An Independent Scientific Assessment of Well Stimulation in California

Executive Summary

An Examination of Hydraulic Fracturing and Acid Stimulations in the Oil and Gas Industry

July 2015

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

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About CCST

CCST is a non-profit organization established in 1988 at the request of the California State Government and sponsored by the major public and private postsecondary institutions of California and affiliate federal laboratories in conjunction with leading private-sector firms. CCST's mission is to improve science and technology policy and application in California by proposing programs, conducting analyses, and recommending public policies and initiatives that will maintain California's technological leadership and a vigorous economy.

Note

Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

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In 2013, the California Legislature passed Senate Bill 4 (SB 4), setting the framework for regulation of hydraulic fracturing and acid stimulation technologies in California. SB 4 also requires the California Natural Resources Agency to conduct an independent scientific study to assess current and potential future well stimulation practices, including the likelihood that these technologies could enable extensive new petroleum production in the state; the impacts of well stimulation technologies (including hydraulic fracturing, acid fracturing and matrix acidizing) and the gaps in data that preclude this understanding; potential risks associated with current practices; and alternative practices that might limit these risks.

The California Council on Science and Technology (CCST) organized and led the study. Members of the CCST steering committee were appointed based on technical expertise and a balance of technical viewpoints. Lawrence Berkeley National Laboratory (LBNL) and subcontractors (the science team) developed the findings based on original technical data analyses and a review of the relevant literature. The science team studied each of the issues required by SB 4, and the science team and the steering committee collaborated to develop a series of conclusions and recommendations. Final responsibility for the conclusions and recommendations in this report 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.

This report has undergone extensive peer review; peer reviewers are listed in Appendix E of the Summary Report, "Expert Oversight and Review." Eighteen reviewers were chosen for their relevant technical expertise. More than 1,500 anonymous review comments were provided to the authors. The authors 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. Report monitors, appointed by CCST, then reviewed the response to the review comments and when satisfied, approved the report.

To create a hydraulic fracture, an operator increases the pressure of a mixture of water and chemicals in an isolated section of a well until the surrounding rock breaks, or "fractures." Sand injected into these fractures props them open after the pressure is released. Acid fracturing, in which a high-pressure acidic fluid fractures the rock and etches the walls of the fractures, is hardly used in California and not discussed further. Matrix acidizing does not fracture the rock; instead, acid pumped into the well at relatively low pressure dissolves some of the rock and makes it more permeable. This study identified seven equally important major principles required for safe hydraulic fracturing and acid stimulation in California. Organized by principle, we draw conclusions and recommendations.

Principle 1. Maintain, expand and analyze data on the practice of hydraulic fracturing and acid stimulation in California.

Public records provide substantial information about the location, frequency of use, and water and chemical use for hydraulic fracturing and acid stimulation in California.

Conclusion 1.1. Most well stimulations in California are hydraulic fracturing and most hydraulic fracturing occurs in the San Joaquin Valley.

About 95% of reported hydraulic fracturing operations in California occur in the San Joaquin Basin, nearly all in four oil fields in Kern County. Over the last decade, about 20% of oil and gas production in California came from wells treated with hydraulic fracturing. Hydraulic fracturing accounts for about 90% of all well stimulations in California; matrix acidizing accounts for only 10%; and acid fracturing operations nearly none. Operators in California commonly use acid for well maintenance, but acid stimulation will not likely lead to major increases in oil and gas production due to the state's geology. Operators of dry (non-associated) gas wells located in Northern California rarely use hydraulic fracturing (Volume I, Chapter 3).

Conclusion 1.2. The California experience with hydraulic fracturing differs from that in other states.

Present-day hydraulic fracturing practice and geologic conditions in California differ from those in other states, and as such, recent experiences with hydraulic fracturing in other states do not necessarily apply to current hydraulic fracturing in California (Volume I, Chapters 2 and 3).

Conclusion 1.3. Hydraulic fracturing in California does not use a lot of fresh water compared to other states and other human uses.

Operators in California use about 800 acre-feet (about a million cubic meters [m^3]) of water per year for hydraulic fracturing. This does not represent a large amount of freshwater compared to other human water use, so recycling this water has only modest benefits. However, hydraulic fracturing takes place in relatively water-scarce regions. Where production was enabled by hydraulic fracturing, at least twice and possibly fourteen times as much fresh water was used for subsequent enhanced oil recovery using water or steam flooding than all the water used for hydraulic fracturing throughout the state. The state has recently begun requiring detailed reporting of water use and produced water disposal in California's oil and gas fields under Senate Bill 1281 (SB 1281). In the future, these data could help optimize oil and gas water practices, including water use, production, reuse, and disposal.

