gas storage facilities pose to health, safety, environment and infrastructure?
- **Key Question 2:** Does California need underground gas storage to provide for energy reliability through 2020?
- **Key Question 3:** How will implementation of California's climate policies change the need for underground gas storage in the future?

ABOUT CCST

CCST is a nonpartisan, nonprofit organization established via the California State Legislature in 1988 to provide objective advice from California's best scientists and research institutions on policy issues involving science. CCST responds to the Governor, the Legislature, and other State entities who request independent assessment of public policy issues affecting the State of California related to science and technology.

STUDY PROCESS

CCST organized and led the study reported on here. Members of the CCST Steering Committee were appointed based on technical expertise and a balance of technical viewpoints. (Appendix C in the Summary Report provides information about CCST's

Steering Committee membership.) All experts who contribute to the study were evaluated for potential conflicts of interest. Under the guidance of the Steering Committee, a team of experts (science team) assembled by CCST developed the findings based on original technical data analyses and a review of the relevant literature. Appendix D of the Summary Report provides information about the science team. Each key question had a lead team member who was also an *ex officio* Steering Committee member. In order for the Steering Committee to oversee the work of the science team and develop recommendations and conclusions based on the findings of the science team, it was important for the Steering Committee to interact regularly with the lead science team members. Therefore, in order for the Steering Committee to receive regular updates on the progress and direction of the study, lead science team members were included as *ex-officio* non-voting *Steering Committee members*.

The science team studied each of the issues identified in the scope of work, and the science team and the Steering Committee collaborated to develop a series of findings, conclusions, and recommendations defined as follows:

- **Finding:** Facts we have found that could be documented or referenced and that have importance to our study.

- **Conclusion:** A deduction we made based on findings.

- **Recommendation:** A statement that recommends what an entity should consider doing as a result of our findings and conclusions.

The committee process ensured that conclusions were based on findings (facts), and recommendations were based on findings and conclusions. Both the science team and the Steering Committee members proposed draft conclusions and recommendations. These were modified based on peer review and discussion within the Steering Committee, along with continued consultation with the science team. Final responsibility for the conclusions and recommendations in this Executive Summary lies with the Steering Committee. All Steering Committee members have agreed with these conclusions and recommendations. Any Steering Committee member could have written a dissenting opinion, but no one requested to do so. The conclusions and recommendations expressed in this publication are those of the Steering Committee, and do not necessarily reflect the view of the organizations or agencies that provided support for this project.

This report has undergone extensive peer review; peer reviewers are listed in Appendix E of the Summary Report, “Expert Oversight and Review”. Fourteen reviewers were chosen for their relevant technical expertise. More than 1,000 anonymous review comments were provided to the science team and Steering Committee (study team). The study team revised the report in response to peer review comments. In cases where the authors disagreed with the reviewer, the response to review included their reasons for disagreement. A report monitor, appointed by CCST, reviewed the responses to comments to ensure an adequate response and when satisfied, approved the report.

Numbering the conclusions and recommendations for easy reference proved challenging in this Executive Summary and the underlying report chapters because the materials differ significantly among the three key questions. Each conclusion and recommendation has a unique number, but the numbering protocol is slightly different in different parts of the report.

In Chapter 1, individual recommendations are typically aligned directly with an associated conclusion, though there are a few conclusions that stand alone without a recommendation. In order to make it clear which conclusions go with which recommendations in Chapter 1, the recommendation has been given the same number as the prior conclusion. This means that the numbering of recommendations in Chapter 1 is not sequential because not every conclusion results in a recommendation. In Chapters 2 and 3, a large number of findings and conclusions support a very small number of recommendations. For these chapters, the conclusions are numbered sequentially and the recommendations are independently numbered sequentially.

DATA AND LITERATURE USED IN THE REPORT

The science team reviewed and analyzed existing data from both voluntary and mandatory reporting sources relevant to underground gas storage, peer-reviewed scientific literature, as well as non-peer reviewed reports and documents if they were topically relevant and determined to be scientifically credible by the authors and reviewers of this volume. The science team did not collect any new data solely for this report, but did do original analysis of available data from a variety of sources. Significant gaps and inconsistencies exist in available voluntary and mandatory data sources, both in terms of duration and completeness of reporting. Gaps and data quality issues in the reporting limited this analysis and may warrant adoption of additional quality assurance, reporting, and data handling requirements. When appropriate, proprietary data were requested by CCST from the CPUC and from utilities. Not all requests were honored. Despite the data limitations, information gathered from multiple independent sources gives largely consistent results, and the authors think the report findings are generally accurate and representative of underground gas storage in California. Additional data in the future might change some of the quantitative findings about underground gas storage in the report, but, absent some major external influence, it is unlikely these will fundamentally alter the report findings.

SITE VISITS

The study team made two site visits during the course of the study to better understand the layout and operations of UGS facilities. On June 14, 2017, the team visited the McDonald Island UGS facility owned by PG&E (Pacific Gas & Electric, Co.). The visit included a tour of the compressor station, storage wells, and the infrastructure to control the pressure and distribution of the gas. After the tour, a team of PG&E operators answered many questions ranging from safety procedures to emissions testing.

Additionally, on June 22, 2017, the study team visited the Wild Goose UGS facility owned by independent operator, Rockpoint Gas Storage, based out of Canada. Rockpoint Gas Storage also owns and operates Lodi UGS facility and Kirby Hills UGS facility. The visit began with a detailed overview of the company and site safety practices which included both operations requirements and safety and personal protective equipment (PPE) requirements. The study team was then presented with information about the reporting practices, prevention measure strategies, and operational systems at the Wild Goose facility. The visit ended with a tour of the compressor station and storage wells.

Overview

The underground natural gas storage system in California today provides essential energy reliability services. California's underground gas storage (UGS) facilities send gas to customers when the State's gas pipelines cannot import gas fast enough to meet consumer demand. These facilities store gas during periods of low demand and make fuel available during periods of high demand, for example for heating on cold winter days or generating electricity for air conditioning on hot summer days. The current configuration of the energy system in California requires essentially all of the State's available underground gas storage capacity, and this complex system works very well from an energy reliability perspective. Currently, underground gas storage facilities regularly obviate the need for California to curtail natural gas delivery during multiday cold winter conditions, provide for storage of natural gas in the summer to meet the total winter season demand, allow for smooth daily operations of electric generators despite intermittent contributions from solar and wind sources, and provide price arbitrage opportunities that can save money for California's consumers.

Although the need for underground gas storage might be reduced in the coming decades in a variety of ways, we found no immediate practical measures that would overcome California's demand for natural gas during peak periods in the winter—a demand that currently exceeds the State's pipeline capacity to import gas. In a post-2020 timeframe, these facilities could be completely replaced with either more pipelines or gas peak-shaving (surface gas storage) units, but not without significant expense (approximately $10-15B capital expenditure), and importantly, not without taking on a new set of incremental risks associated with additional pipelines and associated gas compression systems. To provide some context for this, we note that overall expenditures in California for storage and delivery of natural gas are about $10B/year.

In late 2015, the major well blowout at the Aliso Canyon underground gas storage facility illustrated the risks posed by loss-of-containment at underground gas storage facilities. The Aliso Canyon leak was contained in February 2016, after approximately 100,000 tonnes of methane as well as unknown quantities of other pollutants had leaked into the atmosphere. This loss-of-containment incident caused considerable risks to worker safety and public health.

In the aftermath of the Aliso Canyon well blowout, California moved ahead to develop emergency regulations for all existing underground gas storage facilities in the State. New permanent regulations developed by California's Division of Oil, Gas and Geothermal Resources (DOGGR) will supersede these emergency regulations in January 2018. While many recommendations for further improvement of these regulations are made in this Executive Summary and in Chapter 1 of the report, the emergency regulations now in place and the final ones under development represent a major step forward to reduce the risks to health, safety, environment, and energy infrastructure of underground gas storage facilities, provided these new rules are consistently and thoroughly applied and enforced across all storage facilities. In the future, the effectiveness of the new regulations should be evaluated on a regular basis by an independent peer review or audit program.

Because of the flammability of natural gas and its storage and transport at high pressure, each of the twelve underground gas storage facilities in California presents some non-zero amount of risk to health, safety, the environment, and the underground gas storage infrastructure itself. We have compared the hazards and vulnerabilities of individual facilities based on a set of qualitative risk-related characteristics. For example, facilities that have older repurposed wells (often in former oil reservoirs) have a higher number of reported loss-of-containment incidents, are located in seismic or other natural disaster hazard zones, or are located near large population centers pose relatively greater risks. The Playa del Rey facility, which has a long history of loss-of-containment incidents and is located near a large population center in a very high wildfire hazard zone, stands out as a facility with relatively higher risk to health and safety than the other facilities in California. Aliso Canyon, Honor Rancho, and La Goleta also present higher health and safety risks than other facilities because of their locations near large numbers of people.

The new regulations for underground gas storage require each facility to develop and implement risk management plans comprising of two major elements: risk assessment studies as well as intervention and prevention protocols. This requirement allows regulators to thoroughly evaluate how underground gas storage facilities identify and quantify risks and how these insights are translated into appropriate risk management practices. Each facility needs to conduct a robust *quantitative* risk assessment, which should include the key human, organizational, and technological subsystems, and that each facility should start immediately to develop risk targets that will ultimately guide risk-mitigation decision-making. Quantitative risk assessments will also provide further insight into quantitative risk differences between facilities. The State will be able to use this quantitative risk-related information on each facility to assess the tradeoffs between risks associated with individual facilities and their importance in meeting the demands of the natural gas supply.

Some sites may pose risks that are difficult to mitigate and large enough to warrant closing the facility. However, in many cases implementing better practices can mitigate the largest risks. For example, in facilities like Aliso Canyon, withdrawal of gas occurred in the past both through a production tube in the well and in the annulus outside of this tubing. This means that a single point of structural failure in the well could lead to a loss-of-containment, as in fact appears to have caused the 2015 Aliso Canyon incident. The new DOGGR well regulations significantly decrease the likelihood of well failure and loss of containment because they require at least two barriers between high-pressure fluids in the well and the surrounding environment. This means that at least two structural elements of the well (either the tubing and the casing or the packer and the casing) would have to fail simultaneously to cause a loss-of-containment rather than just one. If the SS-25 well at Aliso Canyon had been operated with two barriers for containment rather than one, a corrosion hole in the casing would not have caused a major blowout because the packer and the tubing would still contain the high-pressure gas. DOGGR estimates the cost of implementing these new regulations will be about $250M/year.

We emphasize that the State needs to weigh the risks associated with underground gas storage against the benefits, and that the State needs to compare potential alternatives to underground gas storage in a similar risk-benefit framework. The State should evaluate the risks posed and specific benefits provided by each *individual* gas storage facility. If risks cannot be mitigated to an acceptable level, then the State could evaluate other options to retain reliability of gas supply. Options could include building compensating infrastructure (for example, by adding peak-shaving units) or determining through detailed time-of-use assessment and hydraulic modeling of pipeline gas flows whether it is possible to do without the specific facility or use it less. (A preliminary example model of this type was produced for this report and described in Appendix K of the Technical Report.)

In the near term, no method of conserving or supplying — 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 gas demand.

Looking to the future, California may be able to reduce the need for natural gas, but cannot count on the implementation of its climate policies to fully eliminate the need for gas storage. California plans to increase its renewable energy portfolio to half of all power generation by 2030, while cutting greenhouse gas (GHG) emission by 40% and, per executive order, is also required to reduce emissions to 80% below 1990 levels by 2050. These significant changes raise as yet unanswered questions about how energy system integration and reliability will be accomplished, and what role natural gas, or other gases requiring storage, will play in that endeavor.

By 2030, California will likely use less natural gas overall than today as renewable energy displaces gas-fired electricity generation. However, if that renewable energy supply has similar characteristics to today's portfolio (domestic onshore wind and solar photovoltaic), then the availability of renewable energy will dip significantly in the winter because of reduced solar insolation and slower wind speeds, exactly when the peak need for gas heating occurs, and at other times when the sun is not shining and the wind is not blowing (conditions known as *dunkleflaute* from the German for "dark doldrums"). These conditions could create a need for gas-fired electricity to back up the intermittent renewable energy during cold winter weather. Thus, absent yet-to-be-identified or deployed seasonal energy storage technologies, electricity reliability will likely require some sort of gas generation and storage function.

The 2050 goals create even more uncertainty about the use of gas. Again, if the renewable energy portfolio looks much as it does today, estimates indicate that California may require nearly as much gas-fired as renewable electricity generation capacity just to ensure electricity reliability. Scenarios that might significantly reduce the need for gas storage would make use of a broader set of energy resources and strategies, such as geothermal, wave-power, imported renewables, a regionalized electricity system, energy storage, renewables curtailment, price responsive demand, or nuclear power. Such resources could provide firm low-greenhouse gas (GHG) electricity, reduce the need for load balancing, and consequently reduce the need for natural gas.

Alternatively, California could meet 2050 goals in ways that increase the need for underground gas storage. For example, gas-fired power plants with carbon capture and storage (CCS)—whereby the carbon dioxide (CO_2) from combustion would be captured and stored underground—may be a cost-effective alternative for meeting emission goals while also meeting energy demand. The CCS approach would likely increase the need for natural gas storage as well as require underground storage of CO_2. Approaches that replace the use of natural gas with lower-GHG alternatives, such as biomethane or hydrogen, would also not reduce the need for underground storage to manage these gases.

The current natural gas system works to provide reliable energy for California. However, changes planned to achieve the State's climate goals and actions taken to address problems revealed by the 2015 Aliso Canyon incident have the potential to disrupt this system. The State needs to closely examine the future of California's energy system as a whole (including tradeoffs among electricity, heat, and transportation demands). California policy makers should develop future scenarios that include detailed information about the time of use of both electricity and natural gas. Scenarios should assess the impact of increasing electrification in all sectors and the possible role for gas with CCS in supplying that electricity generation, incorporate explicit analysis of gas flows, determine the impact of electric regionalization and more dispatchable or firm forms of electricity, and do this on timescales that range from seconds to years. Such analysis would put planning for energy reliability in general, and specifically gas storage, on a much firmer footing.

In summary:

> **Conclusion SR-1:** The risks associated with underground gas storage can be managed and, with appropriate regulation and safety management, may become comparable to risks found acceptable in other parts of the California energy system.
>
> **Recommendation SR-1:** The State should ensure timely and thorough implementation of the new DOGGR regulations at each underground gas storage facility, emphasizing risk and safety management plans, quantitative risk assessment studies, risk mitigation and prevention, requirements for well integrity testing and monitoring, human and organizational factors, and a robust and healthy safety culture. To evaluate the effectiveness of the new regulations and the

rigor of their application in practice, the State should implement an independent and mandatory review program for the new regulations, should publish the review results in publicly available reports, and should provide an opportunity for public comment.

Conclusion SR-2: California's energy system currently needs natural gas and underground gas storage to run reliably. Replacing underground gas storage in the next few decades would require very large investments to store or supply natural gas another way, and such new natural-gas-related infrastructure would bring its own risks. The financial investment would implicitly obligate the State to the use of natural gas for several decades.

Recommendation SR-2: In making decisions about the future of underground natural gas storage, the State should evaluate tradeoffs between the quantified risks of each facility, the cost of mitigating these risks, and the benefits derived from each gas storage facility- as well as the risks, costs, and benefits associated with alternatives to gas storage at that facility.

Conclusion SR-3: Some possible future energy systems that respond to California's climate policies might require underground gas storage—including natural gas, hydrogen, or carbon dioxide—and some potentially would not. California's current energy planning does not include adequate feasibility assessments of the possible future energy system configurations that *both* meet greenhouse gas emission constraints *and* achieve reliability criteria on all timescales, from subhourly to peak daily demand to seasonal supply variation.

Recommendation SR-3: The State should develop a more complete and integrated plan for the future of California's energy system, paying attention to reliability on all timescales in order to understand how the role of natural gas might evolve and what kind of gases (e.g., natural gas or other forms of methane, hydrogen, or carbon dioxide) may need to be stored in underground storage facilities in the future.

KEY QUESTION 1

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

BACKGROUND

The California underground gas storage system in 2016 comprised of thirteen (now twelve) underground gas storage facilities—five (now four) in southern California, seven in northern California, and one in central California—with a working capacity to store just under 400 billion standard cubic feet (Bcf) of natural gas (Figure SR-1.1). The total amount of natural gas (predominantly methane, CH_4) present in the underground gas storage reservoirs is significantly higher than 400 Bcf, because much of the gas in the reservoirs is cushion gas, which provides the driving force for gas withdrawal. The California underground gas storage reservoirs are on average five thousand feet deep and are accessed by wells. At the depth of the reservoirs, natural gas is under high pressure (e.g., >1000 psi (pounds per square inch) or ~ 7 MPa). The handling and containment of high-pressure natural gas, which is highly flammable and contains potentially toxic compounds, creates potential risk to workers, the public, the environment, and the underground gas storage infrastructure itself.

