Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Underground Natural Gas Storage Well Emission Events

This memo discusses updates for the 2024 *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (GHGI) to incorporate emissions for anomalous large emission events at underground natural gas storage wells. A prior version of this memo was released in November 2023 and presented additional considerations for underground natural gas storage well emissions (*Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates Under Consideration for Underground Natural Gas Storage Well Emission Events*).[1]

The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*[2] included guidance on calculating emissions from "anomalous leak events" for national GHG Inventories. The *2019 IPCC Refinement* provides examples of anomalous events, including emergency pressure relieving equipment and well blowouts, and specifies that these events should be evaluated and estimated on a case-by-case basis using the best available data.

The update implemented this guidance by incorporating additional estimates for anomalous leak events into the GHGI, focusing in this memo on the underground storage well source. The events include blowouts and other large emission release events occurring at underground storage wells.

1 Previous (2023) GHGI Methodology

The previous GHGI included emissions from three large emission events for production wells, and one underground natural gas storage (UNGS) facility event at Aliso Canyon.[3] EPA released a memo for the 2018 GHGI that presented methane emissions from the Aliso Canyon leak in 2015 and 2016.[4] EPA used the California Air Resources Board's (CARB) method of estimating methane emitted from the leak.[5]

Using CARB's method, the methane emissions from the Aliso Canyon event were 78,350 metric tons (mt) of methane (CH_4) in 2015 and 21,288 mt CH_4 in 2016. EPA included both 2015 and 2016 emission estimates from the Aliso Canyon event in the 2018 GHGI.

The previous GHGI also included equipment leak emissions (average annual emissions of around 13,000 mt CH_4) from UNGS wells but did not otherwise account for similar non-routine emissions events from these UNGS facilities.

2 Available Data

A recent article from Li et al.,[6] "A national estimate of U.S. underground natural gas storage incident emissions," analyzed UNGS event emissions from 1984-2016. Li et al. 2022 used data from Folga et al. 2016,[7] which contains incidents reported to the Pipeline and Hazardous Materials Safety Administration (PHMSA)[8] for the years 1984-

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1 https://www.epa.gov/system/files/documents/2023-11/ghgi-webinaroct2023_events.pdf

2 *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2, Energy*. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol2.html.

3 https://www.epa.gov/system/files/documents/2022-04/2022_ghgi_update_-_blowouts.pdf

4 https://www.epa.gov/sites/default/files/2017-01/documents/memo_on_aliso_canyon_estimate_for_u.s._ghgi_1.10.17.pdf

5 For more information on the leak measurements and calculations, please see California Air Resources Board. Determination of Total Methane Emission from the Aliso Canyon Natural Gas Leak Incident. October 21, 2016. https://www.arb.ca.gov/research/aliso_canyon/aliso_canyon_methane_emissions-arb_final.pdf.

6 Li, H Z et al. 2022. A national estimate of U.S. underground natural gas storage incident emissions. *Environmental Research Letters*, 17: 084013. https://doi.org/10.1088/1748-9326/ac8069

7 Folga, S et al. 2016. U.S. Natural Gas Storage Risk-Based Ranking Methodology and Results. Technical Report. Office of Scientific and Technical Information, Department of Energy. https://doi.org/10.2172/1337151

8 https://www.phmsa.dot.gov/data-and-statistics/pipeline/distribution-transmission-gathering-lng-and-liquid-accident-and-incident-data

2016; and Evans and Chadwick 2009,[9] which describes worldwide historical UNGS blowout events from 1953-2006.

PHMSA collects data for incidents at UNGS facilities. The available data is split into three distinct subgroups based on the reported PHMSA data.

The subgroups and reported data, as used in Li et al., are as follows:

- 1984-2001: Total property damage cost
- 2002-2009: Cost of gas lost
- 2010-2016: Gas release volume

Li et al. used different methods to estimate methane emissions for each subgroup due to the differences in data. The most recent time frame of incidents reported to PHMSA (i.e., 2010-2016) included the gas release volume, so the method was more straightforward than the methods used for the other two time frames. For reports with the cost of gas lost (i.e., 2002-2009), the gas volume was estimated using the monthly wellhead gas price from the U.S. Energy Information Administration (EIA). There was limited information available for events reported to PHMSA from 1984-2001. The leak size associated with events reported during this time frame was sometimes included in the narrative sections of PHMSA reports. For events without the cost of gas lost or gas release volumes, Li et al. used a formula based on fluid mechanics paired with the cross-section area of the leak and event duration, which was included in the 1984-2001 PHMSA reports, to estimate the methane leak volume.