Recommendation 1.1. Identify opportunities for water conservation and reuse in the oil and gas industry.

When roughly a year of water data becomes available from implementation of SB 1281, the state should begin an early assessment of these data to evaluate water sources, water production, reuse, and disposal for the entire oil and gas industry. Early assessment will shed light on the adequacy of the data reporting requirements and identify additional requirements that could include additional information about the quality of the water used and produced. When several years of data become available, a full assessment should identify opportunities to reduce freshwater consumption or increase the beneficial use of produced water, and regularly update opportunities for water efficiency and conservation (Volume I, Chapter 3).

Conclusion 1.4. A small number of offshore wells use hydraulic fracturing.

California operators currently use hydraulic fracturing in a small portion of offshore wells, and we expect hydraulic fracturing to remain incidental in the offshore environment. Policies currently restrict oil and gas production offshore, but if these were to change in the future, production could largely occur without well stimulation technology for the foreseeable future (Volume III, Chapter 2 [Offshore Case Study]).

Conclusion 1.5. Record keeping for hydraulic fracturing and acid stimulation in federal waters does not meet state standards.

Current record-keeping practice on stimulations in federal waters (from platforms more than three nautical miles offshore) does not meet the standards set by the pending SB 4 well treatment regulations and does not allow an assessment of the level of activity or composition of hydraulic fracturing chemicals being discharged in the ocean. The National Pollutant Discharge Elimination System permits that regulate discharge from offshore platforms do not effectively address hydraulic fracturing fluids. The limited publicly available records disclose only a few stimulations per year.

Recommendation 1.2. Improve reporting of hydraulic fracturing and acid stimulation data in federal waters.

The state of California should request that the federal government improve data collection and record keeping concerning well stimulation conducted in federal waters to at least match the requirements of SB 4. The U.S. Environmental Protection Agency should conduct an assessment of ocean discharge and, based on these results, consider if alternatives to ocean disposal for well stimulation fluid returns are necessary (Volume III, Chapter 2 [Offshore Case Study]).

Principle 2. Prepare for potential future changes in hydraulic fracturing and acid stimulation practice in California.

Conclusion 2.1. Future use of hydraulic fracturing in California will likely resemble current use.

Future use of hydraulic fracturing will most likely expand production in and near existing oil fields in the San Joaquin Basin that currently require hydraulic fracturing. Oil resource assessment and future use of hydraulic fracturing and acid stimulation in the Monterey Formation of California remain uncertain. In 2011, the U.S. Energy Information Administration (EIA) estimated that 15 billion barrels (2.4 billion m^3) of recoverable shale-oil resources existed in Monterey source rock. This caused concern about the potential environmental impacts of widespread shale-oil development in California using hydraulic fracturing. In 2014 the EIA downgraded the 2011 estimate by 96%. This study reviewed both EIA estimates and concluded that neither one can be considered reliable. Any potential for production in the Monterey Formation would be confined to those parts of the formation in the "oil window," that is, where Monterey Formation rocks have experienced the temperatures and pressures required to form oil. The surface footprint of this subset of the Monterey Formation expands existing regions of oil and gas production rather than opening up entirely new oil and gas producing regions.

Recommendation 2.1. Assess the oil resource potential of the Monterey Formation.

The state should request a comprehensive, science-based and peer-reviewed assessment of source-rock ("shale") oil resources in California and the technologies that might be used to produce them. The state could request such an assessment from the U.S. Geological Survey, for example.

Recommendation 2.2. Keep track of exploration in the Monterey Formation.

As expansive production in the Monterey Formation remains possible, Division of Oil, Gas, and Geothermal Resources (DOGGR) should track well permits for future drilling in the "oil window" of the Monterey source rocks (and other extensive source rocks, such as the Kreyenhagen) and be able to report increased activity (Volume I, Chapter 4; Volume III, Chapter 3 [Monterey Formation Case Study]).

Principle 3. Account for and manage both direct and indirect impacts of hydraulic fracturing and acid stimulation.