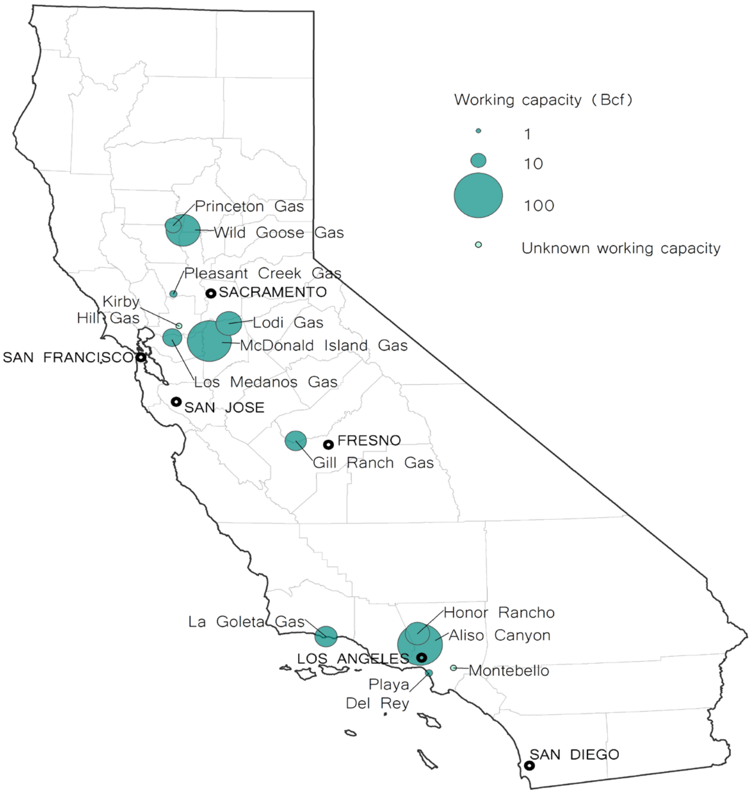

Figure SR-1.1. Underground gas storage facilities with active gas storage in California as of 2016. Gas injection via storage wells ceased in the Montebello facility at the end of 2016.

To address Key Question 1, we provide a review of the state of underground gas storage in California in the context of the risks entailed by the practice of underground gas storage, and how those risks can be managed and mitigated. Potential consequences arising from underground gas storage failures, such as large-scale loss-of-containment by well blowouts, include threats to safety and loss of life, in addition to potential environmental impacts and impacts to the underground gas storage infrastructure itself. Lower flow-rate loss-of-containment through surface infrastructure such as leaky valves may also be a concern for its effects on climate, because methane is a powerful greenhouse gas, and subsurface leakage of reservoir gases and associated components is a concern for contamination of groundwater. In addition, failure of underground gas storage can lead to the inability to provide gas to the energy network, a hazard to the stability and reliability of California's energy infrastructure.

Each underground gas storage facility in California is a combination of surface and subsurface systems (as shown by the schematic in Figure SR-1.2) designed to compress, inject, contain, withdraw, and process natural gas through wells that access the deep pore space of the storage reservoir. At the surface, underground gas storage facilities utilize a pipeline (referred to as the interconnect) to deliver and receive natural gas to and from the transmission pipeline. The interconnect delivers gas to and receives gas from compressors and gas-processing facilities, respectively. These facilities are connected to the wells through flowlines, which are typically relatively small-diameter pipelines. Although transmission pipelines are referred to as high-pressure pipelines, gas for storage normally must be compressed further in order to be injected through the wells into the storage reservoir. Upon withdrawal, gas is normally expanded to lower its pressure, and must be processed (e.g., dehydrated and stripped of chemical impurities) before delivery back to the transmission pipeline. Some processed natural gas may be utilized on-site for powering system components such as turbine compressors.

The subsurface part of underground gas storage comprises the reservoir for storage, the associated deep aquifers that may be present to provide pressure support, the caprock for keeping buoyant gas from flowing upward, the overburden that contributes to additional storage security, and the wells and wellheads used for injection and withdrawal of gas. Additional wells at underground gas storage facilities may include observation or monitoring wells. Other wells not formally part of the underground gas storage system may also be present, e.g., for oil production from reservoirs not connected to the gas storage reservoir. All wells connected to hydrocarbon reservoirs must be sealed to contain high-pressure gas or oil in the reservoirs. The wells connected to the high gas pressure in the storage reservoir must contain that pressure all the way to the wellhead, after which the surface infrastructure is relied on to contain the gas.

Side Bar: Hazard, Risk, and Impact

The terms *hazard*, *risk*, and *impact* are often used interchangeably in everyday conversation, whereas in a regulatory context they represent distinctly different concepts with regard to the formal practice of risk assessment and risk management. A *hazard* is defined as any biological, chemical, mechanical, environmental, or physical stressor that is reasonably likely to cause harm or damage to humans, other organisms, the environment, and/or engineered systems in the absence of control. The term *risk* incorporates the likelihood that a given hazard plays out in a scenario that causes a particular harm, loss, or damage. *Impact* (or consequence) is the particular harm, loss, or damage that is experienced if the risk-based scenario occurs. In quantitative risk assessments, risk is calculated as likelihood multiplied by impact.

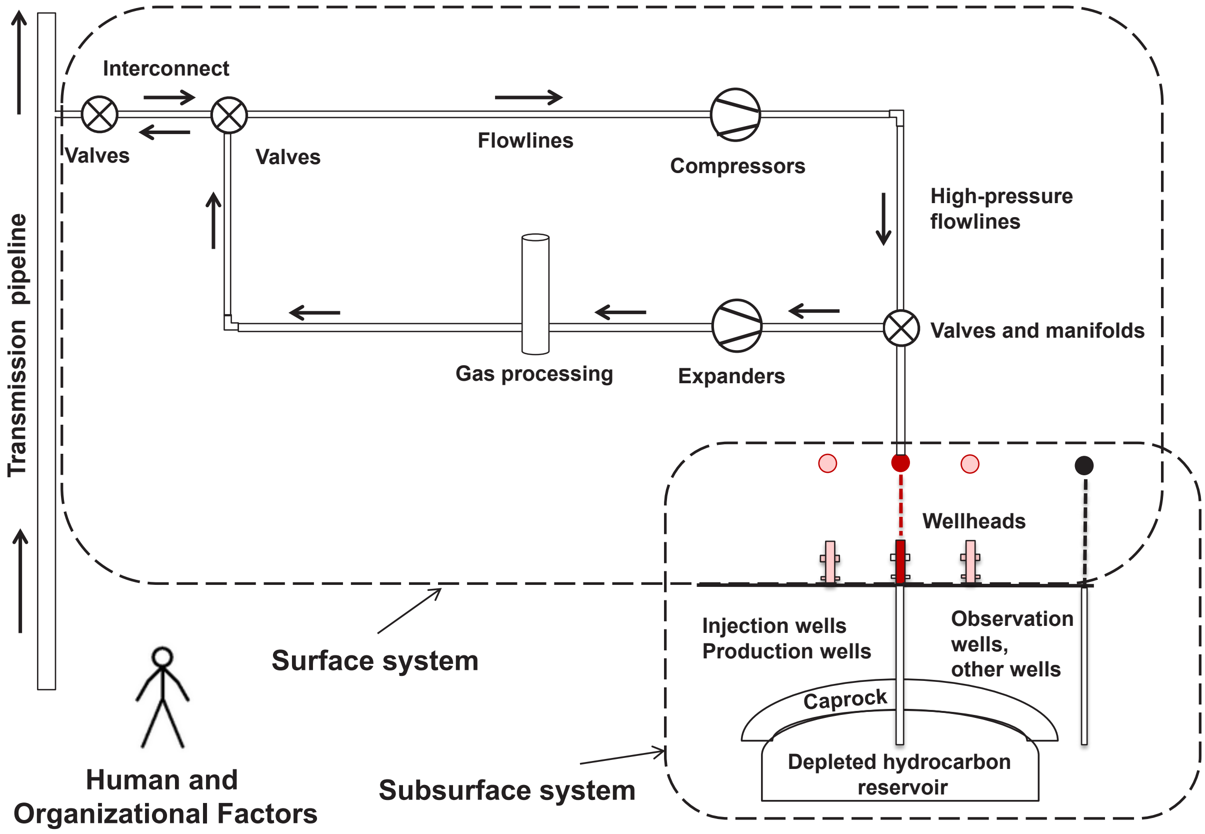

Figure SR-1.2. Simplified schematic of the main components of underground gas storage facilities in California, showing examples of engineered surface components and the wells and geologic features comprising the subsurface system. Human and organizational factors play a critical role in control of both surface and subsurface systems.

The 2015 Aliso Canyon incident was a very severe subsurface blowout of a gas storage well (SS-25) that breached to surface and leaked approximately 100,000 tonnes of methane into the atmosphere over nearly four months without igniting. This severe loss-of-containment incident led to the evacuation of several thousand families from the adjacent Porter Ranch neighborhood downslope of the SS-25 well. The evacuated population either experienced health impacts or was relocated as a precaution to avoid potential health impacts. The California Public Utilities Commission (CPUC) is currently conducting a full root-cause analysis of the 2015 Aliso Canyon incident, which has not yet been published. The scientific assessment conducted here is *not* a root-cause analysis of the particular Aliso Canyon incident, nor does it provide an in-depth analysis of the Aliso Canyon facility. Rather, it does the following:

1. Examines all underground gas storage facilities in the State of California and their risk-related characteristics

2. Analyzes various failure modes and potential hazards that can lead to loss-of-containment incidents

3. Evaluates effects of age and storage integrity on underground gas storage capacity

4. Includes a broad review of the potential risks to workers, the public, and the environment

5. Presents data on methane emissions from underground gas storage facilities

6. Discusses risk management and mitigation practices to reduce future risks associated with underground gas storage operations

7. Points to data gaps and quality control issues

8. Provides a qualitative comparison of risk-related characteristics of all facilities.

The scientific assessment also includes a thorough review of the proposed new regulations for underground gas storage projects developed by DOGGR in the aftermath of the 2015 Aliso Canyon incident. Below, we present the main findings, conclusions, and recommendations from this scientific analysis, in the topical order listed above.

CHARACTERISTICS OF CALIFORNIA UNDERGROUND GAS STORAGE FACILITIES

Gas injection via gas storage wells occurred in thirteen facilities in California in 2015 prior to the 2015 Aliso Canyon well blowout. Gas injection via storage wells ceased in the Montebello facility at the end of 2016 with the approval of the operator's application to inactivate the injection permit. All underground gas storage facilities in the State have been developed in depleted oil and gas reservoirs, all but one of which were originally discovered between 1931 and 1963. About half of the wells in depleted oil reservoirs used for gas storage from 2006 through 2015 were initially built for oil production and subsequently converted to natural gas storage wells. In contrast, less than a tenth of the wells used for storage in depleted gas reservoirs were repurposed from gas production. Most of the wells in facilities operated by utilities were installed more than four decades ago, whereas most of the wells in facilities operated by independent (non-utility) companies were installed in the last two decades.

This study examined all currently operating facilities in the State in terms of various risk-related characteristics. These characteristics include attributes related to the subsurface aspects of the storage facilities and the wells used to access the storage reservoirs (e.g., depleted gas or oil reservoirs, depth, lithology, hydrology, trap configuration, age of wells, etc.) and geographic surface characteristics (e.g., topography, elevation, vegetation, location in or near hazard zones for earthquakes, landslides, floods or wildfires, proximity to population, etc.).

There are important regional risk-related differences in the gas storage fields statewide. Three facilities in southern California currently store gas in depleted oil reservoirs. The remaining facility in southern California, the one facility in central California, and the seven facilities in northern California store natural gas in depleted gas reservoirs. Various aspects of the facilities utilizing oil reservoirs differ from those utilizing gas reservoirs. For instance, the depleted oil reservoir storage sites have deeper wells drilled longer ago (half of which were originally for oil production), more vertical wells with wellheads distributed more widely across the field, and lower operating pressures as a fraction of the initial reservoir pressure. In addition, the gas withdrawn from depleted oil reservoirs can include residues of crude oil such as benzene, toluene, and other toxic chemicals, making them potentially harmful to worker and community populations during loss-of-containment incidents.

There are also differences in ownership and operation of underground gas storage facilities. For instance, all underground gas storage sites utilizing depleted oil reservoirs are operated by the utility Southern California Gas Company (SoCalGas). In contrast, some of the underground gas storage facilities in central and northern California utilizing depleted gas reservoirs are operated by independent companies, whose primary business is operating the underground gas storage facility. Almost all of the wells in the underground gas storage facilities operated by independent companies were installed in the last two decades, and were mostly custom-built for gas storage rather than repurposed.

Some facilities are in zones delineated for earthquake hazard and/or have high anticipated ground shaking (Aliso Canyon, Honor Rancho, La Goleta, Playa del Rey), high landslide hazard (Aliso Canyon, Honor Rancho, Playa del Rey, La Goleta), flooding hazard (La Goleta, McDonald Island, Princeton, Wild Goose), and very high wildfire hazard (Aliso Canyon, Honor Rancho, Playa del Rey). Five operating facilities are located near populations of more than 100,000: Aliso Canyon, Honor Rancho, La Goleta, Los Medanos, and Playa del Rey. A summary discussion of all risk-related characteristics by facility is provided in the section below entitled “Summary Assessment of Risk-Related Characteristics of Underground Gas Storage Facilities,” along with related conclusions and recommendations.

FAILURE MODES, LIKELIHOOD, AND CONSEQUENCES

Successful underground gas storage operation involves containing high-pressure natural gas through multiple repeated cycles of compression, injection, storage, withdrawal, decompression, processing, and utilization. As such, loss-of-containment is the main failure mode of interest with respect to risk to health, safety, and the environment. Because of the many components involved in underground gas storage, loss-of-containment can occur for many reasons and by a variety of failure sequences. Insight into the likelihood of loss-of-containment failures can be gathered from records of frequency of occurrence as documented in incident databases. Consequences of failure can be assessed by review of historical incidents, and by modeling and analysis.

History of Failure Rates of Underground Gas Storage Facilities in California

Using compilations of underground gas storage incidents worldwide and in California, we have analyzed relevant failure modes and their likelihood of leading to loss-of-containment in underground gas storage facilities. In general, failure can occur in the subsurface part of underground gas storage, where well integrity and reservoir integrity are needed to contain natural gas, and in the surface part, where failure can occur by damage to, or defects in, pipelines, valves, and other components. Gas storage has been carried out in California for over 70 years at about 20 different sites. Of the twelve facilities operating today, seven have recorded loss-of-containment incidents. While these statistics must be used cautiously because the overall number of events is relatively small—and reporting of incidents has not been regulated or standardized—the record of reported incidents suggests that on average about four incidents of severity significant enough to be reported will occur every year in a underground gas storage facility somewhere in California, presuming continued operation of twelve facilities. Nearly all of these recorded incidents are minor and do not involve injuries, evacuations, or significant costs, and they are easily fixed. But some incidents can be major, the most recent of which was the 2015 Aliso Canyon well blowout that occurred in a well in which a single barrier, the 62-year-old steel production casing wall, was relied upon to contain high-pressure gas. This steel casing wall likely corroded, or otherwise degraded over time, before rupturing and producing a leakage pathway to the surface. Analysis of underground gas storage incidents worldwide and in California generally shows that loss-of-containment incidents are often caused by a chain of events. These events involve system component failures and external events, as well as human and organizational factors. Although possibly artifacts of reporting or the fact that California's larger facilities are larger than the worldwide average, the failure rate of underground gas storage 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 1.1:** 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.
>
> **Recommendation 1.1:** 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.

Importance of Subsurface Integrity and Well Integrity in California

Queries of the database compilations of underground gas storage incidents in California show that well-related leakage is by far the most common failure mode for loss-of-containment incidents in this state. In contrast, compilations of underground gas storage failures worldwide suggest there are four times more loss-of-containment incidents related to aboveground infrastructure (valves, pipes, wellheads, compressors, and other systems) than subsurface incidents. It appears that California's subsurface loss-of-containment incidents are substantially higher than the worldwide average.

> **Conclusion 1.2:** 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.

The Need for Multiple Barriers to Minimize Risk of Major Well Blowouts

Well integrity failures are common to many types of wells (e.g., wastewater disposal, oil and gas production, underground gas storage) and can occur for many reasons, but failure of cement seals and corrosion of casing are two of the main causes. For underground gas storage wells, there is an additional concern: In California and elsewhere in the U.S. as a rule, underground gas storage operators have carried out injection and withdrawal not only through tubing, as in nearly all other injection and production wells (e.g., in oil and gas, and in deep disposal operations), but also through the casing, or so-called A-annulus. The use of the A-annulus for injection and withdrawal allows high-pressure gas to contact the casing along the entire length of the well, including regions of the well with no cement outside of casing. This practice allows for a single-point failure, wherein any failure of the casing integrity can lead to high-pressure gas leakage. Normally, oil and gas wells and injection wells regulated under the U.S. Environmental Protection Agency's (U.S. EPA) underground injection control program are not constructed nor configured to operate in this way. Instead, normal oil and gas wells and injection wells only inject or produce high-pressure fluids through the tubing, reserving the A-annulus to serve as a secondary volume available for monitoring leaks and well integrity—confined by the casing as the secondary barrier in case the packer or tubing fails (i.e., creating a two-point failure configuration). In other words, in order for the well to lose integrity as a result of tubing, packer, or casing failure, more than one of these components would have to fail at the same time. Two-point failure configurations are much safer than single-point-failure configurations. The new regulations proposed by DOGGR currently under consideration effectively ban single-point-failure configurations.