3 Analysis of Available Data

The Li et al. 2022 data included 69 UNGS events between 1990 and 2016 with data available to estimate gas releases. EPA reviewed Li et al. to determine whether the events occurred at storage wells, or if the events were for other types of incidents at the UNGS facility. Of the 69 incidents, EPA identified 10 events that occurred at storage wells. Of these, five were blowouts. EPA classified the events as blowouts based on the proposed definition of a "well blowout" in the recent subpart W proposed rule, which identified blowout events as having "a complete loss of well control for a long duration of time".[10] Evidence of wellhead failure, casing failure, or a casing leak for these five events was also indicated in the narrative information. The other five well events not classified as blowouts were periods of shorter gas release due to well equipment damage.

Li et al. presented an estimate of methane release from the large events without taking into account methane combustion. Combustion reduces methane release emissions from events and increases CO_2 emissions. EPA reviewed supporting information available for all 10 storage well events and identified 4 events where the gas ignited or there was an explosion.

The percentage of gas that was combusted was not available in Li et al. or the supporting information for each event. For the 2024 GHGI, EPA applied a combustion efficiency of 60 percent to events that were identified as including combustion. A study by Maasakkers et al. characterized emissions from a well blowout in Louisiana.[11] In the study, Maasakkers et al. assume a combustion efficiency range of 60 to 99 percent when emissions are combusted using a flare. The 60 percent estimate is on the lower range of combustion efficiencies used for well blowout events with flared emissions. Combustion resulting from UNGS well events is assumed to not oxidize methane as efficiently as when flared, which is why the lowest estimate was applied.

[9] Evans, DJ & Chadwick, RA. 2009. (eds) Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe. *The Geological Society, London, Special Publications*, 313: 173–216. https://doi.org/10.1144/SP313.12

[10] EPA. Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems. EPA–HQ–OAR–2023–0234; FRL–10246–01– OAR https://www.govinfo.gov/content/pkg/FR-2023-08-01/pdf/2023-14338.pdf

[11] Maasakkers, JD et al. 2022. Reconstructing and quantifying methane emissions from the full duration of a 38-day natural gas well blowout using space-based observations. *Remote Sensing of Environment*, 270: 112755. https://doi.org/10.1016/j.rse.2021.112755

EPA identified one high-emission storage well event, the Moss Bluff incident, that occurred in 2004 and released gas containing 107,933 mt CH_4. Based on supporting documentation, the fire resulting from the Moss Bluff explosion burned for six days until the fire self-extinguished, indicating a fraction of the released methane was combusted.[12] The description from Evans and Chadwick 2009 also included information about how the escaping gas ignited and caused the wellhead to fail. After applying a combustion efficiency of 60 percent, EPA calculated emissions from the Moss Bluff event to be 43,173 mt CH_4 and 203,310 mt CO_2.

Another event with possible emissions combustion occurred at the Yaggy field in Kansas in 2001. The Yaggy event released gas containing 2,572 mt CH_4. According to Evans and Chadwick 2009, there was a fire and an explosion because of the event. Applying a 60 percent combustion efficiency factor, 1,092 mt CH_4 and 4,846 mt CO_2 were calculated to be emitted.

Appendix A includes further information for each of the 10 storage well events identified by EPA in the Li et al. data, including identifying those that were well blowouts.

EPA also reviewed PHMSA data beyond what is presented in Li et al. 2022 to determine if there were more recent large emission events. To evaluate large emission events at UNGS wells from 2017 to 2022, EPA reviewed PHMSA reports, which include a detailed narrative section describing each event. EPA reviewed the narrative sections to determine whether an event occurred at a storage well and if the event can be described as a well blowout. EPA did not identify any large well blowout events from 2017 through 2022 and thus did not incorporate additional events for the 2024 GHGI. For future Inventories, if large UNGS well events are identified, EPA would use the quantity of gas released from the PHMSA report to calculate the amount of methane released. EPA would then investigate if there was ignition of gas or an explosion during the event to see if the combustion efficiency should be applied to the amount of methane released to account for combustion.