Hydraulic fracturing or acid stimulation can cause direct impacts. Potential direct impacts might include a hydraulic fracture extending into protected groundwater, accidental spills of fluids containing hydraulic fracturing chemicals or acid, or inappropriate disposal or reuse of produced water containing hydraulic fracturing chemicals. These direct impacts do not occur in oil and gas production unless hydraulic fracturing or acid stimulation has occurred. This study covers potential direct impacts of hydraulic fracturing or acid stimulation.

Hydraulic fracturing or acid stimulation can also incur indirect impacts, i.e., those not directly attributable to the activity itself. Some reservoirs require hydraulic fracturing for economic production. All activities associated with oil and gas production enabled by hydraulic fracturing or acid stimulation can bring about indirect impacts. Indirect impacts of hydraulic-fracturing-enabled oil and gas development usually occur in all oil and gas development, whether or not the wells are stimulated.

Conclusion 3.1. Direct impacts of hydraulic fracturing appear small but have not been investigated.

Available evidence indicates that impacts caused directly by hydraulic fracturing or acid stimulation or by activities directly supporting these operations appear smaller than the indirect impacts associated with hydraulic-fracturing-enabled oil and gas development, or limited data precludes adequate assessment of these impacts. Good management and mitigation measures can address the vast majority of potential direct impacts of well stimulation.

> **Recommendation 3.1. Assess adequacy of regulations to control direct impacts of hydraulic fracturing and acid stimulations.**
>
> *Over the next several years, relevant agencies should assess the adequacy and effectiveness of existing and pending regulations to mitigate direct impacts of hydraulic fracturing and acid stimulations.*

Conclusion 3.2. Operators have unrestricted use of many hazardous and uncharacterized chemicals in hydraulic fracturing.

The California oil and gas industry uses a large number of hazardous chemicals during hydraulic fracturing and acid treatments. The use of these chemicals underlies all significant potential direct impacts of well stimulation in California. This assessment did not find recorded negative impacts from hydraulic fracturing chemical use in California, but no agency has systematically investigated possible impacts. A few classes of chemicals used in hydraulic fracturing (e.g. biocides, quaternary ammonium compounds, etc.) present larger hazards because of their relatively high toxicity, frequent use, or use in large amounts. The environmental characteristics of many chemicals remain unknown. We lack information to determine if these chemicals would present a threat to human health or the environment if released to groundwater or other environmental media. Application of green chemistry principles, including reduction of hazardous chemical use and substitution of less hazardous chemicals, would reduce potential risk to the environment or human health.

Recommendation 3.2. Limit the use of hazardous and poorly understood chemicals.

Operators should report the unique Chemical Abstracts Service Registry Number (CASRN) identification for all chemicals used in hydraulic fracturing and acid stimulation, and the use of chemicals with unknown environmental profiles should be disallowed. The overall number of different chemicals should be reduced, and the use of more hazardous chemicals and chemicals with poor environmental profiles should be reduced, avoided, or disallowed. The chemicals used in hydraulic fracturing could be limited to those on an approved list that would consist only of those chemicals with known and acceptable environmental hazard profiles. Operators should apply green chemistry principles to the formulation of hydraulic fracturing fluids, particularly for biocides, surfactants, and quaternary ammonium compounds, which have widely differing potential for environmental harm. Relevant state agencies, including DOGGR, should as soon as practical engage in discussion of technical issues involved in restricting chemical use with a group representing environmental and health scientists and industry practitioners, either through existing roundtable discussions or independently (Volume II, Chapters 2 and 6).

Conclusion 3.3. The majority of impacts associated with hydraulic fracturing are caused by the indirect impacts of oil and gas production enabled by the hydraulic fracturing.

Impacts caused by additional oil and gas development enabled by well stimulation (i.e. indirect impacts) account for the majority of environmental impacts associated with hydraulic fracturing. A corollary of this conclusion is that all oil and gas development causes similar impacts whether the oil is produced with well stimulation or not. As hydraulic fracturing enables only 20-25% of production in California, only about 20-25% of any given indirect impact is likely attributable to hydraulically fractured reservoirs.

Recommendation 3.3. Evaluate impacts of production for all oil and gas development, rather than just the portion of production enabled by well stimulation.