> **Conclusion 1.3:** 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.

If the SS-25 well at Aliso Canyon had been operated using tubing and packer for injection and withdrawal, the hole in the casing that is suspected to have been caused by corrosion would not have allowed gas to escape to surface. This difference in behavior arises because there would be no reservoir pressure support and gas supply to the A-annulus to feed an ongoing blowout (major loss-of-containment incident) through a hole caused by corrosion.

Natural Hazards Can Affect Integrity of Underground Gas Storage Facilities

Some California underground gas storage facilities are located in regions with particular hazards that can affect underground gas storage 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 new DOGGR regulations now require 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 near the Aliso Canyon facility, including a probabilistic seismic hazard analysis and a probabilistic fault displacement analysis.

> **Conclusion 1.4:** Natural hazards can significantly affect the integrity of underground gas storage facilities.
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> **Recommendation 1.4a:** 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.
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> **Recommendation 1.4b:** 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.

HUMAN HEALTH HAZARDS, RISKS, AND IMPACTS

The environmental, public- and occupational-health hazards associated with underground gas storage in California were assessed using three primary approaches: (1) an analysis of air toxic emission data reported to regional air districts and the State of California; (2) an analysis of the numbers, density, and demographics of people in proximity to underground gas storage facilities and their potential exposure to toxic air pollutants and natural gas fires; and (3) an assessment of air quality and human health impact datasets collected during and after the 2015 Aliso Canyon incident. Human health hazards of underground gas storage include exposure to airborne toxic secondary constituents and other health-damaging air pollutants, sourced from the stored gas and other facility processes during normal operations and from off-normal loss-of-containment events, as well as exposure to potential explosions and fires during large loss-of-containment events.

For a given loss-of-containment incident, the human health risks of underground gas storage (underground gas storage) facilities depend on (a) the magnitude and duration of emissions during containment failures; (b) the composition of stored, produced, stripped, and compressed gases; (c) the atmospheric dispersion conditions during the period of release; (d) the activities and locations of on-site workers and contractors; (e) the location and density of downwind populations; and (f) the location of sensitive populations as reflected by the very young, the elderly, schools, child care facilities, hospitals, and homes for the aged. Effective risk management requires that such information is readily available to regulators, decision-makers, site managers, and local emergency managers, so that decisions can be well informed.

Emissions Inventory Information Gaps and Uncertainty

There are a number of human health hazards associated with underground gas storage 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, as well as benzene, toluene, and other potentially toxic chemicals incidentally extracted from residual oil in depleted oil reservoirs. Given the limited number of compounds monitored during the 2015 Aliso Canyon incident compared to the number of compounds reported to the California Air Resources Board as emitted from underground gas storage facilities, there is significant uncertainty as to the human health risks and impacts of this large loss-of-containment event, both over the short- and long-term. Our repeated attempts to obtain useful information about gas composition at each underground gas storage facility in California were unsuccessful.

Conclusion 1.5: 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.

Recommendation 1.5: 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.

Health Symptoms near Underground Gas Storage Facilities and Need for Improved Monitoring and Exposure Assessment

Large loss-of-containment incidents (e.g., the 2015 Aliso Canyon incident) can cause health symptoms and impacts in nearby populations. The majority of households near the Aliso Canyon facility experienced health symptoms during the SS-25 blowout and after the well was sealed. The symptom reports together with environmental monitoring indicate that chemicals and materials sourced from the Aliso Canyon incident entered residences, demonstrating clear indoor and outdoor exposure pathways. However, air pollutant exposures remain quite 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 well 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 noncontinuous; and (3) only a small fraction of pollutants known to be associated with underground gas storage facilities was included in the monitoring.

Conclusion 1.6a: 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.

Recommendation 1.6a: 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.

Conclusion 1.6b: 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.

Recommendation 1.6b: 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.

Population Exposure to Air Pollutants and Mitigation Options

Approximately 1.85 million residents live within five miles of underground gas storage facilities in California. For given emission inventories and expected release rates, potential health hazards to these residents can be evaluated using normalized source-receptor relationships obtained from atmospheric dispersion models and best estimates of population distance and density. Preliminary analysis conducted in this study suggests that such models provide helpful tools to assess the variability of potential exposures and risks among different underground gas storage facilities.

Conclusion 1.7: 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.

Recommendation 1.7: 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.

Occupational Health and Safety Considerations

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 developed a list of probable toxic chemicals used at and emitted from underground gas storage 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 1.8: 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.

Recommendation 1.8a: 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.

Recommendation 1.8b: 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.

The exact chemicals to be monitored should be evaluated when more data are available about potential exposures, but some important ones include hydrogen sulfide where it is present, benzene, formaldehyde, the odorants in use at the facility (e.g., mercaptans), methanol, triethylene glycol, and other dehydrants.

Monitor for and Reduce Air Pollutant Emissions from Routine Operations

Many underground gas storage facilities emit multiple health-damaging air pollutants during *routine* operations. Available emissions inventories suggest that the most-commonly emitted air pollutants associated with underground gas storage 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 1st, 2017 require continues methane concentration monitoring at facilities upwind and downwind locations (at least one pair of upwind and downwind locations), but without air sampling.

> **Conclusion 1.9:** There is a need to track and if necessary reduce emissions of toxic air pollutants from underground gas storage facilities during routine operations.
>
> **Recommendation 1.9:** 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.

Flammability and Explosion Hazards Near Underground Gas Storage Facilities

During large loss-of-containment events, downwind methane concentrations can be higher than flammability or explosion limits. This poses a significant threat to people and property, due to the possibility of 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. Based on our modeling, 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. Model results suggest that the methane concentrations in the close vicinity of the leakage points can exceed the lower flammability limits for typical “off-normal” leakage fluxes. However, flammable zones are typically not expected to extend beyond underground gas storage facility boundaries, unless the leak rates are extremely large, i.e., larger than the fluxes experienced in the 2015 Aliso Canyon incident.

> **Conclusion 1.10:** 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.
>
> **Recommendation 1.10:** 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.

ATMOSPHERIC MONITORING FOR QUANTIFICATION OF GREENHOUSE GAS EMISSIONS AND UNDERGROUND GAS STORAGE INTEGRITY ASSESSMENT

At the time of the Aliso Canyon incident in 2015, there was no reported quantitative monitoring program for ambient methane or other trace gases at Aliso Canyon (or any other underground gas storage facility in California). A variety of methane measurement methods was deployed in the months that followed to improve confidence in the SS-25 well leak-rate estimate, as it evolved in response to efforts to regain control and withdraw reservoir gas. These methods include complementary airborne surveys using low-altitude *in situ* sampling and high-altitude remote sensing: (1) total methane emissions were determined using an aircraft equipped with an *in situ* methane analyzer flying cylindrical patterns around a facility; and (2) spatially resolved emissions from individual infrastructure components were estimated using an aircraft equipped with infrared imaging spectrometry. Both airborne methods have since been applied to other underground gas storage facilities in California: Total facility methane emissions were measured at selected facilities roughly 40 times from June 2014 through August 2017. Local methane emissions were measured roughly 80 times from January 2016 through August 2017. Operators are also subjected to daily surveys of all wellheads with hand-held gas analyzers, offering the ability to find small concentration anomalies at wellheads. Together, these measurements provide relevant information on current underground gas storage facility emissions discussed below in the context of greenhouse gas (GHG) emissions, as well as with regard to integrity implications.

As of October 1st, 2017, regulations of CARB on GHG emissions from crude oil and natural gas facilities went into effect. These regulations now require underground gas storage operators to develop monitoring plans that need to be approved by CARB and also specify detailed report requirements, in case leaks have been detected. At a minimum, operators are required to continuously monitor meteorological conditions, including temperature, pressure, humidity, and wind speed and direction, monitor predominantly upwind (background) and downwind methane concentrations in the 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 the CARB monitoring requirements is to detect and locate leakage, not quantify emissions (i.e., leakage rates). Once leaks are detected and located, they can be addressed. However, wellhead-focused leak monitoring may not detect leakage coming out of the ground away from the wellhead, which may be indicative of a nascent or well-developed subsurface blowout. We also note that the measurements under these regulations are concentration measurements used to detect leakage, rather than to quantify emissions (leakage rates).

Atmospheric Monitoring of GHG Emissions from Underground Gas Storage Facilities

We compared the recent (June through August 2017) airborne measurements of methane emissions from gas storage facilities with annual GHG reports that gas storage facilities provide to the California Air Resources Board. We note that the directly observed emissions are about 2.6 times higher than the average of emissions reported by the facilities to CARB. Those emissions are dominated by three facilities: Honor Rancho, Aliso Canyon (after the SS-25 well leak repair), and McDonald Island contribute on average 45%, 16%, and 14%, respectively, of all underground gas storage emissions. In terms of emission rates, most sites were found to emit less than 100 kg/hr (kilogram/hour)(<1 Gg CH_4/yr, or <0.052 Bcf/yr = 142 Mcf/d = 1476 therms/d); the three larger emitters mentioned above were found to have occasional readings of up to 1000 kg/hr. (These emission rates remain very small, however, compared to the 35,000 kg/hr emitted on average during the Aliso Canyon well blowout.) Taken together, the methane emissions from California's underground gas storage facilities are ~9.3 GgCH_4/yr (≈1% of California's total methane emissions), which is <0.1% of California's GHG emissions. Compressors and aboveground infrastructure apparently contribute the majority of the emissions. In comparison, the total emissions from the Aliso Canyon incident over nearly four months, beginning in late October 2015, were more than 100 Gg (~5 Bcf). Thus, the current annual emissions of all underground gas storage facilities in the State are roughly equivalent to one Aliso Canyon incident every 10 years.

> **Conclusion 1.11:** 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.

Recommendation 1.11a: 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.

Recommendation 1.11b: 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 concentration) 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.

Atmospheric Monitoring for Integrity Assessment

A well-designed monitoring strategy for natural gas leakage at underground gas storage facilities can provide a valuable early-warning system for integrity losses of surface and subsurface infrastructure. Early detection can help minimize the impact of leaks and may help avoid larger loss-of-containment incidents and other hazardous situations. 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 toxic air pollutants such as benzene. There are many methane measurement methods that can be applied to underground gas storage 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.”

Conclusion 1.12: 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.

Recommendation 1.12: An optimized methane emission monitoring system 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.

Protocol for Assessment, Management, and Mitigation Actions In Case of Local Methane Leakage Observations

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 aboveground 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 1.13: 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.

Recommendation 1.13: 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 in which periodic airborne and surface-based methane surveys identify potential emission hot spots of concern.

For example, if a leakage hot spot is located, the operator would be required within one week to provide to DOGGR or CARB a detailed assessment of the hot spot(s), with information on how large the leak is (flux or flow rate), what is leaking, where is it leaking from, etc. If the leak cannot be immediately fixed, the operator should be required to develop and present to DOGGR a plan within the following week of how to fix the leak. The follow-up would consist of agency staff visiting the site to observe the mitigation of the leak. We note that irrespective of leakage emission rate, the CARB regulations in place since October 1st, 2017 outline a detailed timeframe for fixing leaks detected on the basis of anomalous concentration, depending on concentration and duration of thresholds.

RISK MITIGATION AND MANAGEMENT

In California, the subsurface portions of underground gas storage facilities have been regulated on the State level by DOGGR, both prior to and since the Aliso Canyon incident. DOGGR considers the subsurface portion as including the reservoir used for storage, the confining caprock, gas storage wells and wellheads, observation wells, and any other wells approved for use in the project. The California Public Utilities Commission (CPUC) regulates the surface infrastructure at underground gas storage facilities. The California Air Resources Board (CARB) regulates greenhouse gas (GHG) emissions from UGS facilities as of October 1, 2017. Until early 2017, federal regulation did not provide operational, safety, or environmental standards for the subsurface portions of underground gas storage. Although the Natural Gas Pipeline Safety Act of 1968 has been found by a U.S. District Court to provide authority to the U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA) over such facilities, until 2017, the agency declined to develop regulations around them, stating in a 1997 Advisory Bulletin that operators should consult industry guidelines and State regulations on the subject. Meanwhile, underground gas storage has been excluded from the U.S. EPA's Underground Injection Control program, which regulates various types of fluid injection into the subsurface under the Safe Drinking Water Act (e.g., liquid waste, oil and gas waste water, CO_2, etc.).

In the immediate aftermath of the 2015 Aliso Canyon incident, DOGGR moved ahead to develop emergency regulations for the existing underground gas storage facilities in the State. These emergency regulations were intended to quickly and efficiently reduce the loss-of-containment risk of these facilities, focusing mainly on the subsurface portion of underground gas storage as described above. These emergency regulations will be superseded in January 2018 by permanent regulations now under development. DOGGR published on May 19, 2017 a draft of the new permanent regulations, which was reviewed for the purpose of this study. In addition to various new technical and administrative requirements, the emergency regulations and the draft permanent regulations require that each underground gas storage facility in California must develop and implement a Risk Management Plan (RMP) with certain specified features.

Meanwhile, in December 2016, PHMSA introduced an Interim Final Rule (IFR) that incorporated two American Petroleum Institute (API) Recommended Practices (RP) (API RP

1170, "Design and Operation of Solution-mined Salt Caverns Used for Natural Gas Storage," issued in July 2015 (17), and API RP 1171, "Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs," issued in September 2015). The IFR became effective as of January 18, 2017. States are now required to adopt the federal standards but they may certify, as did California, to act as PHMSA's agent and impose their own rules that go beyond the federal standard. DOGGR's interim and proposed final rules go beyond PHMSA's IFR recommended practices. These are the rules that we have reviewed in this study, results of which are given below.

Overall Assessment of DOGGR's New Emergency and Proposed Draft Regulations for Underground Gas Storage Facilities

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

> **Conclusion 1.14:** 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.

Evaluating Risk Management Plans as a Major Element of Underground Gas Storage Integrity

One of the major and most important elements of both the emergency regulations and the draft permanent regulations is that each underground gas storage facility in California must develop and implement a Risk Management Plan (RMP), which is required to include a description of the methodology employed to conduct a risk assessment for each facility and identify prevention protocols. Further, the regulations prescribe that the risk assessment methodology shall identify potential threats and hazards associated with operation of the underground gas storage project and evaluates the probability of threats, hazards, and consequences related to the events.

> **Conclusion 1.15:** 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.

> **Recommendation 1.15:** 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.

We emphasize that the quantitative risk assessment recommended here need not be an exhaustive probabilistic risk study requiring multiple person-years of effort for every conceivable failure scenario. Instead, we recommend that a formal, practical, and efficient risk assessment be carried out for each facility, incorporating the most important site-specific risk categories and failure scenarios. The state-of-the-art quantitative risk assessments currently offered by several engineering consulting companies can provide the adequate rigor. Furthermore, we propose that development of these risk assessments be accomplished in stages, the first stage being a scoping analysis to provide a short-term understanding at each underground gas storage facility of the various risks and the issues that give rise to those risks. These short-term scoping studies, to be supplemented later by more detailed analyses, can provide early guidance to decision-makers about what interventions may be needed, if it is concluded that some of the risks require early intervention to reduce either their likelihood of occurring or their consequences. In parallel, an activity needs to begin promptly to develop the risk targets or goals that will ultimately guide risk-mitigation decision-making. Whether this process should be led by the industry or by a government agency is a decision that is beyond the remit of this CCST study; however, the development process definitely requires broad stakeholder input.

Recommendations Regarding Specific Well Integrity Requirements

The draft DOGGR 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 underground gas storage 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 of the main report.

> **Conclusion 1.16:** 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.
>
> **Recommendation 1.16:** 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).

Need for Regular Peer Review or Auditing of New DOGGR Regulations

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 or auditing teams. For example, the Groundwater Protection Council organizes peer reviews of the Class II Underground Injection Control Program in certain states to which U.S. EPA has delegated regulatory authority. (Class II wells are used to inject fluids associated with oil and natural gas production.) 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.

> **Conclusion 1.17:** 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.

In contrast to purely prescriptive regulations, the risk management planning and analysis to be conducted as part of DOGGR’s new regulations requires judgment-based decisions by the risk “assessor” where expert knowledge comes into play. A risk analysis, for example, requires decisions about which risk scenarios to consider (or not), which probability a certain accident scenario may have, or what the uncertainties are about probabilities and impacts. It follows that regulatory review of such risk analysis requires expert knowledge in order to agree or disagree with the assumptions going into the analysis.

Recommendation 1.17: 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 and other state, academia, consultants, and environmental 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.