4 Time Series Considerations

Previously, Aliso Canyon was the only storage well blowout incident included in the overall time series. EPA incorporated the 10 identified storage well events into the 2024 GHGI as one-off events and included emissions for each in the year the event occurred. UNGS events occurred in 10 inventory years with one event occurring each year.

5 National Emissions Estimates

EPA analyzed the scope of incident emissions from 1990-2016, as presented in Li et al, coupled with considerations for the combustion efficiency of events with a fire or explosion. Table 1 and Table 2 below present the number of incidents, volume of gas lost, CH_4 released, CH_4 emissions, and CO_2 combusted emissions by year and by state, respectively. EPA incorporated the emissions for each of the events into the 2024 GHGI.

[12] Djizanne, H et al. 2014. Blowout in Gas Storage Caverns. *Oil & Gas Science and Technology - Revue d'IFP Energies nouvelles*, 69: 1251-1267. https://doi.org/10.2516/ogst/2013208ff.

Table 1. Total Incident Emissions by Year from 1990-2016 (mt CH_4)

Year	Number of Incidents	Volume of Gas Lost (mcf)	CH_4 Release (mt)[a]	CH_4 Emissions (mt)[b]	CO_2 Emissions (mt)[c]
1990	0	0	0	0	0
1991	0	0	0	0	0
1992	1	14	0.3	0.1	0.5
1993	0	0	0	0	0
1994	0	0	0	0	0
1995	0	0	0	0	0
1996	0	0	0	0	0
1997	0	0	0	0	0
1998	1	8,500	153	153	0
1999	0	0	0	0	0
2000	0	0	0	0	0
2001	1	143,000	2,572	1,029	4,846
2002	1	10,185	183	183	0
2003	1	350,000	6,296	6,296	0
2004	1	6,000,000	107,933	43,173	203,310
2005	0	0	0	0	0
2006	1	675,000	12,142	12,142	0
2007	0	0	0	0	0
2008	0	0	0	0	0
2009	0	0	0	0	0
2010	1	1,970	35	14	69
2011	1	42,919	772	772	0
2012	0	0	0	0	0
2013	0	0	0	0	0
2014	0	0	0	0	0
2015 [d]	1	4,500,000	78,350	78,350	0
2016 [d]	1	1,200,000	21,288	21,288	0
Total	**10**	**12,931,588**	**229,726**	**163,401**	**208,226**

[a] Methane released by the event, estimated using methane composition and density data from the inventory.
[b] Methane emissions from the event, taking into account any combustion by applying a 60 percent combustion efficiency value to events indicated as including gas ignition or explosion.
[c] Carbon dioxide emissions from events indicated as including gas ignition or explosion, calculated by applying a 60 percent combustion efficiency value. Methane and carbon dioxide composition data from the inventory was used to estimate carbon dioxide emissions.
[d] The Aliso Canyon event is included for 2015 and 2016 in Table 1. These values are already in the GHGI.

UNGS well events occurred in 10 inventory years with one event occurring each year. Other than 2015, which includes emissions from Aliso Canyon, the year with the highest methane emission is the year 2004 with 43,173 mt of CH_4 emissions. Incidents with emissions lower than 2,000 mt of CH_4 took place in the years 1992, 1998, 2001, 2010, and 2011.

Table 2. Total Incident emissions by State from 1990-2016 (mt of CH_4)

State	Number of Incidents	Volume of Gas Lost (mcf)	CH_4 Release (mt)[a]	CH_4 Emissions (mt)[b]	CO_2 Emissions (mt)[c]
TX	1	6,000,000	107,933	43,173	203,310
CA[d]	1	5,700,000	99,638	99,638	-
CO	1	675,000	12,142	12,142	-
LA	1	350,000	6,296	6,296	-
KS	2	153,185	2,756	1,212	4,846
OK	2	51,419	925	925	-
IA	1	1,970	35	14	69
KY	1	14	0.3	0.1	0.5
Total	**10**	**12,931,588**	**229,726**	**163,401**	**208,226**

[a] Methane released by the event, estimated using methane composition and density data from the inventory.
[b] Methane emissions from the event, taking into account any combustion by applying a 60 percent combustion efficiency value to events indicated as including gas ignition or explosion.
[c] Carbon dioxide emissions from events indicated as including gas ignition or explosion, calculated by applying a 60 percent combustion efficiency value. Methane and carbon dioxide composition data from the inventory was used to estimate carbon dioxide emissions.
[d] The Aliso Canyon event (already incorporated into the Inventory) is included with California in Table 2.