Concern about hydraulic fracturing might cause focus on impacts associated with production from fractured wells, but concern about these indirect impacts should lead to study of all types of oil and gas production, not just production enabled by hydraulic fracturing. Agencies with jurisdiction should evaluate impacts of concern for all oil and gas development, rather than just the portion of development enabled by well stimulation. As appropriate, many of the rules and regulations aimed at mitigating indirect impacts of hydraulic fracturing and acid stimulation should also be applied to all oil and gas wells (Volume II, Chapters 5 and 6).

Conclusion 3.4. Oil and gas development causes habitat loss and fragmentation.

Any oil and gas development, including that enabled by hydraulic fracturing, can cause habitat loss and fragmentation. The location of hydraulic-fracturing-enabled development coincides with ecologically sensitive areas in the Kern and Ventura Counties.

> **Recommendation 3.4. Minimize habitat loss and fragmentation in oil and gas producing regions.**
>
> *Enact regional plans to conserve essential habitat and dispersal corridors for native species in Kern and Ventura Counties. The plans should identify top-priority habitat and restrict development in these regions. The plan should also define and require those practices, such as clustering multiple wells on a pad and using centralized networks of roads and pipes, which will minimize future surface disturbances. A program to set aside compensatory habitat in reserve areas when oil and gas development causes habitat loss and fragmentation should be developed and implemented (Volume II, Chapter 5; Volume III, Chapter 5 [San Joaquin Basin Case Study]).*

Principle 4. Manage water produced from hydraulically fractured or acid stimulated wells appropriately.

Large volumes of water of various salinities and qualities get produced along with the oil. Oil reservoirs tend to yield increasing quantities of water over time, and most of California's oil reservoirs have been in production for several decades to over a century. For 2013, more than 3 billion barrels (.48 billion m^3) of water came along with some 0.2 billion barrels (.032 billion m^3) of oil in California. Operators re-inject some produced water back into the oil and gas reservoirs to help recover more petroleum and mitigate land subsidence. In other cases, farmers use this water for irrigation; often blending treated produced water with higher-quality water to reduce salinity.

Conclusion 4.1. Produced water disposed of in percolation pits could contain hydraulic fracturing chemicals.

Based on publicly available data, operators disposed of some produced water from stimulated wells in Kern County in percolation pits. The effluent has not been tested to determine if there is a measureable concentration of hydraulic fracturing chemical constituents. If these chemicals were present, the potential impacts to groundwater, human health, wildlife, and vegetation would be extremely difficult to predict, because there are so many possible chemicals, and the environmental profiles of many of them are unmeasured.

Recommendation 4.1. Ensure safe disposal of produced water in percolation pits with appropriate testing and treatment or phase out this practice.

Agencies with jurisdiction should promptly ensure through appropriate testing that the water discharged into percolation pits does not contain hazardous amounts of chemicals related to hydraulic fracturing as well as other phases of oil and gas development. If the presence of hazardous concentrations of chemicals cannot be ruled out, they should phase out the practice of discharging produced water into percolation pits. Agencies should investigate any legacy effects of discharging produced waters into percolation pits including the potential effects of stimulation fluids (Volume II, Chapter 2; Volume III, Chapters 4 and 5 [Los Angeles Basin and San Joaquin Basin Case Studies]).

Conclusion 4.2. The chemistry of produced water from hydraulically fractured or acid stimulated wells has not been measured.

Chemicals used in each hydraulic fracturing operation can react with each other and react with the rocks and fluids of the oil and gas reservoirs. When a well is stimulated with acid, the reaction of the acid with the rock minerals, petroleum, and other injected chemicals can release contaminants of concern in the oil reservoirs, such as metals or fluoride ions that have not been characterized or quantified. These contaminants may be present in recovered and produced water.

Recommendation 4.2. Evaluate and report produced water chemistry from hydraulically fractured or acid stimulated wells.

Evaluate the chemistry of produced water from hydraulically fractured and acid stimulated wells, and the potential consequences of that chemistry for the environment. Determine how this chemistry changes over time. Require reporting of all significant chemical use, including acids, for oil and gas development (Volume II, Chapters 2 and 6).

Conclusion 4.3. Required testing and treatment of produced water destined for reuse may not detect or remove chemicals associated with hydraulic fracturing and acid stimulation.