Emphasizing Human Factors and Safety Culture at Underground Gas Storage Facilities

Conclusion 1.18: The draft DOGGR regulations ignore how human and organizational factors as well as a healthy safety culture drive safety outcomes and performance.

Recommendation 1.18: 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."

Regular Training of Operators and Maintenance Personnel

Regular training of operators and maintenance personnel can be a significant factor in decreasing the likelihood as well as the severity of large accidents. This is true even if the training, which may consist of written material or lectures, is offered only sporadically. When this training is linked to the use of written procedures to help the personnel to respond to off-normal conditions, and when the training involves periodic updates, the benefits are enhanced.

Conclusion 1.19: 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.

Recommendation 1.19: 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.

Capability to Predict Site-Specific Dispersion and Fate of Accidental Gas Releases into the Atmosphere

Loss-of-containment incidents can sometimes lead to very large releases such as those that occur during well blowouts or field line rupture. More often, loss-of-containment incidents occur without impacts to safety but with potential long-term impact to the environment, as in the case of chronic low-flow-rate leakage of methane, a potent greenhouse gas. In either case, the ability of operators to deal with off-normal events in terms of intervention or emergency response depends on fast, reliable predictions, in near real time, of the atmospheric dispersion of natural gas that has leaked to the surface. Such models would deliver estimates of the time-dependent spatial distribution of leaked gas (as a function of leakage rate and location, as well as wind and weather conditions), thereby providing information on the expected concentrations of methane and other components in the vicinity of underground gas storage facilities.

Conclusion 1.20: Although a range of practical and sophisticated models are readily available for predicting the impacts of off-normal loss-of-containment events, there is currently no requirement for underground gas storage facilities to possess, or have access to, atmospheric dispersion models that can predict the fate of natural gas 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 underground gas storage facilities.

Recommendation 1.20: 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.

One example of an institution with this skillset is the National Atmospheric Release Advisory Center at Lawrence Livermore National Laboratory in Livermore, CA, a national support and resource center for emergency planning, real-time assessment, emergency response, and detailed studies of atmospheric releases. As discussed in Recommendation 1.12, an optimized combination of on-site measurements and airborne surveys should be deployed at each underground gas storage facility to provide reliable spatially and temporally varying input data on gas releases for such analysis. On-site weather stations should be installed at each underground gas storage facility, following National Weather Service guidelines, to provide continuous near-real-time meteorological data to the simulation models.

DATA REPORTING GAPS AND DATA QUALITY ISSUES

Data on past and current practices of underground gas storage facilities in California have been assembled from various sources and databases for this study. Significant gaps and inconsistencies exist in available voluntary and mandatory data sources, in terms of duration, completeness, and accuracy of reporting. Examples of suggested additional reporting and data quality requirements include:

Improvements to DOGGR's Well Databases for Gas Storage

DOGGR maintains public databases that provide various types of information about California's oil and gas, geothermal, or underground gas storage wells. These are, for example, the AllWells file for well location and type, or the Annual Production and Injection Database, with information on fluids produced/withdrawn and/or injected and pressures.

> **Conclusion 1.21:** 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.
>
> **Recommendation 1.21:** 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.

Disclosure of Chemicals Used For Well Drilling and Maintenance

Chemicals used for routine well operations (e.g., for drilling, routine maintenance, completions, well cleanouts) and well stimulation (e.g., hydraulic fracturing) in oil and gas production operations in the Los Angeles area are reported to the South Coast Air Quality Management District. Currently, no such disclosures need to be made for chemical use in underground gas storage wells statewide. Further, data on chemicals being stored on-site are reported to the California Environmental Reporting System (CERS), but 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 chemical additive use occurs for routine well operations, 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 underground gas storage facilities, remain unknown.

> **Conclusion 1.22:** 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.
>
> **Recommendation 1.22:** 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.

Need for Routine Reporting of Off-Normal Events Relevant to Safety

Although minor off-normal events arising from equipment failures, human errors in operations or maintenance, or other causes are assumed to occur at today’s operating underground gas storage facilities in California, just as they do in every other industrial setting, there is currently no requirement that these events or other failures be routinely reported and compiled into a shared database.

> **Conclusion 1.23:** 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.
>
> **Recommendation 1.23:** 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.

Integration, Access, and Sharing of Monitoring/Testing Data

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 underground gas storage facilities, in particular with regards to integrity issues and potential loss-of-containment. For example, airborne-based measurements of local methane emissions can 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 1.24:** 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.
>
> **Recommendation 1.24a:** 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.
>
> **Recommendation 1.24b:** 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.

SUMMARY ASSESSMENT OF RISK-RELATED CHARACTERISTICS OF UNDERGROUND GAS STORAGE FACILITIES

This section provides a summary table that allows readers to see at a glance the most salient characteristics related to risk of each of the underground gas storage sites in California.

The rows in Table SR-1.1 comprise a short-list of selected descriptive attributes, specific hazard categories, health- and exposure-related aspects, and GHG emissions; we provide a more comprehensive table in Section 1.7 of the main report. The columns of the table list the thirteen names of the California underground gas storage facilities organized by ownership, with the independent facilities listed first, the northern California utility-owned facilities listed second, and the southern California facilities listed third. Where appropriate, we made a judgment about the qualitative relative hazard associated with each value or descriptor in the table, as shown by the shading of the color. Specifically, darker shades correspond to larger hazard, while lighter shades correspond to lesser hazard. We emphasize that this qualitative assessment is independent of (i.e., does not take into account) any and all risk mitigation actions that may have been implemented at the sites. In addition, the storage capacity attribute can be seen as both a risk-related characteristic—more mass available to leak in a blowout—or a benefit—more capacity to store gas, yet the shadings refer only to the hazard level and not the benefit. Furthermore, the qualitative comparative assessments made possible by the information in Table SR-1.1 in no way take the place of the formal risk assessments recommended previously for each facility. Instead, Table SR-1.1 is useful for comparing underground gas storage sites qualitatively across all facilities in California. Finally, we note that the Montebello facility was officially closed December 31, 2016, following extensive surface leakage of natural gas over decades; it is included in Table SR-1.1 because it apparently operated for some periods during our 10-year study period January 1, 2006, to December 31, 2015.

As evident from Table SR-1.1, the hazards and vulnerabilities are generally different for facilities that store gas in former gas fields versus former oil fields, and also differ qualitatively among individual facilities based on their unique characteristics. Identification of such differences allows some preliminary assessments of which underground gas storage sites in California may present higher risk to health and safety than others, overall or for certain risk scenarios. As an example of one particular risk scenario, an initiating event for a large-scale loss-of-containment event might be well integrity failure by corrosion or sand erosion of steel pipe or casing. Both of these are more likely to become problems for older and repurposed wells. Therefore, age of wells is a relevant attribute. From the underground gas storage Characteristics section of the table, we note that the median age of wells open in 2015 for the Playa del Rey, La Goleta, and Aliso Canyon facilities are all from before the mid-1950s, and for Playa del Rey, the median age is 1935.

Other initiating events that could rupture a well or flowline leading to significant loss-of-containment are landslides and earthquakes, especially those that may cause slip on faults intersected by wells. Table SR-1.1 shows that Aliso Canyon and Honor Rancho have relatively high landslide hazard, while Aliso Canyon, Honor Rancho, La Goleta, and Playa del Rey all have relatively high seismic hazard. Wildfire is another hazard that could impact surface infrastructure and its ability to contain high-pressure gas. Table SR-1.1 also shows that Aliso Canyon, Honor Rancho, and Playa del Rey all have very high wildfire hazard. Regarding the likelihood side of this qualitative risk assessment, we note that Aliso Canyon and Playa del Rey have a history of multiple recorded loss-of-containment incidents and higher rates per facility year. The table also shows that McDonald Island has two recorded incidents of significant loss-of-containment, and there have been reports of recent surface gas leakage not yet included in publications. Finally, as we turn now to consider potential consequences of large-scale loss-of-containment incidents, Table SR-1.1 shows very low populations surrounding most of the underground gas storage facilities in California, with notable exceptions at Aliso Canyon, Honor Rancho, La Goleta, Los Medanos, and Playa del Rey. The implication is that larger numbers of people could be impacted by loss-of-containment incidents from these five facilities relative to comparable releases from the other facilities.

What emerges from the above examples of qualitative comparative risk assessment of the operating underground gas storage facilities in California is that 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. Of the thirteen underground gas storage facilities in the State, Playa del Rey stands out as a facility with risk-related characteristics of relatively greater concern than those at other sites. Aliso Canyon, Honor Rancho, and La Goleta also have characteristics suggestive of higher health and safety risks than other facilities, in part because of their location near large numbers of people. Los Medanos is also near significant population and has recorded loss-of-containment incidents, but its wildfire and landslide hazards are only moderate. We note again that Table SR-1.1 presents qualitative attributes that in the near future can be further quantified based on the risk management plans that each facility is now required to develop according to DOGGR's emergency and draft regulations, along with the quantitative risk assessment (QRA) recommended in this report.

> **Conclusion 1.25a:** 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.
>
> **Conclusion 1.25b:** 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.

Identification of such risk-related differences can lead to more specialized and effective risk management and mitigation approaches for each setting. In the near future, the risk management plans that each facility is now required to develop according to DOGGR's emergency and draft regulations will provide further (and more quantitative) insight into risk differences between facilities, and how these facilities translate expected risk into risk management practices. The qualitative risk-related information in Table SR-1.1, and in the near future more quantitative risk assessments of each facility, can be used by decision-makers to examine the tradeoffs between potential hazards and risks associated with facilities and their importance in meeting the demands for natural gas supply. This can and should be done facility by facility: For example, Table SR-1.1 suggests that the Aliso Canyon facility may be at relatively higher risk because of certain attributes and the nearby population, but it also has important benefits because of its large gas storage capacity. In contrast, Playa del Rey also has a high loss-of-containment incident rate, is near a large population center, features earthquake and wildfire threats, but it has a relatively small gas storage capacity.

> **Recommendation 1.25:** 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 SR-1.1, 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.

Table SR-1.1. Selected comparative risk-related characteristics for California underground gas storage facilities. Darker shades generally correspond to larger values or larger expected hazard, while lighter shades correspond to less expected hazard from that attribute.

		Independents					Pacific Gas and Electric			Southern California Gas			
	Facility[1]	Gill Ranch Gas	Kirby Hill Gas	Lodi Gas	Princeton Gas	Wild Goose Gas	Los Medanos Gas	McDonald Island Gas	Pleasant Creek Gas	Aliso Canyon	Honor Rancho	La Goleta Gas	Playa del Rey
UGS facility characteristics	2015 Capacity (Bcf)	20.0	15.0	17.0	11.0	75.0	17.9	82.0	2.3	86.2	27.0	19.7	2.4
	Average depth (range) of storage reservoir(s) (ft)	5,850 - 6,216	1,550 - 5,400	2,280 - 2,515	2,170	2,400 - 2,900	4,000	5,220	2,800	9,000	10,000	3,950	6,200
	Average annual gas transfer per well per from 2006 to 2015 (million scf)	150	69	511	78	866	255	75	22	197	244	232	13
	Number of open[2] wells connected to storage reservoir in 2015	12	18	26	13	17	21	88	7	115	41	18	54
	Median age of open[2] wells as of 2015 (yrs)	5	7	13	4	7	36	41	41	42	39	63	79
Failure modes, likelihoods, and hazards	Maximum deep-seated landslide susceptibility	0	VII	0	0	0	VI	0	VII	X	X	X	X
	Last fault rupture through or (*) within 500 m of flow line(s) (yrs ago)	None	<130,000	None	None	None	<130,000*	None	None	<15,000*	<15,000*	<130,000*	None
	Hazard of Quaternary fault shearing of well(s) present	No	Yes	No	No	No	Maybe	No	No	Yes	Unlikely	Unlikely	No
	Max. 2% probability of exceeding 0.2-sec spectral acceleration in 50 years (g)	1.45	1.55	1.25	0.95	0.65	2.15	1.25	1.85	2.75	2.45	2.65	1.65
	Earthquake-induced landslide hazard zone	No	?	No	No	No	?	No	No	Yes	Yes	?	Yes
	Tsunami hazard	No	No	No	No	No	No	No	No	No	No	Yes	?
	Flooding hazard	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	No
	Fire hazard severity zones - predominant (maximum, if different)	Not zoned (moderate)	Moderate	Not zoned (moderate)	Not zoned (moderate)	Not zoned (moderate)	Moderate	Not zoned (moderate)	Moderate	Very high	Very high	Not zoned	Very high
	Number of reported distinct LOC incidents in Evans (2008) and in Folga et al. (2016)	0	0	0	0	1	1	2	1	3	1	0	3
Health and safety	Proximity of handling plant (center) to well field (km)	0.0	0.7	6.5	0.9	8.0	0.3	0.0	0.4	0.2	0.0	0.5	0.0
	Population in proximity to UGS	909	401	23,771	848	195	223,069	6,473	8,821	325,330	180,359	101,371	691,757
	Median (max) formaldehyde emissions from 1996 - 2015, predominantly from compressors (lbs/yr)	4 (5)	108 (205)	1,291 (1,291)	not reported	not reported	4,968 (7,204)	11,163 (11,163)	not reported	15,001 (20,640)	18,675 (27,296)	2,197 (3,456)	3,038 (5,772)
GHG emissions	Average observed methane emission rate (kg CH4/hr)	88	37	0	43	35	11	150	16	200[3]	740	36	0
	Extrapolated annual emissions/average annual gas injection (%)	0.8	0.4	0.0	0.4	0.1	0.1	0.2	0.4	0.2[3]	1.2	0.1	0.0

[1] Storage in facilities whose name includes "Gas" is in depleted gas reservoirs; otherwise storage is in depleted oil reservoirs

[2] "open" includes wells with DOGGR status "Active" and "Idle", which are unplugged and have a wellhead

[3] Aliso emissions measured following repair of the 2015 blowout

KEY QUESTION 2

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

WHAT IS THE CURRENT ROLE OF GAS STORAGE IN CALIFORNIA?

The Aliso Canyon well blowout in 2015, which caused the largest gas leak in history, resulted in major disruption and exposures to the Porter Ranch community. The leak has raised serious questions as to whether and why California needs underground gas storage and what options might eliminate the need for these facilities. To help answer these questions, this report describes how California uses underground gas storage and how storage affects reliability of gas and electric supply, i.e., it describes the services and benefits underground gas storage provides. It also identifies and evaluates alternatives to underground gas storage that California could pursue if a decision is made to forgo underground gas storage in the near future, i.e., by 2020.

California has a robust and attractive market for natural gas, characterized by a large number of consumers, many marketers, and a combination of pipeline capacity and underground gas storage that has (except for a few isolated instances) successfully met California's need for gas. California consumes more natural gas per year than any other state except for Texas. In states that do not have any underground gas storage, local gas distributors are forced to pay for firm interstate pipeline capacity that is used only in peak months or to restrict use of natural gas in winter demand months.

The regulatory framework for natural gas in California separates gas supply service from transportation service and splits customers into core and non-core customers. Residential and small commercial customers are deemed *core* customers. The remaining customers are deemed *non-core*. California gas utilities should curtail non-core customers first in the event of a gas supply or a gas capacity shortage. Only core customers are entitled to firm uninterruptible service because of the high cost and safety issues involved in restoring service after a curtailment. However, because non-core customers include needed electricity generation and crucial industrial processes, California essentially provides firm service to all customers.

Multiple pipelines that bring gas from a variety of gas supply producing areas, in combination with underground gas storage located near the State's load centers, give consumers in California a diversity of supply and flexibility that consumers in other markets do not have. SoCalGas owns all the gas storage in southern California (Figure SR 2.1). PG&E owns some of the storage in its region, and independent providers own the rest. The

California Legislature explicitly encouraged “independent gas storage” to help create open and competitive markets for storage services. The Legislature also encouraged unbundling, or separation, of storage costs from the rates charged by public utilities for services such as gas transportation or supply sales.

Existing interstate pipeline capacity can, in theory, bring 10.6 Bcf per day (Bcfd) of natural gas per day to the state line. However, PG&E and SoCalGas cannot take very much gas away from the interstate pipelines and bring it to their load centers. The “receipt point” capacity or “take-away” capacity is approximately 3 Bcfd for PG&E and almost 4 Bcfd for SoCalGas. This capacity, plus direct delivery through Kern River pipeline of over 1 Bcfd, adjusted for supply restrictions, totals slightly more than 7.5 Bcfd. The receipt point pipelines are not all connected to each other within the State (See Figure SR-2.1). Utilities cooperate to allow customers in the north to buy from suppliers that deliver to the south and vice versa, as long as these amounts balance. If not, a limited amount of physical gas transfer between PG&E and SoCalGas can take place through the Kern River pipeline.