The state with the highest UNGS well incident emissions identified in this analysis, other than California, from 1990-2016 is Texas, which is due to the Moss Bluff incident. The most incidents at storage facilities occurred in Kansas and Oklahoma, with two events occurring in both states.

6 Requests for Stakeholder Feedback

EPA sought stakeholder feedback on the updates under consideration through a webinar, the November 2023 Storage Well Events memo, and in the public review draft of the GHGI. EPA received feedback from one stakeholder, and their feedback is summarized here.

The stakeholder recommended EPA use a combustion efficiency of 30 percent for uncontrolled release events, as presented in Gvakharia et al. 2017, instead of a combustion efficiency of 60 percent.[13] The commenter noted the study used to justify the 60 percent combustion efficiency evaluated engineered flares which may not be representative of combustion during emergency events.[14]

The requests for stakeholder feedback below were not updated for this memorandum and are copied from the November 2023 Storage Well Events memo:

EPA seeks stakeholder feedback on the updates under consideration discussed in this memo and the questions below.

1. EPA seeks feedback on including emissions resulting from UNGS well events to the time series.
2. EPA seeks feedback on the preliminary combustion efficiency value of 60 percent.
3. EPA seeks feedback on additional data sources or studies with information on anomalous leak events at storage wells.
4. EPA seeks feedback on whether and how events other than storage well events from Li et al. could be incorporated into the GHGI.

[13] Gvakharia et al. 2017. Methane, Black Carbon, and Ethane Emissions from Natural Gas Flares in the Bakken Shale, North Dakota. *Environmental Science & Technology.* 51: 5317-5325. https://doi.org/10.1021/acs.est.6b05183.
[14] Maasakkers, JD et al. 2022. Reconstructing and quantifying methane emissions from the full duration of a 38-day natural gas well blowout using space-based observations. *Remote Sensing of Environment*, 270: 112755. https://doi.org/10.1016/j.rse.2021.112755

Appendix A

Field Name	State	Date	Identified as a Well Blowout?	Leak Size (mcf)	CH_4 Release (mt)	CH_4 Emissions (mt)	CO_2 Emissions (mt)	Reference/PHMSA Report Number [a]
Aliso Canyon	CA	10/23/2015 – 2/18/2016	Y	5,000,000	99,638	99,638	-	(See Li et al. 2015)
Moss Bluff Storage	TX	8/19/2004-8/26/2004	Y	6,000,000	115,560	46,224	203,310	(See Evans and Chadwick 2009)
Fort Morgan	CO	10/1/2006	Y	675,000	13,001	13,001	-	(See Evans and Chadwick 2009)
Magnolia Gas Storage	LA	12/24/2003	Y	350,000	6,741	6,741	-	(See Evans and Chadwick 2009)
Yaggy	KS	1/1/2001	Y	143,000	2,754	1,102	4,846	(See Evans and Chadwick 2009)
Edmond	OK	5/24/2011	N	42,919	827	827	-	20110199
Cunningham	KS	10/1/2002	N	10,185	196	196	-	20020084
Stuart Storage	OK	12/10/1998	N	8,500	164	164	-	19990009
Redfield	IA	1/10/2010	N	1,970	38	15	69	20100019
Hawesville N W	KY	6/1/1992	N	14	0.3	0.1	0.5	19920093

[a] Additional information, including the event narrative, can be found for events with PHMSA numbers from the downloadable files at the following website: https://www.phmsa.dot.gov/data-and-statistics/pipeline/distribution-transmission-gathering-lng-and-liquid-accident-and-incident-data. For events without a PHMSA report number, the reference with narrative information is listed instead.