Produced water from oil and gas production has potential for beneficial reuse, such as for irrigation or for groundwater recharge. In fields that have applied hydraulic fracturing or acid stimulations, produced water may contain hazardous chemicals and chemical byproducts from well stimulation fluids. Practice in California does not always rule out the beneficial reuse of produced water from wells that have been hydraulically fractured or stimulated with acid. The required testing may not detect these chemicals, and the treatment required prior to reuse necessarily may not remove hydraulic fracturing chemicals.

Recommendation 4.3. Protect irrigation water from contamination by hydraulic fracturing chemicals and stimulation reaction products.

Agencies of jurisdiction should clarify that produced water from hydraulically fractured wells cannot be reused for purposes such as irrigation that could negatively impact the environment, human health, wildlife and vegetation. This ban should continue until or unless testing the produced water specifically for hydraulic fracturing chemicals and breakdown products shows non-hazardous concentrations, or required water treatment reduces concentrations to non-hazardous levels (Volume II, Chapter 2; Volume III, Chapter 5 [San Joaquin Basin Case Study]).

Conclusion 4.4. Injection wells currently under review for inappropriate disposal into protected aquifers may have received water that contains chemicals from hydraulic fracturing.

DOGGR is currently reviewing injection wells in the San Joaquin Valley for inappropriate disposal of oil and gas wastewaters into protected groundwater. The wastewaters injected into some of these wells likely included stimulation chemicals because hydraulic fracturing occurs nearby.

Recommendation 4.4. In the ongoing investigation of inappropriate disposal of wastewater into protected aquifers, recognize that hydraulic fracturing chemicals may have been present in the wastewater.

In the ongoing process of reviewing, analyzing, and remediating the potential impacts of wastewater injection into protected groundwater, agencies of jurisdiction should include the possibility that hydraulic fracturing chemicals may have been present in these wastewaters (Volume II, Chapter 2; Volume III, Chapter 5 [San Joaquin Basin Case Study]).

Conclusion 4.5. Disposal of produced water by underground injection has caused earthquakes elsewhere.

Fluid injected in the process of hydraulic fracturing will not likely cause earthquakes of concern. In contrast, disposal of produced water by underground injection could cause felt or damaging earthquakes. To date, there have been no reported cases of induced seismicity associated with produced water injection in California. However, it can be very difficult to distinguish California's frequent natural earthquakes from those possibly caused by water injection into the subsurface.

Recommendation 4.5. Determine if there is a relationship between wastewater injection and earthquakes in California.

Conduct a comprehensive multi-year study to determine if there is a relationship between oil and gas-related fluid injection and any of California's numerous earthquakes. In parallel, develop and apply protocols for monitoring, analyzing, and managing produced water injection operations to mitigate the risk of induced seismicity. Investigate whether future changes in disposal volumes or injection depth could affect potential for induced seismicity (Volume II, Chapter 4).

Conclusion 4.6. Changing the method of produced water disposal will incur tradeoffs in potential impacts.

Based on publicly available data, operators dispose of much of the produced water from stimulated wells in percolation pits (evaporation-percolation ponds), about a quarter by underground injection (in Class II wells), and less than one percent to surface bodies of water. Changing the method of produced water disposal could decrease some potential impacts while increasing others.

Recommendation 4.6. Evaluate tradeoffs in wastewater disposal practices.

As California moves to change disposal practices, for example by phasing out percolation pits or stopping injection into protected aquifers, agencies with jurisdiction should assess the consequences of modifying or increasing disposal via other methods (Volume II, Chapter 2; Volume II, Chapter 4).

Principle 5. Add protections to avoid groundwater contamination by hydraulic fracturing.

Conclusion 5.1. Shallow fracturing raises concerns about potential groundwater contamination.

In California, about three quarters of all hydraulic fracturing operations take place in shallow wells less than 2,000 feet (600 meters) deep. In a few places, protected aquifers exist above such shallow fracturing operations, and this presents an inherent risk that hydraulic fractures could accidentally connect to the drinking water aquifers and contaminate them or provide a pathway for water to enter the oil reservoir. Groundwater monitoring alone may not necessarily detect groundwater contamination from hydraulic fractures. Shallow hydraulic fracturing conducted near protected groundwater resources warrants special requirements and plans for design control, monitoring, reporting, and corrective action.

Recommendation 5.1. Protect groundwater from shallow hydraulic fracturing operations.