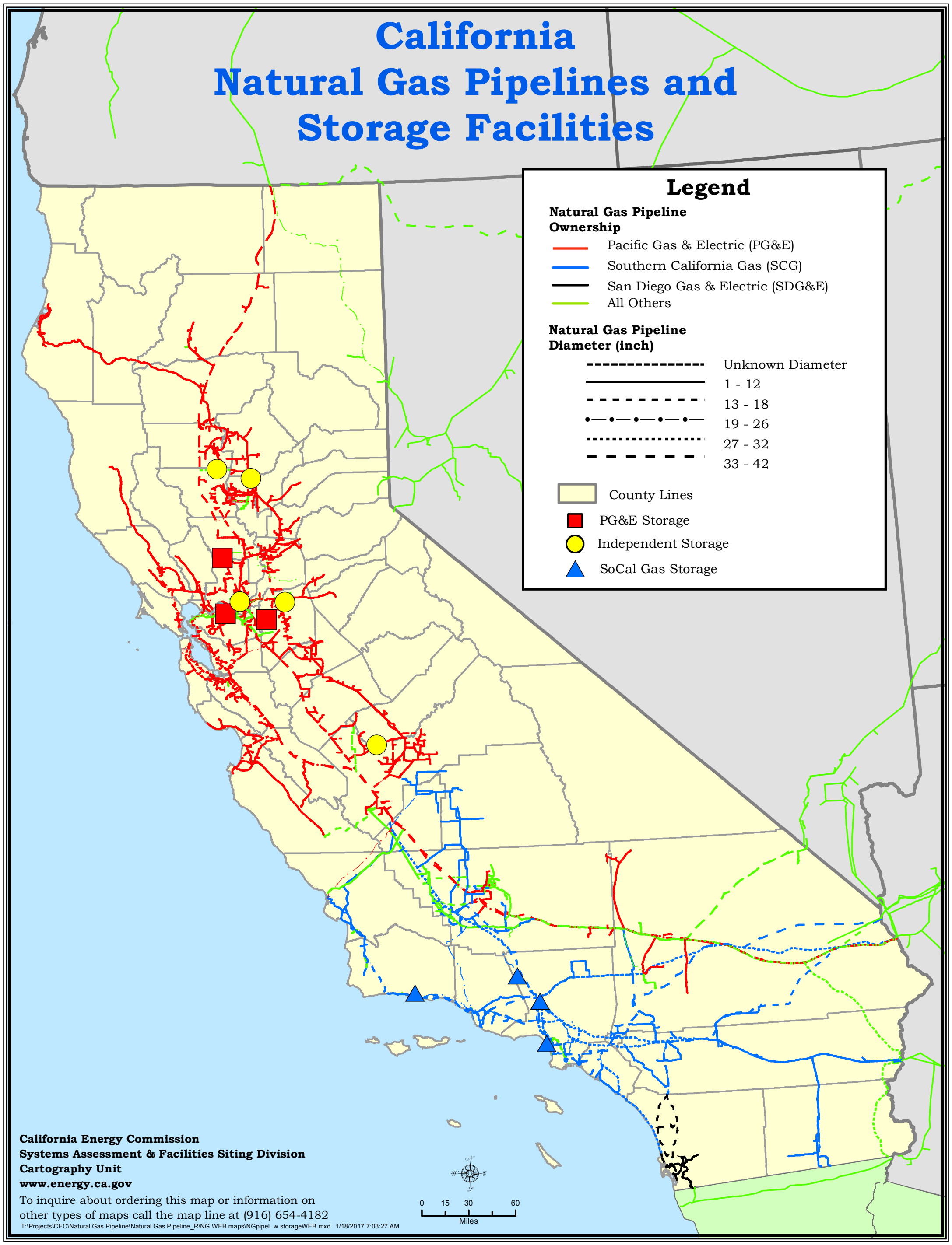


Figure SR-2.1. General Layout of California High Pressure Pipeline and Storage Facilities.

Underground gas storage serves as a key component of California's gas infrastructure. The Energy Information Administration (EIA) reports a working capacity to store 380 Bcf of natural gas in California's twelve individual storage facilities (Table SR-2.1). (Appendix 2-2 in Chapter 2 contains a detailed identification of each facility and key characteristics.)

Table SR-2.1. Underground Gas Storage Working Inventory Capacity (EIA, US Field Level Storage Data.

	Working Capacity (Bcf)	**Maximum Withdrawal Capacity (Bcfd)**
U.S.	4700	
California	370	
Utility-Owned & Controlled	240	5.9
PG&E	100	2.2
SoCalGas	*140*	3.7
Independently Owned	130*	2.7

**Based on CPUC operating certificate documents. Other table values are from the U.S. Energy Information Administration (EIA). EIA reports higher working capacities for three facilities (Los Medanos, Lodi, and Wild Goose) than the CPUC does.*

The "working capacity" or inventory shown in Table SR-2.1 reflects the quantity of gas that can be injected and withdrawn from the field. It excludes what is known as "cushion gas," which is natural gas that is held in the field (not produced) and serves to maintain pressure in the reservoir to drive working gas out.

The seven major functions that underground gas storage provides in California today are briefly introduced in Table SR-2.2, followed by more detailed discussions of each function.

Table SR-2.2. Functions of Underground Gas Storage in California.

Function	**Short Description**
Physical balancing of supply and demand functions	
1. Monthly Winter Demand	Storage provides supply when monthly winter needs exceed the available pipeline capacity.
2. Gas Production Limits	Storage provides supply when production does not match demand.
3. Daily Winter Peak Demand	Storage provides supply when daily winter peak day demands exceed pipeline capacity.
4. Intraday Balancing	Storage provides intraday balancing to support hourly changes in demand that the receipt point pipelines cannot accommodate. This service is essential in allowing the flexible use of gas-fired electricity generators to back up renewable generation.
5. Stockpile	Storage provides an in-state stockpile of supply in case of upstream pipeline outage or other emergency such as wildfires.
Financial functions	
6. Seasonal Price Arbitrage	Storage allows savings through seasonal price arbitrage (winter prices for out-of-state natural gas are usually, but not always higher than summer prices)
7. Liquidity/Short-term Arbitrage	Storage provides marketers a place to hold supply and take advantage of short-term prices for liquidity and short-term arbitrage.

Monthly Winter Demand

Although the average annual use of gas in California has remained relatively steady for years, the demand varies considerably during the year. In the winter, more gas is needed for heat by core customers, causing a larger demand. In the summer, demand for heat declines, but non-core customers have to provide more electricity for air conditioning, and this increases the demand for gas-generated electricity. To meet demand, on average California stores gas in the summer and withdraws it from storage in the winter.

Nearly every winter has a month with average daily demand that exceeds, or nearly exceeds, pipeline take-away capacity. Figure SR-2.2 shows a stylized version of a typical year for purposes of illustration; actual supply, demand, and daily injection and withdrawal rates vary from these stylized monthly averages. While the “flat” line is labeled “Supply,” it can represent both production supply or pipeline take-away capacity, as the same logic holds.

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

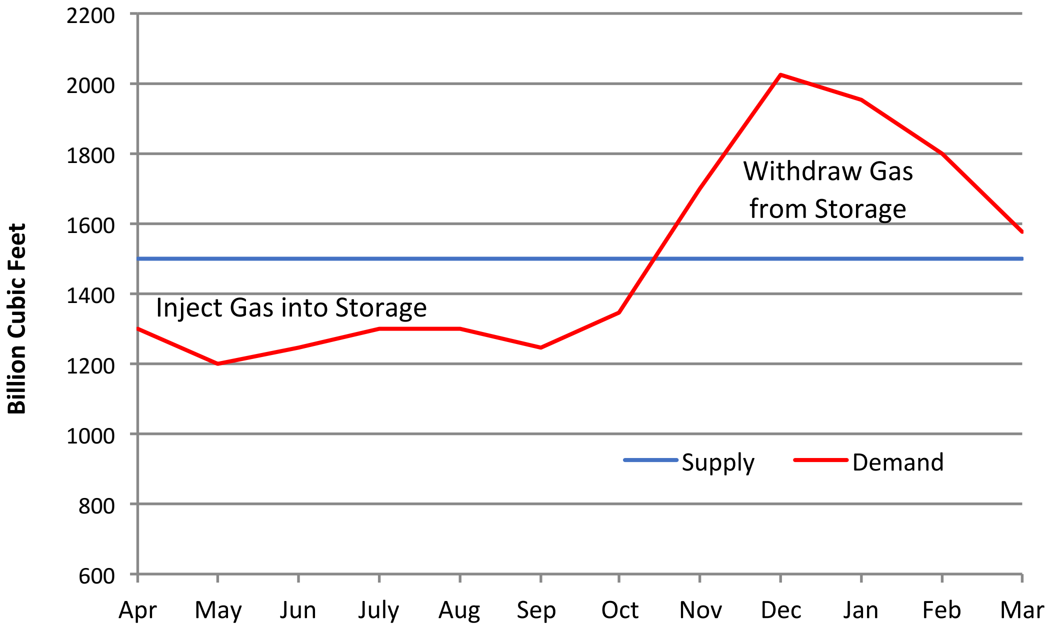


Figure SR-2.2. Example: Using Storage to Manage Variable Demand Against Flat Supply.

Gas Production Limits

Gas production constraints also limit the rate of gas imports to California. Gas producers who serve California are not required to modify production patterns to follow load and would object to such a requirement.

> **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.

Daily Winter Peak Demand

Gas demand also varies on a daily basis. Most winters include days where the demand for gas exceeds the capacity of the receipt point pipelines to deliver gas (Figure SR-2.3). That is, total California demand exceeds the maximum pipeline take-away capacity of 7.5Bcfd. As shown in Table SR-2.3, the highest recorded total demand in the last five years was 11.2 Bcfd on December 9, 2013. The second-highest was 9.4 Bcfd, occurring on December 19, 2012.

A second peak occurs during the summer because of demand for air conditioning. The highest summer day sendout recorded by the utilities in the last five years was 7.8 Bcfd per day on August 13, 2012, followed by 7.8 Bcfd on September 10, 2015. California's 7.5 Bcfd total pipeline take-away capacity is insufficient to serve these levels of demand. However, if the gas system can meet the winter peak demand, then it can also provide enough gas for the smaller summer peak.

Table SR-2.3 also provides forecasts of gas demand on winter peak days expected for 2020. These forecasts are based on historical data and represent peak demands used for planning the gas system for reliability and approved by the CPUC. The table provides explicit information about the expected recurrence interval for these demands. For example, a 1-in-10 year demand is a peak demand that will happen once every 10 years based on recorded demand levels in the past.

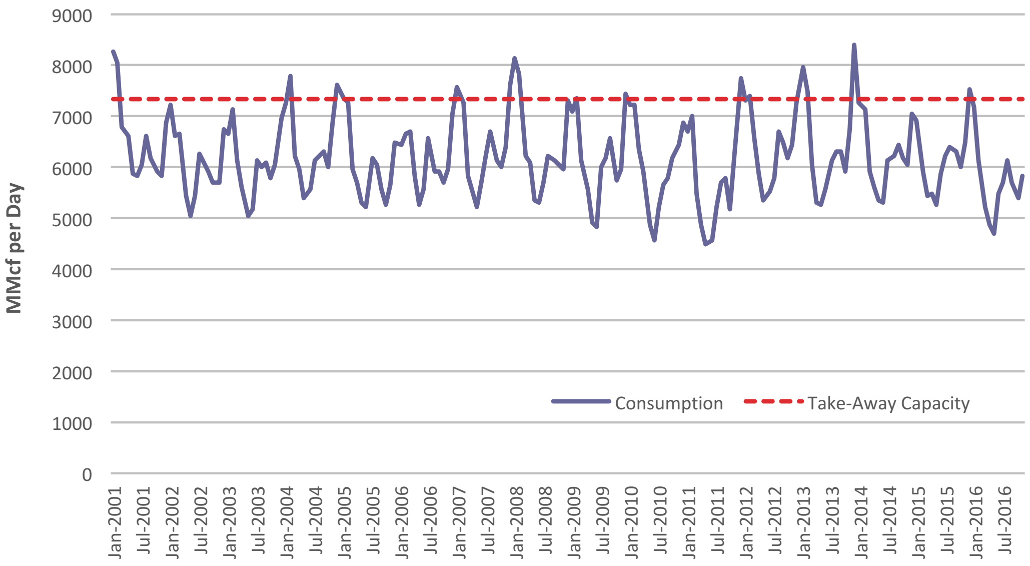


Figure SR-2.3. Average Daily Gas Consumption By Month vs. Pipeline Take-Away Capacity (MMcfd - millions of standard cubic feet per day).

Table SR-2.3. State-wide Peak Day Demand Deficit Relative to Intrastate Pipeline Take-Away Capacity.

Date	**Pipeline Capacity**	**- Demand =**	**Deficit**
	(Bcfd)		
Recorded			
August 13, 2012	7.5	7.8	-0.3
September 10, 2015	7.5	7.8	-0.3
December 9, 2013	7.5	11.1[1]	-3.6
December 19, 2012	7.5	9.4	-1.9
Forecast			
Cold Temperature Dry Hydro Year (Average Day)	7.5	6.0	surplus
Winter Peak Day 2020 PG&E 1-in-10 for core and non-core SoCalGas 1-in-10 for non core and 1-in-35 for core Direct serve load	7.5	10.2	-2.7
Winter Peak Day 2020 PG&E 1-in-90 core and 1-in-10 for non core SoCalGas 1-in-35 for core and 1-in-10 for non core Direct serve load	7.5	11.8	-4.3
Summer 1-in-10 Peak Day 2020 + Direct Serve	7.5	6.4	surplus

[1] *Of this, 4,836 MMcfd occurred on the PG&E system (see Pipe Ranger archives for date) and 5,011 MMcfd on SoCalGas (see Envoy archives for date). This leaves 1,310 MMcfd of direct-served load to reach the 11,157 MMcfd statewide total shown.*

Even if the interstate pipelines were providing full capacity supply to the California state line (which cannot be guaranteed), California has no way to get that gas from the state line to the State's gas consumers without using in-state gas storage. For example, meeting the demand for a 1-in-90-year cold snap results in a peak-day pipeline capacity deficit of 4.3 Bcfd relative to the pipeline take-away capacity. The actual delivery deficit may be worse than the simple pipeline capacity deficit, because other local constraints may exist in the gas system.

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 in 2020.

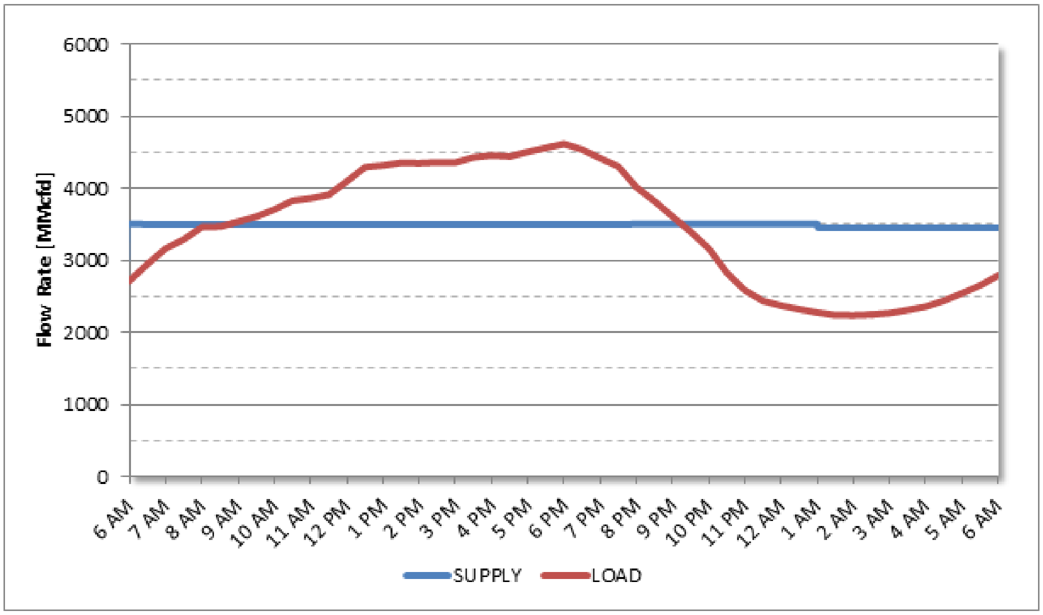
> **Conclusion 2.3:** California does not have enough intrastate pipeline take-away capacity to meet forecasted peak winter demand. Currently, winter peak load of 11.8 Bcfd can only be met reliably if storage can deliver 4.3 Bcfd.

Together, the utilities have 4.8 Bcfd of gas withdrawal capacity from California's underground gas storage facilities (including Aliso Canyon before the leak). This exceeds the 4.3 Bcfd shortfall difference between winter peak day demand and intrastate pipeline capacity by 0.5 Bcfd per day (assuming no gas system outages).

Daily and Hourly Balancing

Underground gas storage also facilitates daily and hourly balancing as shown in Figure SR-2.4. The utilities use gas from storage to remedy the hourly mismatch between receipts of gas into its system and demand from customers. SoCalGas must either pull from storage or curtail load when demand outstrips supply and system operating pressures fall below acceptable levels. Average daily scheduling of gas delivery generally works because the gas company covers the hourly mismatch between flat deliveries and variable usage. Electric generation load causes the change in gas load shown in Figure SR-2.4 in the hours between 12 noon through 7 p.m. Since gas-powered electricity generation has to schedule the same quantity of gas delivery each hour, a mismatch between planned delivery and actual demand.

PG&E and SoCalGas reserve some of their storage capability explicitly for balancing. PG&E reserves 75 million standard cubic feet per day (MMcfd) of injection and withdrawal, and up to 4 Bcf of inventory capacity to balance its system. SoCalGas reserves 8.0 Bcf of storage inventory capacity, 200 MMcfd of storage injection capacity, and 525 MMcfd of storage withdrawal capacity to balance its system.



Source: Aliso Canyon 2016 Summer Technical Assessment
Figure SR-2.4. Supply Receipts and Total Load by Hour for SoCalGas September 9, 2015.

Even on days when natural gas capacity appears to be adequate, demand can outstrip supply for a few hours. Gas utilities can remedy the imbalance using gas from underground storage. Gas-powered electricity generation often causes these imbalances, because its demand varies inconsistently and often unpredictably relative to the hourly flow rate of pipelines.

> **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.

Upstream Outages and Emergency Response

Extreme cold weather can pose a threat to gas supply coming into California, and extreme hot weather can lead to wildfires, which can disrupt high-voltage electricity transmission lines. Gas drawn from underground storage ameliorates both of these potential emergencies.

Gas storage provides California with a reserve, or stockpile, should one of the interstate gas pipelines fail or should weather to the east cause a reduction in gas supply available through the pipelines. Weather events, such as unusually cold weather leading to wellhead and gathering line freeze-offs, can and have disrupted supplies flowing in on the interstate pipelines. These same unusually cold events concurrently create much higher gas demand in California and in states to the east, which further reduces gas supplies available to California from the interstate pipelines. Prior cold weather events have resulted in curtailing more than 100,000 gas customers in Texas, New Mexico, Arizona, and San Diego. For example, in 1989, even with gas from storage, the drop in interstate deliveries to California caused SoCalGas to curtail service to 59 non-core (including electric generation) customers; San Diego Gas and Electric (SDG&E) curtailed nearly all non-core load.

California wildfires increasingly present concerns for electricity balancing authorities, a trend that may exacerbate with climate change. Fires create the risk of either burning a major high-voltage, aboveground transmission line or de-energizing it for a period of time. The Blue Cut fire on August 16, 2016, is an example of an event that caused additional gas supply to be called upon to support electric reliability. Operating data from SoCalGas shows that gas was withdrawn from underground gas storage to provide alternative electric generation.

Underground gas storage protects California from outages caused by extreme events, notably extreme cold weather, which 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.

Seasonal Price Arbitrage

Underground gas storage allows seasonal price arbitrage to California gas consumers whenever winter prices are higher than summer prices. Summer natural gas prices, however, are not always lower than winter prices, with the result that the arbitrage allowed by gas storage does not always work out in favor of consumers. Arbitrage was more successful when California first added underground storage, which was before the U.S. moved to competitive natural gas markets with prices set in monthly and daily markets.

To the extent that gas can be injected when prices are low and withdrawn when prices are high, storage becomes a physical hedge against those higher prices (for price arbitrage). “Slow-turn” storage, i.e., storage which can cycle once per year, is good for this type of summer versus winter price arbitrage. The average net result for the five-year period of 2012 through 2016 is a small gain for consumers of ~ $4.8 million.

Recently, flatter prices have reduced the value of using gas storage for seasonal arbitrage, because the risk of price volatility is lower. Also, hedging does not necessarily require physical storage because financial contracts can be purchased that lock in winter prices ahead of time.

> **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.

Market Liquidity

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 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.

Summary of the Uses of Underground Gas Storage in California

Underground gas storage helps California to meet the winter demand for gas and provides a vehicle for intraday balancing of supply and demand, which has become of critical value as intermittent renewable electricity generation has become more important. Although demand varies by season, available pipeline capacity and relatively constant gas production limit gas deliveries. Storage allows gas imported during the summer to be used when demand is higher during the winter, and to meet demand on individual winter peak days when demand exceeds the pipeline capacity. Storage also creates a way to stockpile supplies inside the State should interstate pipelines fail or should weather to the east of California cause interruptions in either natural gas production or higher demand. Storage allows daily gas-balancing service and allows physical price arbitrage, by storing gas when prices are low to use later when prices are high. Storage also gives buyers and sellers an extra “sink” or “source” to make the market more fluid.

> **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.

The findings and conclusions drawn above about the need for underground gas storage in California are based on a general understanding of how the system works today. A number of physical, market, and policy changes might reduce or eliminate the need for underground gas storage in California. Understanding the utility of these proposals will require a much more detailed understanding of how the system works and what role each of these facilities plays. Closure of underground gas storage facilities could be considered on a case-by-case basis rather than an all-or-nothing basis. The State's energy system may adapt easily to the closure of some underground storage facilities, but have an extremely difficult time providing reliable energy without others. Understanding the importance of any given facility and the evaluation of proposals to reduce dependence on underground gas storage requires detailed modeling of the flow of gas through the pipelines (i.e., hydraulic modeling). An example of such a model was constructed for this study (see Appendix K of the Summary Report).

The role of gas storage may be changing as markets and policies evolve, including price changes, demand changes, and generation changes. More renewables on the grid can require a greater use of gas-fired generation to back up renewables. The need for load following and other ancillary services, although likely, was not captured in forecasts for gas demand, and these forecasts do not report on or address hourly gas load. Utilities have no published estimates of the impact of significant changes on their gas systems and use patterns by generators.

Additional renewables will reduce the aggregate need for burning gas in power plants. The remaining use, however, may be "peakier" or more variable. Sudden increases in net electricity demand occur, for example, when people get home in the late afternoon and begin to consume electricity just as solar production begins to wane. This gap between supply and demand might require backup with gas-fired generation. The gas system was not configured to support large increases such as sudden use in the afternoon. Currently, the system accommodates sudden increases either serendipitously or because storage has been available, and the utility has sufficient control to allow it to make up the imbalance created on its system when the gas generator comes online.

> **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.
>
> **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.

ALTERNATIVES TO UNDERGROUND GAS STORAGE THROUGH 2020

Of the seven uses for underground gas storage in California, the magnitude of gas required to meet winter demand and winter daily peak demand dominates. Any viable replacement in the 2020 timeframe would have to demonstrate that it could effectively match supply to demand in the winter.

Many, but not all, of the alternatives reviewed in this study come from suggestions in the Joint Agency reliability action plans or public comment. Virtually no detailed studies are available in the public domain looking at options to replace any aspect of underground gas storage, and the analysis done for this report is necessarily limited. Even so, we find that these alternatives cannot address the overarching need to use stored gas to meet winter demand (or balance the gas system on an intraday basis) by 2020, either because they provide insufficient relief, impose extraordinary cost, or take too long to construct.

Pipeline Capacity

We found only two options that could possibly replace the function of underground gas storage facilities and maintain energy reliability in the 2020 timeframe: (1) make supply volumes more flexible by building more pipeline capacity into and within the State or (2) replace underground gas storage with above-ground gas storage units or LNG peak shavers.

California's intrastate capacity is too small to meet winter demand without gas from storage, while its interstate capacity would fall short in meeting the full requirements of a winter peak day. So, from an engineering perspective, the most straightforward solution to eliminating underground gas storage would involve building out the existing pipeline systems. Currently, State pipelines can move 7.5 Bcfd in the State. Meeting the planning level for winter demand would require building 4.3 Bcfd of new intrastate pipeline capacity. Replacing storage would entail expanding existing pipelines and building as many as four additional pipelines and associated compressor stations. However, the peak winter day demand is 11.8 Bcfd, and the interstate pipelines are only capable of delivering 10.6 Bcfd. The State would also need additional interstate pipeline capacity of approximately 1.2 Bcf.

California may find it difficult to reach agreement on, gain commitments to, and get approvals for this magnitude of pipeline capacity by 2020. However, gas demand is forecasted to decline due to increasing amounts of renewable energy on the grid. If in fact demand declines, the needed expansion quantity would be smaller, and California could possibly build adequate additional pipelines by 2025—based on recent pipeline construction costs, estimated at close to a $15 billion capital cost to add 4.3 Bcfd of large-diameter intrastate pipeline capacity and one new interstate pipeline. Customers would be paying for the entire capacity year-round, but only use it part of the year.

The option of building more pipeline capacity effectively shifts the obligation to meet peak demand from inside California to producers outside California. We may build the pipeline capacity, but California would have to rely on how the gas market responds to the new capacity. More interstate capacity will only be built and financed if producers or customers contract for the capacity. Pipelines also present their own set of risks, environmental and otherwise.

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

> **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.

LNG Peak Shaving

Another option is to build liquefied natural gas (LNG) peak shaving units and store the liquefied gas in tanks located aboveground. Close to 100 of these facilities exist in the U.S. today, with the one nearest to California being in Lovelock, Nevada. These units provide aboveground gas storage: they take pipeline gas that exceeds requirements in low demand seasons, convert it into LNG and store it in a large tank, then reheat it and inject it back into the pipeline when needed to meet demand.

Three recent projects illustrate what such facilities might cost California; their costs and capabilities range widely. The simple average of these projects' capital cost per MMcfd of sendout, is $2.25 million. Replacing 4.3 Bcfd of underground gas storage with aboveground LNG peak shavers works out to a capital investment of about $10 billion. This capital investment would ostensibly be recovered through rates over time from customers deemed to benefit from the facility.

Liquefaction (chilling) of pipeline gas requires energy, as does vaporizing (reheating) it back to its gaseous state. This energy use would produce GHG emissions and potentially criteria pollutants. Siting and land requirements would pose obstacles, depending on the sites selected. Storing LNG poses safety concerns. A blast in 2014 at a Williams Partners facility in Plymouth, Washington (located along The Williams Companies' Northwest Pipeline), injured five people and caused $46 million in damage.

> **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.

Intermodal containers designed to specifications approved by the International Organization of Standardization (ISO) can deliver liquid natural gas (LNG) to remote customers. A 50 MW gas fired electric generator would require 500 containers to supply natural gas to generate electricity for one hour (50 MWh (megawatt hours)).

> **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.

CNG in a Box

Compressed gas (which is different from liquefied gas) stored in containers, such as the GE version trademarked as "CNG In A Box™", could provide storage service. Replacing the full 4.3 Bcfd pipeline capacity deficit California would face absent underground gas storage would require close to 8,000 boxes, and would only deliver for one day before needing a day to compress again. They could not cover the multiple days of gas from storage often needed in the winter.

> **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.

LNG via Ocean Terminal

One other approach that could marginally impact the amount of underground gas storage required, but not replace it, would be for San Diego Gas and Electric (SDG&E) to import LNG from Sempra's LNG terminal in Mexico. This would displace interstate gas going to SDG&E and allow more flowing supply to continue on into the Los Angeles Basin, thereby augmenting SoCalGas' operational flexibility. This represents a likely net cost increase over pipeline-delivered natural gas of $1.5 billion over five years, and could add 0.3 Bcfd of supply. We found no regulatory impediments to this option beyond SoCalGas and SDG&E needing permission from the CPUC and a determination of allocation for additional costs.

Using LNG to supply SDG&E would leave flowing pipeline supply available for Los Angeles rather than using gas from storage. This solution could be implemented as soon as the CPUC orders it and LNG cargoes are procured. This option is the only option that can be implemented immediately, without constructing new facilities. Purchasing LNG to meet SDG&E's average gas requirement of 300 billion Btu per day (0.3 Bcfd) would result in an incremental cost of $332 million per year. This appears to be less costly than adding an equivalent amount of new intrastate pipeline capacity. Although the load in San Diego that can be served from the Costa Azul LNG terminal is not necessarily as large as the quantity of gas SoCalGas might withdraw from Aliso Canyon, serving San Diego from Costa Azul can at least offset some of the need for gas from underground storage.

> **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.

Another idea would be to replace natural gas with renewable natural gas or use off-peak or stranded power to produce gaseous fuel. Methane gas, or CH_4, can in fact be produced via a number of methods from a variety of sources. Biogas is called "renewable" when it is produced from the natural decomposition of organic matter in landfills, livestock manure, and wastewater treatment plants. Once processed to remove impurities and meet existing pipeline standards, it can be injected into the utilities' natural gas pipeline systems. The CPUC refers to it as "biomethane."

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.

Changes to the Electricity System

Options that would reduce the gas used for electricity generation include bringing in electricity through new transmission lines, storing electrical energy (instead of chemical energy stored in gas) to meet peak demand, or reducing the demand through energy efficiency and demand side management approaches. None of these would significantly help to meet the winter peak demand in the 2020 timeframe, but could alleviate the use of gas storage in the summer.

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.

Statewide gas import capacity is limited to 7.5 Bcfd. Monthly-average gas demand for electric generation in winter months is ~2 Bcfd. The highest recorded total gas demand in the recent five-year period was about 11.1 Bcfd (December 9, 2013), very close to the planning 1-in-90 year probability event benchmark of 11.8 Bcfd. Curtailing electric generation in favor of core customers, even if this were advisable, would be insufficient to meet peak winter demand. Curtailing all electricity generation from gas-fired power plants would subtract about 2 Bcfd of demand from this day, but this is still well above the State's maximum import capacity; e.g., gas storage would still be required.

> **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.

Although changes to the electricity system in the 2020 timeframe will not obviate the need for gas storage in winter, electricity, primarily used for air-conditioning, drives the summer peak in gas demand. Consequently, modifications that would result in lower gas-fired electricity demand would affect the need for gas storage in the summer.

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 low end of current cost estimates (~$400/kWh (kilowatt hour)). Even if costs fall an additional 75%, the cost would be $44 billion to offset the summer peak demand for electricity, but would still leave the question of how to meet the winter peak unresolved.

Energy efficiency measures including the committed savings for natural gas, combined with the reductions expected from the Additional Achievable Energy Efficiency estimates and the doubling required under SB 350, appear to total less than 0.4 Bcfd, if all of the electric-side savings reduce the need for gas-fired generation. If achieved every day, this could free up 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 on exactly which measures are adopted, what technologies are affected, and what the hourly use pattern changes are.

The demand response potential appears large enough to offset a significant 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.

These potential alternatives would not necessarily reduce the need for the intraday balancing that is especially important to electric reliability (and also used by other customers and their suppliers). Some on-site storage at electricity generation facilities would likely be required to replace intraday use of utility-scale gas storage, increasing total cost and risk near those facilities.

Summary of Technical Approaches to Replacing Underground Gas Storage

A summary review of options for replacing underground gas storage in California is given in Table SR-2.4, followed by more detailed discussion of each option.

Table SR-2.4. *Supply and Demand Options to Replace Gas Storage for the Existing Gas System in the 2020 Timeframe.*

Physical Alternatives to Storage	Rough Cost Estimate ($2017)	Summary Comments
Alternatives that could completely offset the need for 4.3 Bcfd gas storage in winter		
New Intrastate Pipeline Capacity	~$15 Billion	• Not achievable by 2020 • Maybe one or two pipelines by 2025 • As peak demand declines the additional pipeline capacity required would also decline • Addresses winter needs but probably not intraday needs • May pose siting issues to reach load centers • Requires environmental review and mitigation
Liquid Natural Gas (LNG) Peak Shavers	~$10 Billion	• Depending on size, could require 4 to 10 units • Unclear effectiveness to load follow during the gas day • Conversion from gas to LNG and back requires energy that would increase GHG and criteria pollutant emissions • Poses siting and safety concerns.
Alternatives that could reduce the need for gas storage somewhat		
LNG Via Costa Azul Ocean Terminal	$332 million per year incremental cost to purchase 315 MMcfd of LNG	• Use of Sempra's Costa Azul to serve SDG&E (an average of 315 MMcfd) appears immediately feasible • Would allow pipeline supply to serve LA, reducing need to pull gas from storage for LA. • Not clear if reduction in withdrawals from storage in LA is 1:1 with gas demand on all days but at least 200 MMcfd (~5%) seems reasonable to consistently expect • Increases GHG and criteria pollutant emissions from LNG transport and vaporization
Alternatives that will have little impact on winter gas storage requirements		

Physical Alternatives to Storage	Rough Cost Estimate ($2017)	Summary Comments
Containerized LNG	Infrastructure cost of $13 million for 1 Bcf per year plus 440 containers.	• Not utility-scale (10 Containers per MW) but may have limited application for intraday balancing at power plants • Poses additional siting and safety risks plus emissions with conversion from gas to LNG and vice versa
Compressed Natural Gas (CNG) in a Box	$600,000 for ~2 MMcfd, so 500 MMcfd (for example) amounts to $150 million (excludes pipeline interconnection costs). A total of 8000 containers would cost $4.8 billion.	• Not utility-scale but may have limited application for intraday balancing at power plants • Requires many containers and poses additional siting and safety risks • Takes a whole day to compress and fill a container
New Electric Transmission Capacity to Reduce Electricity Generation (EG) Gas Use	Transmission that could deliver 15 GW of electricity is estimated to cost $6.6 Billion	• 15,100 MW is equivalent to 800 MMcfd or 27.5% of the 2.9 Bcf needed on an average gas summer peak day, so this transmission doesn't offset entire summer peak demand • Would not address the winter peak because winter peak is caused by burning gas for heat • Wouldn't address intraday gas balancing need
Electricity Storage	The cost of a four-hour lithium ion energy storage installation estimated to be between $417 and $949/kWh, or $167-380 million for a 100 MW, 400 MWh system	• Can address intraday balancing with 4- and 8- hour storage, but cannot address winter gas requirements
Diesel Fuel	Assuming CARB-standard diesel @$3.00 per gallon and 7.2 gallons per MMBtu = $21.6 per MMBtu *million British thermal units (MMBtu)	• Not desirable for AQ reasons and would need to reinstall handling and on-site storage equipment largely removed in 1990s • Amber 360 is "cleaner" but even if enough were produced and available, need to address the generator warranty void
Renewable Natural Gas and Power-to-Gas	~$30 million to process about 100 MMcfd to pipeline quality plus up to $3 million per interconnection. Hydrogen Business Council says P2G would be 2.5X current natural gas price by 2030.	• Not available at scale by 2020 and production profile does not help solve gas storage problem

Physical Alternatives to Storage	Rough Cost Estimate ($2017)	Summary Comments
Energy Efficiency (EE) and Demand Response (DR)	EE is required under statute so will be a sunk cost.	• EE is already in the demand forecast • A gross read of the SB 350 requirement to double EE by 2030 (suggested by gas utilities) implies an additional reduction of 156 MMcfd ignoring cost-effectiveness • Additional potential electricity DR could reduce the need for intraday balancing • Implementation would require examination of how often that DR could be used • DR used to curtail electric generation (EG) in favor of core customers would be insufficient to meet peak winter demand • Statewide gas import capacity is limited to 7,511 MMcfd. Monthly-average gas demand for EG in winter months is ~2,000 MMcfd • The highest recorded total gas demand (EG + non-EG) in the recent five-year period was 11,157 MMcfd (December 9, 2013) • Curtailing all EG would subtract 2,200 MMcfd of demand from this day, but this is still well above the State's maximum import capacity - e.g., gas storage would still be required

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.