Agencies with jurisdiction should act promptly to locate and catalog the quality of groundwater throughout the oil-producing regions. Operators proposing to use hydraulic fracturing operation near protected groundwater resources should be required to provide adequate assurance that the expected fractures will not extend into these aquifers and cause contamination. If the operator cannot demonstrate the safety of the operation with reasonable assurance, agencies with jurisdiction should either deny the permit, or develop protocols for increased monitoring, operational control, reporting, and preparedness (Volume I, Chapter 3; Volume II, Chapter 2; Volume III, Chapter 5 [San Joaquin Basin Case Study]).

Conclusion 5.2. Leakage of hydraulic fracturing chemicals could occur through existing wells.

California operators use hydraulic fracturing mainly in reservoirs that have been in production for a long time. Consequently, these reservoirs have a high density of existing wells that could form leakage paths away from the fracture zone to protected groundwater or the ground surface. The pending SB 4 regulations going into effect July 2015 do address concerns about existing wells in the vicinity of well stimulation operations; however, it remains to demonstrate the effectiveness of these regulations in protecting groundwater.

Recommendation 5.2. Evaluate the effectiveness of hydraulic fracturing regulations designed to protect groundwater from leakage along existing wells.

Within a few years of the new regulations going into effect, DOGGR should conduct or commission an assessment of the regulatory requirements for existing wells near stimulation operations and their effectiveness in protecting groundwater with less than 10,000 TDS from well leakage. This assessment should include comparisons of field observations from hydraulic fracturing sites with the theoretical calculations for stimulation area or well pressure required in the regulations (Volume II, Chapter 2; Volume III, Chapters 4 and 5 [San Joaquin Basin and Los Angeles Basin Case Studies]).

Principle 6. Understand and control emissions and their impact on environmental and human health.

Gaseous emissions and particulates associated with hydraulic fracturing can arise from the use of fossil fuel in engines, outgassing from fluids, leaks, or proppant. Emissions can also result from all production processes. Such emissions have potential environmental or health impacts.

Conclusion 6.1. Oil and gas production from hydraulically fractured reservoirs emits less greenhouse gas per barrel of oil than other forms of oil production in California.

Burning fossil fuel to run vehicles, make electricity, and provide heat accounts for the vast majority of California's greenhouse gas emissions. In comparison, publicly available California state emission inventories indicate that oil and gas production operations emit about 4% of California total greenhouse gas emissions. Oil and gas production from hydraulically fractured reservoirs emits less greenhouse gas per barrel of oil than production using steam injection. Oil produced in California using hydraulic fracturing also emits less greenhouse gas per barrel than the average barrel imported to California. If the oil and gas derived from stimulated reservoirs were no longer available, and demand for oil remained constant, the replacement fuel could have larger greenhouse gas emissions.

Recommendation 6.1. Assess and compare greenhouse gas signatures of different types of oil and gas production in California.

Conduct rigorous market-informed life-cycle analyses of emissions impacts of different oil and gas production to better understand GHG impacts of well stimulation (Volume II, Chapter 3).

Conclusion 6.2. Air pollutant and toxic air emissions from hydraulic fracturing are mostly a small part of total emissions, but pollutants can be concentrated near production wells.

According to publicly available California state emission inventories, oil and gas production in the San Joaquin Valley air district likely accounts for significant emissions of sulfur oxides (SO_x), volatile organic compounds (VOC), and some air toxics, notably hydrogen sulfide (H_2S). In other oil and gas production regions, production as a whole accounts for a small proportion of total emissions. Hydraulic fracturing facilitates about 20% of California production, and so emissions associated with this production also represent about 20% of all emissions from the oil and gas production in California. Even where the proportion of air pollutant and toxic emissions caused directly or indirectly by well simulation is small, atmospheric concentrations of pollutants near production sites can be much larger than basin or regional averages, and could potentially cause health impacts.

Recommendation 6.2. Control toxic air emissions from oil and gas production wells and measure their concentrations near productions wells.

Apply reduced-air-emission completion technologies to production wells, including stimulated wells, to limit direct emissions of air pollutants, as planned. Reassess opportunities for emission controls in general oil and gas operations to limit emissions. Improve specificity of inventories to allow better understanding of oil and gas emissions sources. Conduct studies to improve our understanding of toxics *concentrations near stimulated and un-stimulated wells (Volume II, Chapter 3; Volume III, Chapter 4 [Los Angeles Basin Case Study]).*

Conclusion 6.3. Emissions concentrated near all oil and gas production could present health hazards to nearby communities in California.