REGULATORY AND OPERATIONAL OPTIONS FOR REDUCING THE NEED FOR UNDERGROUND GAS STORAGE

Table SR-2.5 lists eight regulatory, operational, and market changes that might reduce the need for underground gas storage in California. Given that Aliso Canyon's usage was reduced after the 2015 loss-of-containment, several of these changes are already being implemented.

Table SR-2.5. Operational and Market Alternatives to Underground Gas Storage.

Operational and Market Alternatives to Storage	**Summary Comments**
Tighter Balancing Rules	• Sempra has moved to 8% balancing. • Can reduce to 5% balancing on a daily basis when needed. • These changes have reduced need to use gas storage by 0.15 Bcfd.
Balancing Core to Actual Load Instead of Forecast	• Sempra filed proposal in September 2017 as required (CPUC review pending). • Could reduce use of storage for difference between actual load and forecast.
Greater Use of Linepack (the ability to store gas by compressing it into the pipelines)	• Raises safety concerns as Sempra has very little linepack. • They can only store about ~0.13 Bcfd by compressing gas in their pipelines. • They strive to get their system back into balance before the start of each gas day. • PG&E has ~0.4 Bcfd of linepack and already uses what it has. • If new intrastate pipeline capacity were added, linepack capability might increase by 50%.
Closer Gas-Electric Coordination	• Unprecedented levels of coordination implemented after the Aliso event means further gains will be more difficult. • There could be benefits from formalizing joint reliability planning.
Advance Notice on Expected Burn and Day-Ahead Limits on Gas Burn	• Both electricity balancing authorities are doing this now for southern California. • Advance notice aids generators in complying with tighter gas balancing. • When gas burn is limited, it creates uneconomic dispatch. • No studies available on feasibility for northern California or that calculate minimum EG gas burn needed to prevent blackouts.
Shifting Generation to Out-of-Area	• When available, shifting to other generators outside a constrained gas area can avoid the need to pull gas from storage. • However, higher electricity prices will result from uneconomic dispatch. • No studies are available on feasibility for northern California or that calculate minimum electricity generation gas supply needed to prevent blackouts.

Operational and Market Alternatives to Storage	**Summary Comments**
Shaped Nominations and Hourly Gas Market	• Hourly natural gas prices would require industry-wide acceptance. • Could potentially send price signals to reduce gas consumption during peak hours or hours when storage would have provided balancing service. • Shaped nominations would require the support of some storage or available linepack.
Weekend Natural Gas Market and Nominations	• Requires industry-wide acceptance. • Prior discussions of this concept were not fruitful. • Could help all customers and shippers (but especially electricity generation) by eliminating the Friday nomination for Sat/Sun/Monday. • Would allow more realistic opportunity with balancing loads on weekends.

Utilities and pipeline companies already use the linepack (the ability to store gas by compressing it into the pipelines) they have available. Using linepack 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.

Opportunities to shift to out-of-area generation on gas-challenged days are limited and not reliable. The technical assessments for 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. 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.

> **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.

Given that there are no alternatives that will obviate the need for storage in the 2020 timeframe, it seems likely that the State will continue to operate at least some of these facilities. Operation of these facilities provides for energy reliability, so safe operations will remain critical.

THE EFFECTS OF DOGGR REGULATIONS ON GAS STORAGE OPERATIONS

DOGGR rules will require all underground storage wells to have multiple barriers to failure. Specifically, all wells will be fitted with tubing liners and packers or seals that isolate segments of the wells from each other, which will eliminate the possibility of a single-point failure causing a blow-out disaster such as occurred at the Aliso Canyon facility. This requirement means that, in many cases, gas will be injected and withdrawn through smaller-diameter tubing than previously used. Storage providers estimate that this will reduce existing gas storage injection and withdrawal capacity by 30 to 40 percent, depending on the provider. Forty percent of just the current utility-owned maximum withdrawal capacity of 4.8 Bcf implies a new maximum withdrawal capability of 2.9 Bcf, which is less than the 4.3 Bcf needed to serve all gas demand on a winter peak day.

> **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.

PG&E and SoCalGas spent an average of $500,000 per Bcf of cycling capability in 2015 on operations and maintenance 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 (operating and maintenance) expense and capital expenditure has been sufficient to maintain the facilities. Furthermore, we could not determine 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 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?

BACKGROUND

California leads the nation in developing policies to address climate change. Perhaps the most fundamental of these policies requires that California reach greenhouse gas (GHG) emission goals in 2020, 2030, and 2050. Based on AB 32, California is required to reduce GHG emissions to 1990 levels by 2020. SB 32 requires California to further reduce its GHG emissions to 40% below the 1990 level by 2030. Finally, Governor Schwarzenegger's Executive Order E-3-05, and Governor Brown's Executive Order B-30-15, both require the State to reduce GHG emissions to 80% below the 1990 level by 2050. These policies codify energy system *goals*.

California also has a number of complementary climate policies that encourage renewable electricity, as well as energy efficiency, electricity storage, emissions limits from long-term power purchase agreements, biofuels, increases in electric or hydrogen fueled transport, and decreases in short-lived climate pollutants (SLCPs) (such as methane). These policies codify specific *means* to move towards the energy system goals. California also has a cap-and-trade program to provide an economically efficient framework for reaching emission targets.

However, none of these policies specifies the end-state energy system that would reliably meet California's energy needs as well as the emission goals. Maintaining the reliability that people count on for well-being and the economy will become increasingly challenging with increasingly aggressive emission goals. Natural gas currently provides the primary method for backing up renewable energy in California. If this does not change (or cannot change), natural gas could remain an important part of the State's energy system for some time. On the other hand, it may be possible to reduce or even eliminate the need for natural gas, and therefore the need for gas storage, with a combination of technical advances, efficiency mandates, and regionalization. California needs to vet these alternative ideas for maintaining reliability. Until another option can be demonstrated to work, gas cannot be ruled out as part of a future energy system that has extensive intermittency.

Climate regulation could cause the use of gas to increase or decrease. For example, more intermittent renewable electricity might replace gas that we use for electricity generation. But even if we use less gas overall, the peak use of gas could increase. More intermittent electricity could mean that gas storage requirements will increase in order to provide reliable ("firm") electricity generation when intermittent electricity output (primarily wind and solar photovoltaic (PV) is low. Energy storage devices such as batteries or pumped hydroelectric storage can help with this problem, but decreased solar PV and wind output lasting between days and months as a result of weather events and/or seasonal patterns, or increasingly frequent wildfires that disrupt transmission, might increase the need for underground gas storage.

Understanding the net impact of changes designed to meet the climate goals on underground gas storage requires information about the time of gas use during the day (diurnal variation), but also how the demand for gas might vary on multiday to seasonal timescales, as well as other emergency issues that can affect electric reliability.

Studies that explore options for meeting California's climate goals provide some information relative to the future need for underground gas storage. These mirror the two types of climate policies the State currently has. One kind of study projects the impacts of specific *means* policies designed to move California towards the climate goals. For example, studies that project the time of use of electricity in 2030 do not assess the energy system as a whole, or even the entire gas sector. A California Energy Commission (CEC) study estimates hourly gas demand over the entire year that results from implementation of California's energy efficiency and electrification policies, but it only estimates gas use for electricity, and does not include any extensive assessment of renewable variability.

A second type of study develops alternative energy system scenarios that meet the overall climate policy *goals*. These studies provide ranges for the amount of possible gas use in the future, constrained by having an energy system that, overall, meets climate goals. They do not, however, generally include information about the time of use of gas, nor factor in seasonal variation in either renewable electricity output or gas use. This assessment of the need for underground gas storage in 2030 and 2050 was limited to making inferences from scenario studies that provide little information about time of use within a year.

We found no 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 timescale from seconds to years.

> **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.

Based on our review of the literature, scenarios that meet California's 2050 climate goal all contain significant increases relative to today in several elements of the energy system, including:

- Increased energy efficiency in all sectors, somewhat moderating demand increases from population and economic growth, as well as the magnitude of some demand peaks
- Increased transportation electrification (portions of light- and heavy-duty vehicles)
- Increased renewable electricity generation (primarily wind and solar)
- Increased electricity storage and flexible electric loads

In addition, some scenarios employ significant implementation of:

- Fossil fuel with CO_2 capture and storage (CCS) in electricity generation (and to a limited extent, industrial facilities)
- Flexible, non-fossil electricity generation: nuclear, geothermal, biomass with or without CCS, marine/hydrokinetic technologies, solar thermal with storage, etc.
- Building electrification in residential, commercial, and possibly industrial sectors
- Low-carbon gas production: biomethane, synthetic natural gas (SNG), and/or hydrogen blended in pipelines[1]
- Pure hydrogen production, used in vehicles and possibly other sectors
- Power-to-gas (P2G): load-balancing technology that converts excess electricity into hydrogen and/or methane, typically for direct pipeline injection

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[1] Here, "low-carbon" refers to net GHG emissions, not just the emissions encountered when the gas is burned. Both biomethane and SNG, while chemically identical to natural gas-derived methane, have the potential to be much lower in net GHG emissions than natural gas, though for both SNG and hydrogen, the source of CO_2 can make a critical difference to net emissions.

- Increased regional electricity transmission capacity to allow more imports of out-of-state resources (particularly renewables) to help smooth supply-demand imbalances. California policy counts the GHG emissions from out-of-state generation in its GHG inventory, so high-GHG generation resources would have to be used very sparingly.

While many of these elements play prominent roles in 2050 in most scenarios, they are more subdued or not even present in 2030 scenarios. As a result, the scenarios we examined did not start to diverge significantly in terms of their potential impact on underground gas storage until after 2030.

The need for gas storage depends mostly on the needs for balancing both total and peak demand in the winter as well as daily balancing. We assessed how balancing needs might change in the future as a result of climate policies. The use of gas storage to respond to emergencies, especially extreme weather events or wildfires, could remain or even become more important as climate change causes more extreme weather and exacerbates the occurrence of wildfires. The need for gas storage to address loss of power due to wildfires will likely remain important past 2020, but this need will likely be insensitive to California climate policies. We found no reason to expect arbitrage issues to change as a result of climate policies, so we did not consider these two issues in evaluating the possible changes in the need for underground gas storage in the future.

In the winter, cold weather has generated peak demand for heating fuel that frequently exceeds the capacity of the pipeline to deliver adequate gas supply. At these times, utilities are able to draw from storage and get customers the heating fuel they need. Intraday electricity supply-demand balancing is largely handled today with gas generation, and balancing issues may become exacerbated by increasing the percentage of intermittent renewable energy on the grid.

Subsecond (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.

Most forms of energy storage as currently conceived will probably be inadequate for managing daily peak demand that can occur over multiple days, or for managing seasonal demand imbalances. However these technologies could help with shorter time-scale imbalances.

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

Production of either hydrogen or methane would utilize excess power when supply exceeds demand. This is called “Power to Gas” or P2G (see Appendix 3.2 in Chapter 3). However, while P2G allows more use of low-GHG generation technologies to avoid burning as much natural gas, it still produces gases that must be transported and stored.

> **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.

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. Together with summer increases in electricity demand and decreases in transmission capacity under climate change, 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.

DEMAND FOR UNDERGROUND GAS STORAGE IN 2030

Energy system scenarios pertinent to 2030 (described in Chapter 3) differ only modestly from the current conditions. The variation in total annual demand for natural gas in 2030 ranged from between 78% and 100% of current levels in the six GHGcompliant studies we reviewed.

Among the scenarios for 2030, 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.

> **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.

Gas use for electricity generation is currently highest during summer months, roughly July-October (Figure SR-3.1). Both wind and solar output are much greater in summer months, though output peaks in June in both cases. 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.

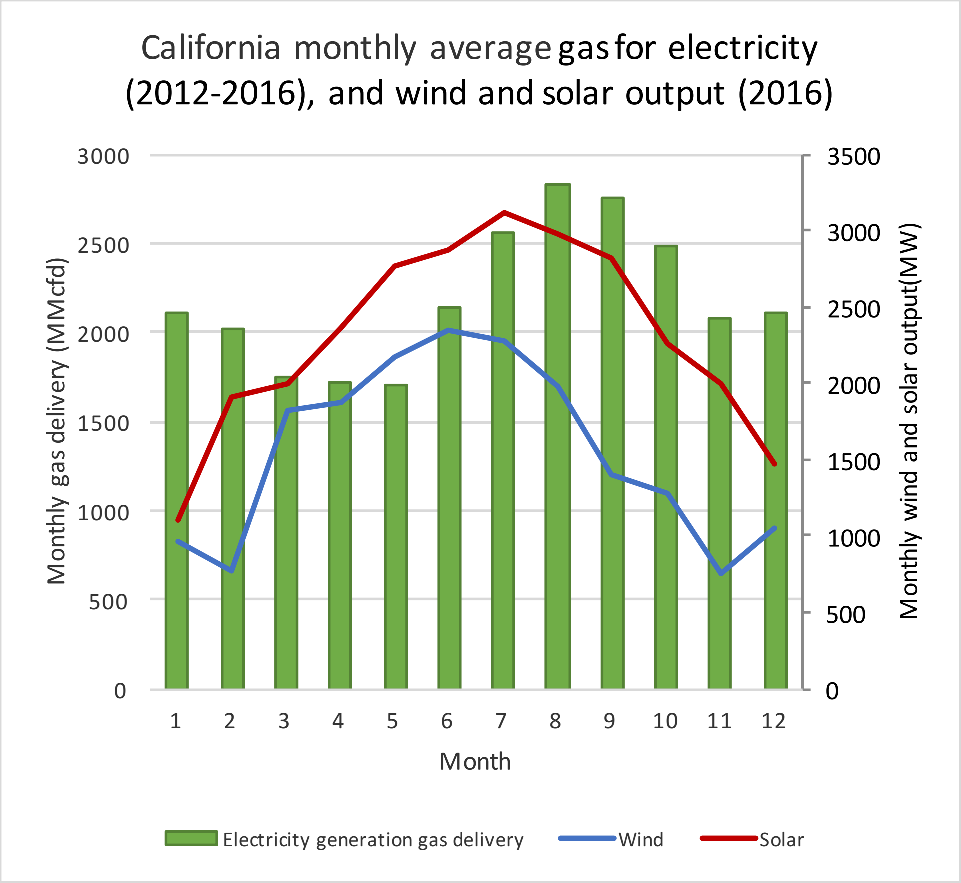


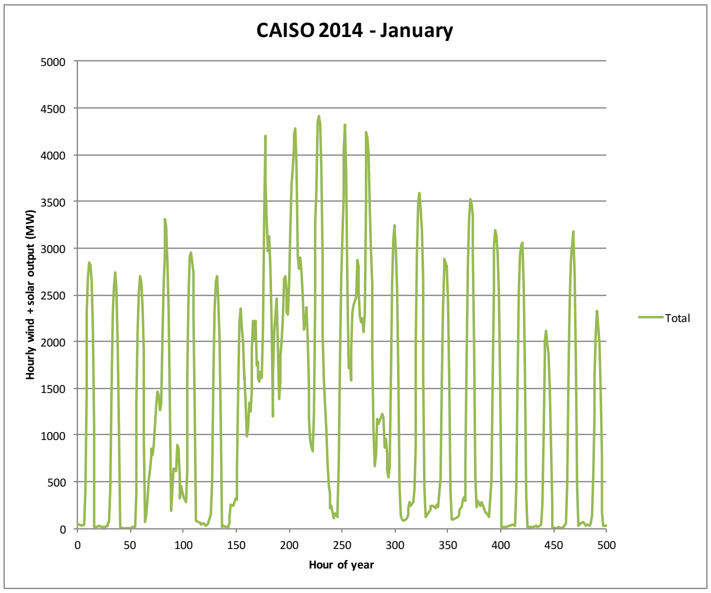
Figure SR-3.1. California average monthly gas demand for electricity (2012-2016), and statewide wind and solar output for 2016.