Many of the constituents used in and emitted by oil and gas development 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. Health risks near oil and gas wells may be independent of whether wells in production have undergone hydraulic fracturing or not. Consequently, a full understanding of health risks caused by proximity to production wells will require studying all types of productions wells, not just those that have undergone hydraulic fracturing. Oil and gas development poses more elevated health risks when conducted in areas of high population density, such as the Los Angeles Basin, because it results in larger population exposures to toxic air contaminants.

Recommendation 6.3. Assess public health near oil and gas production.

Conduct studies in California to assess public health as a function of proximity to all oil and gas development, not just stimulated wells, and develop policies such as science-based surface setbacks, to limit exposures (Volume II, Chapter 6; Volume III, Chapters 4 and 5 [San Joaquin Basin and Los Angeles Basin Case Studies]).

Conclusion 6.4. Hydraulic fracturing and acid stimulation operations add some occupational hazards to an already hazardous industry.

Studies done outside of California found workers in hydraulic fracturing operations were exposed to respirable silica and VOCs, especially benzene, above recommended occupational levels. The oil and gas industry commonly uses acid along with other toxic substances for both routine maintenance and well stimulation. Well-established procedures exist for safe handling of dangerous acids.

Recommendation 6.4. Assess occupational health hazards from proppant use and emission of volatile organic compounds.

Conduct California-based studies focused on silica and volatile organic compounds exposures to workers engaged in hydraulic-fracturing-enabled oil and gas development processes based on the National Institute for Occupational Safety and Health occupational health findings and protocols (Volume II, Chapter 6).

Principle 7. Take an informed path forward.

Conclusion 7.1. Data reporting gaps and quality issues exist.

Significant gaps and inconsistencies exist in available voluntary and mandatory data sources, both in terms of duration and completeness of reporting. Because the hydrologic and geologic conditions and stimulation practices in California differ from other unconventional plays in this country, many data gaps are specific to California.

> **Recommendation 7.1. Improve and modernize public record keeping for oil and gas production.**
>
> *DOGGR should digitize paper records and organize all datasets in databases that facilitate searches and quantitative analysis. DOGGR should also institute and publish data quality assurance practices, and institute enforcement measures to ensure accuracy of reporting. When a few years' reporting data become available, a study should assess the value, completeness, and consistency of reporting requirements for hydraulic fracturing and acid treatment operations—and as necessary, revise or expand reporting requirements. The quality and completeness of the data collected by the South Coast Air Quality Management District provides a good example of the completeness and availability the state should seek to emulate. The Department of Conservation should reevaluate well stimulation data trends after 3–5 years of reporting.*

Conclusion 7.2. Future research would fill knowledge gaps.

Questions remain at the end of this initial assessment of the impacts of well stimulation in California that can only be answered by new research and data collection. Volumes II and III of this report series provide many detailed recommendations for filling data gaps and additional research. Some examples of key questions include:

- Has any protected groundwater been contaminated with stimulation chemicals in the past, and what would protect against this occurrence in the future? No records of groundwater contamination due to hydraulic fracturing were found, but there were also few investigations designed to look for contamination.
- What environmental risks do stimulation chemicals pose, and are there practices that would limit these risks?
- Can water being produced from hydraulically fractured wells become a resource for California?
- How does oil and gas production as a whole (including that enabled by hydraulic fracturing) affect California's water system?

- Does California's current or future practice of underground injection of wastewater present a significant risk of inducing earthquakes?
- How can the public best be protected from air pollution associated with oil and gas production?
- What are the ecological impacts of oil and gas development in California?

Recommendation 7.2. Conduct integrated research to close knowledge gaps.

Conduct integrated research studies in California to answer key questions about the environmental, health, and seismic impacts of oil and gas production enabled by well stimulation. Integrated research studies should include regional hydrologic characterization and field studies related to surface and groundwater protection, induced seismicity, ecological conditions, as well as air and health effects.

Conclusion 7.3. Ongoing scientific advice could inform policy.

As the state of California digests this assessment and as more data become available, continued interpretation of both the impacts of well stimulation and the potential meaning of scientific data and analysis would inform the policy framework for this complex topic.

Recommendation 7.3. Establish an advisory committee on oil and gas.

The state of California should establish a standing scientific advisory committee to support decisions on the regulation of oil and gas development.

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