> **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.

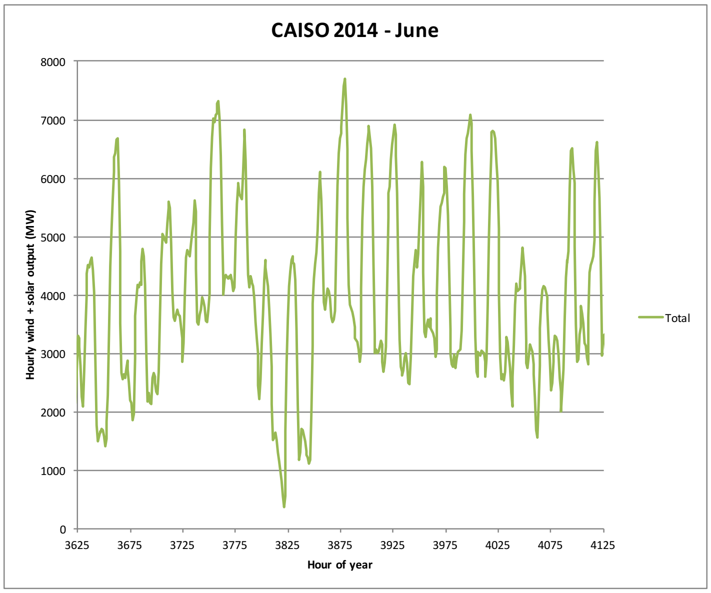
CEC projections based on State policies indicate that overall demand for natural gas will decrease in both summer and winter, allowing for increased flexibility for natural gas injection into storage. However, projections also indicate that the requirement for natural gas ramping capability will increase on a daily basis 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.

As California increases the amount of intermittent solar and wind power on the grid, the need for backing up this power will increase. Figure SR-3.2 shows the combined output of solar and wind power in the State for January and June (2014 reference case).



(a)



(b)

Figure SR-3.2. Combined wind and solar output for (a) January and (b) June 2014.

In January, particularly at night when solar PV is not operating and the wind dies down, the combined output of wind and solar can regularly drop to nearly zero. 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, they have called such periods *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.

Whereas wind generation capacity has not increased since 2014 at ~4.9 GW (gigawatt)(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 SR-3.2 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.

To mitigate expected generation variability, 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. See Figure SR-3.3.

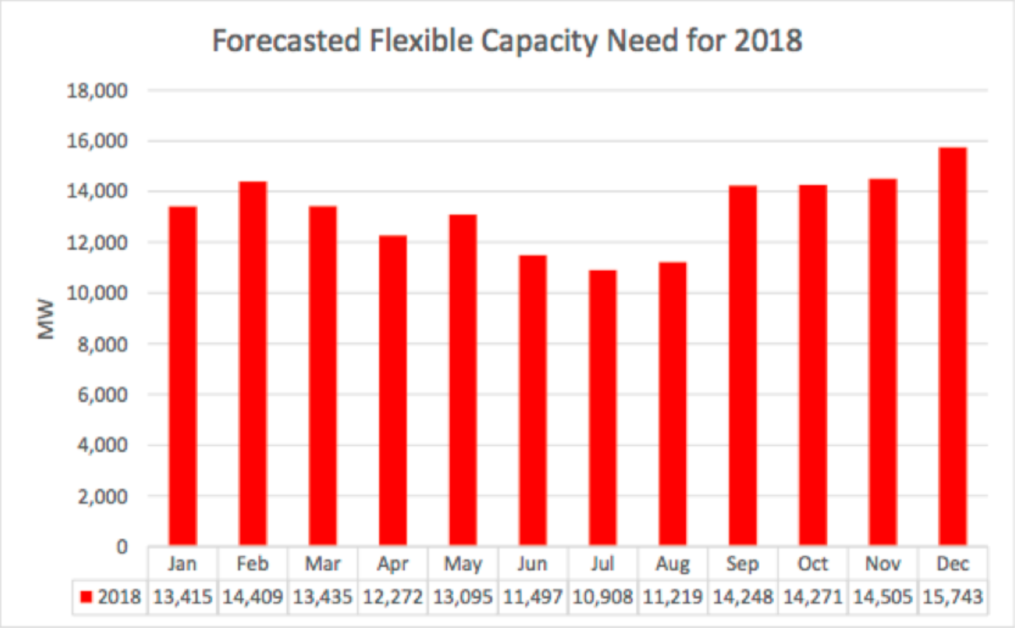


Figure SR-3.3. Forecasted flexible generation needed to balance CAISO intermittent renewables in 2018.

A model of California's electricity system in 2030 under a 50% GHG reduction scenario, which assumed 56% renewable electricity generation, found that up to 30 GW of gas generation would be needed to backup these renewables. However, half of this gas generation capacity would be utilized less than ~25% of the time, making capital investments to insure the availability of such gas generation difficult.

The ~30 GW of backup natural gas capacity needed in 2030 translates into ~5 Bcfd. The demand for gas to provide backup for renewable energy comes close to current pipeline capacity of ~7.5 Bcfd.

> **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.

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. This potential peakiness could be nearly as large as today on an hourly or seasonal basis. However, these additional demands on underground gas storage are likely to be small compared with the ~1,000 Bcf that is normally injected into and withdrawn from storage every year.

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.

UNDERGROUND GAS STORAGE DEMAND IN 2050

The ambitious GHG targets of an 80% reduction below the 1990 level by 2050 will require much more dramatic changes to California's energy system than were found for 2030. Scenarios of the energy system in 2050 that meet these climate goals have widely differing estimates of the amount of natural gas in use. Some significantly increased their natural gas demands (to ~150% of the current level), while others remained close to today's level, or significantly decreased them (to ~50% or less of today's level). All scenarios showing natural gas demand significantly increased made heavy use of carbon capture and storage (CCS) technology, allowing for the expansion of natural gas while dramatically reducing associated GHG emissions. Scenarios with the lowest demand for natural gas tended to have significant building electrification, and greatly expanded the use of non-fossil electricity generation (either renewables, nuclear, or both), though these elements were also present in scenarios with higher natural gas demand levels.

The scenarios logically divide as shown in Figure SR-3.4. First, they split into whether or not they use a lot of intermittent electricity generation. Those with less intermittency have to provide low-GHG electricity from either fossil fuel with CCS (A), which increases the use of natural gas, or a combination of non-fossil flexible generation and building electrification (B), which likely decreases natural gas use. If they do use substantial intermittent electricity, then they have to manage the intermittency (C). Some use low-carbon gas (D), which results in a pattern of gas use much like today. All scenarios but (D) also increase building electrification to reduce the use of gas for heating. Pure hydrogen can also be used to some extent to do this.

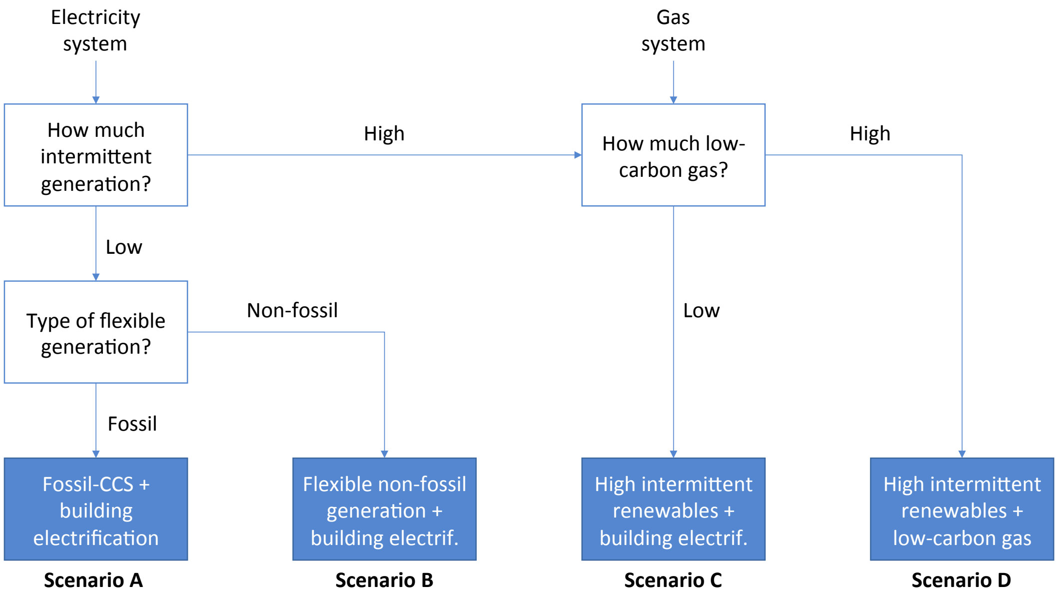


Figure SR-3.4. Logic diagram for 2050 scenario classification.

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.

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.

In general, the feasibility and desirability of different models for reaching 2050 goals and maintaining a reliable supply of energy have not been assessed, especially with regard to their costs, required build-out rates, required management changes, and the certainty of technology availability.

> **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.

OVERARCHING CONCLUSIONS AND RECOMMENDATIONS

> **Conclusion SR-1:** The risks associated with underground gas storage can be managed and, with appropriate regulation and safety management, may become comparable to risks found acceptable in other parts of the California energy system.
>
> **Recommendation SR-1:** The State should ensure timely and thorough implementation of the new DOGGR regulations at each underground gas storage facility, emphasizing risk and safety management plans, quantitative risk assessment studies, risk mitigation and prevention, requirements for well integrity testing and monitoring, human and organizational factors, and a robust and healthy safety culture. To evaluate the effectiveness of the new regulations and the rigor of their application in practice, the State should implement an independent and mandatory review program for the new regulations, should publish the review results in publicly available reports, and should provide an opportunity for public comment.
>
> **Conclusion SR-2:** California's energy system currently needs natural gas and underground gas storage to run reliably. Replacing underground gas storage in the next few decades would require very large expenditures to store or supply natural gas another way, and these investments would bring its own risks. The financial

investment would implicitly obligate the State to the use of natural gas for several decades.

Recommendation SR-2: In making decisions about the future of underground natural gas storage, the State should evaluate tradeoffs between the quantified risks of each facility, the cost of mitigating these risks, and the benefits derived from each gas storage facility- as well as the risks, costs, and benefits associated with alternatives to gas storage at that facility.

Conclusion SR-3: Some possible future energy systems that respond to California's climate policies might require underground gas storage including natural gas, hydrogen, or carbon dioxide, and some potentially would not. California's current energy planning does not include adequate feasibility assessments of the possible future energy system configurations that *both* meet greenhouse gas emission constraints *and* achieve reliability criteria on all timescales, from subhourly to peak daily demand to seasonal supply variation.

Recommendation SR-3: The State should develop a more complete and integrated plan for the future of California's energy system, paying attention to reliability on all timescales in order to understand how the role of natural gas might evolve and what kind of gases (e.g., for natural gas or other forms of methane, hydrogen, or carbon dioxide) may need to be stored in underground storage facilities in the future.

Concluding Remarks

The California Legislature mandated this study in mid-2016, and CCST conducted the study in a eleven-month period ending December 2017. Effectively, the research was conducted over a very short period of about seven months. CCST could not fully investigate many issues raised by the study because of time constraints. In addition, the study predates the availability of some pertinent information, specifically the results of the root-cause analysis of the 2015 Aliso Canyon incident. Because of the need to publish the report by December 2017, several topics will likely require further exploration.

Despite the limitations noted below, we believe that this study provides useful information to aid decision-makers and the public in their assessment of the long-term viability of underground gas storage in California. In particular, the undertaking of effective risk mitigation as an alternative to underground storage facility closure, and the need to understand how a completely de-carbonized energy system is going to provide *reliable* energy, emerge as important elements for decision-making. It is our hope that this study illuminates these topics, provides important information on which additional studies can build, and above all, proves useful in assessing the overall long-term viability for underground gas storage in California.

CCST could not investigate the feasibility and impacts on reliability of closing one or more underground gas storage sites in the State while leaving the others open. For example, the Playa del Rey facility apparently does not store or withdraw a large amount of gas, providing only about 1% of total natural gas storage across California. However, Playa del Rey is close to a densely populated area, and the risk of loss-of-containment at Playa del Rey is higher than most other natural gas storage facilities. Our report questions, but does not answer, the impact of closing this site. The State should commission a cost-benefit analysis including full consideration of risks associated with loss-of-containment from this facility.

We also recommend a detailed research study of how California's natural gas system functioned during the several-month shutdown of Aliso Canyon. Researchers should document where the natural gas came from (e.g., other storage facilities, pipelines, etc.) that otherwise would have been supplied by Aliso Canyon, and what the weather conditions were during this interval that impacted demand in both cold and hot weather, and supply from renewable sources. The conditions over the last two years should be compared to historical conditions and the specific conditions required for reliability planning. Such a study would provide important insight about the utility of Aliso Canyon and data for stakeholders about whether Aliso Canyon should remain open.

The State deserves an assessment of these storage facilities based on the best available data and should strive to improve data transparency and availability for follow-on studies. The Steering Committee and investigators made several requests for data in the course of this assessment. The report findings reflect data we were able to obtain. In a number of cases we requested data and did not receive them. For example, daily injection and withdrawal data would help to assess hazards related to loss of well integrity, but DOGGR has these data available only on a monthly basis. The team also requested facility-specific data on withdrawn gas composition, or in the case of the 2015 Aliso Canyon incident, the composition of the gas escaping from the (SS-25) well blowout. An assessment of human health hazards for populations exposed to gas emitted from underground gas storage facilities requires knowing the composition of the gas, but the team could not obtain this detailed information. Never-the-less, we think this report represents the best scientific assessment of underground gas storage in California that was possible in the timeframe and with the data available. We hope the citizens and policy makers of the State find it useful.

Table SR-2.6. Record of data requests made by CCST.

Record of data requests made by CCST

Subject	**Date of Request**	**Request Made to**	**Results**
Daily injection volumes from underground gas storage operators	5/17/17	DOGGR	No response
Process/protocol/procedures for detection, identification, and characterization of well's casing and tubing integrity-related issues	6/16/17	PG&E (after tour)	Acknowledged request but sent no information
Copy of PG&E's Process Safety Management Process Analysis, Incident Investigation protocol, and Contractor Safety protocol	6/16/17	PG&E (after tour)	Acknowledged request but sent no information
Gas composition at each underground gas storage facility in order to understand health and environmental impacts	5/1/17	CPUC	All underground gas storage facilities responded with the information they had. Unfortunately, most of the information we needed is apparently not collected by facilities.

In addition, the root-cause analysis of the 2015 Aliso Canyon incident is still ongoing, and there are fundamental aspects of why the SS-25 well failed, and why it was so hard to stop, that are unknown at the time of publication of this report. An analysis and synthesis of underground gas storage well risk statewide, based on the SS-25 root-cause analysis, should be undertaken once the root-cause analysis is published.

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, Energy Geosciences 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

Chief Systems Engineer, Earth Science and 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
- **Berne Mosely**, Energy Projects Consulting
- **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

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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

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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

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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

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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

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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

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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

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Environmental Energy Technologies Division
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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

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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

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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

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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

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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

BERNE L. MOSLEY

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EDUCATION

1982	BS-CIVIL ENGINEERING Auburn University, Auburn, AL

CURRENT AND PAST POSITIONS

Since 2012	President, Energy Projects Consulting
2009-2012	Deputy Director, Office of Energy Projects, Federal Energy Regulatory Commission (FERC)
2003-2009	Director, Division of Pipeline Certificates, Office of Energy Projects, FERC
2002-2003	Assistant Director, Office of Energy Projects, FERC
1984-2002	Civil Engineer and Gas Utility Specialist, Division of Pipeline Certificates, FERC

KULDEEP R. PRASAD

National Institute of Standards and Technology (NIST)
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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

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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

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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

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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

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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

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 F

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 G

Acknowledgements

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CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

CCST is a nonpartisan, nonprofit organization established via the California State Legislature — making California's policies stronger with science since 1988. We engage leading experts in science and technology to advise State policymakers — ensuring that California policy is strengthened and informed by scientific knowledge, research, and innovation.

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