ATTACHMENT 2: Estimate of Methane Emissions from Major Dams and Reservoirs in the State of California

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Four Klamath River dams were removed which eliminated the emission of ~275,000 metric tonnes of CO2e/year

Summary

This report provides an estimate of methane emissions caused by major dams and reservoirs in the state of California. Emissions of methane, a powerful greenhouse gas, from reservoir surfaces and hydropower turbine degassing are significant and deeply concerning sources of human-caused greenhouse gas pollution identified by the Intergovernmental Panel on Climate Change (IPCC)[1]. This project utilized the greenhouse gas inventory methods described by the IPCC for surface methane emissions from reservoirs[2], using data provided by agencies within the State of California as well as academic and other public sources. The Open Source Global Dam Watch Consensus Database (GDWdb) was the primary source for information on reservoir location, size, and use[3]. The database identified 368 reservoirs wholly within the state of California with an area of approximately 4 hectares (10 acres) or larger in size, which represents more than 95% of the surface area and volume of the total number of reservoirs (>1,200) in the state of California. Within the database there were 96 dam facilities identified as providing hydroelectricity as a primary or secondary use.

Total surface methane emissions from these reservoirs are estimated to be 4.1 +/- 0.51 million metric tonnes (Tg) CO_2e per year. Total turbine degassing emissions are estimated to be 1.2 +/- 0.22 million metric tonnes (Tg) CO_2e per year. When combined, these are equal to approximately 1.4% of the State of California's emissions reported in 2022[4].

On a carbon dioxide equivalency basis (CO_2e), surface methane emissions from the reservoirs analyzed for this study are comparable to total emissions from aviation, or the total emissions from ships, and are comparable to about half of the emissions within California from the waste sector, or about half of the emissions from cement manufacturing. Turbine degassing methane emissions from the facilities analyzed are estimated to be about a quarter of the emissions from reservoir surface methane emissions.

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[1] Lovelock *et* al. 2019. Chapter 7: Wetlands, in 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch07_Wetlands.pdf

[2] *Ibid*.

[3] Lehner, Bernhard; Beames, Penny; Mulligan, Mark; Zarfl, Christiane; De Felice, Luca; van Soesbergen, Arnout; et al. (2024). Global Dam Watch database version 1.0. figshare. Dataset. https://doi.org/10.6084/m9.figshare.25988293.v1

[4] California Air Resources Board. 9/20/2024. California Greenhouse Gas Emissions from 2000 to 2022: Trends of Emissions and Other Indicators. https://ww2.arb.ca.gov/sites/default/files/2024-09/nc-2000_2022_ghg_inventory_trends.pdf

The largest estimated point-source emissions from turbine degassing methane emissions are from B.F. Sisk/"San Luis Dam" (285,100 metric tonnes CO_2e/yr) and Lake Almanor Dam (221,100 metric tonnes CO_2e/yr).

This analysis does not include other significant emissions pathways from operating dams and reservoirs that are currently not inventoried by the State of California, including emissions from reservoir sediments after dam decommissioning.

The emissions estimates provided in this report are likely conservative under-estimates of the actual emissions. Improvements to the IPCC method, combined with improvements in data gathering and incorporating emissions from out-of-state reservoirs used to capture and store water and/or generate electricity imported to California, could increase the estimate of reservoir surface and turbine degassing methane emissions by a factor of 2x-4x, making surface methane emissions comparable to emissions from California statewide emissions categories including refrigerants, commercial buildings, general fuel use, or livestock.

Introduction

Over the last two decades, knowledge about the environmental impacts of dams and reservoirs has increased significantly, with a focus on the greenhouse gas (GHG) emissions they cause. Recent science has shown that dam, reservoir, and hydropower facilities worldwide cause the emission of hundreds of millions of tons of greenhouse gases including carbon dioxide, methane, and nitrous oxide each year. The emissions are present throughout the life cycle of dam and reservoir systems, including:

- Construction
- Facility operations and maintenance
- Reservoir surfaces
- Degassing methane through hydropower turbines and non-hydropower bypasses and spillways
- Carbon leakage from land use changes beyond the reservoir, including deforestation and vegetation changes, to replace inundated farmland, grazing land, and homes
- Land use changes beneath the reservoir, including loss of carbon sequestration by vegetation that becomes inundated and emissions from anaerobic decay of that vegetation, as well as the lost ecosystem function of future carbon sequestration in the inundated former forest

- Downstream effects caused by altered river hydrographs and reductions in river flows, including carbon loss from dewatering of inland and coastal wetlands, riparian forests, and estuary ecosystems
- Facility decommissioning

Emissions using cradle-to-grave life cycle inventory methods have been described in the scientific literature[5]. Tell the Dam Truth has analyzed life cycle greenhouse gas emissions from four sets of dam, reservoir & hydropower facilities in California, including on the Klamath[6], Colorado[7], and Yuba Rivers[8], as well as one proposed new off-channel facility (Sites Reservoir[9]).

None of the above-listed emissions sources attributed to dam facilities are currently included in the State of California's efforts to inventory greenhouse gas emissions. This report includes estimates from, and demonstrates potential methods for, biogenic methane emissions inventories from reservoir surfaces and turbine degassing.

Emissions of methane from reservoir surfaces and turbine degassing have been demonstrated to dominate the greenhouse gases in these systems. Methane is particularly concerning, and research studies have identified reducing and eliminating human-caused methane emissions as a critical challenge of the next two decades[10]. Methane emissions from reservoir surfaces and turbine degassing have not, however, been included in national, state, or regional greenhouse gas inventories until recently. In 2022, the United States was the first country to include greenhouse gas emissions from reservoir surfaces and turbine degassing in its yearly greenhouse gas inventory. At the time of this report, the State of California has not yet included reservoir surface or turbine degassing emissions in its statewide inventory of greenhouse gas emissions[11].

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[5] Song, Cuihong, Kevin H. Gardner, Sharon J.W. Klein, Simone Pereira Souza, and Weiwei Mo. "Cradle-to-Grave Greenhouse Gas Emissions from Dams in the United States of America." *Renewable and Sustainable Energy Reviews* 90 (July 2018): 945–56. https://doi.org/10.1016/j.rser.2018.04.014.
[6] Wockner, G., M. Easter, and G. McCurry. 2025. Greenhouse Gas Emissions at Four Klamath River Dam Facilities, and Post-Dam Removal Carbon Sequestration, Estimated by the All-Res Modeling Tool. https://tellthedamtruth.com/wp-content/uploads/2025/11/Klamath-All-Res-Final-2025-11-21.pdf
[7] Wockner, G., M. Easter, and G. McCurry. 2025. Estimate of Greenhouse Gas Emissions for the Glen Canyon and Hoover Dam Facilities using the All-Res Modeling Tool. https://tellthedamtruth.com/wp-content/uploads/2025/02/Glen-Canyon-and-Hoover-Emissions-Final.pdf
[8] Wockner, G., M. Easter, and G. McCurry. 2024. Estimate of Greenhouse Gas Emissions for the Englebright Dams and Reservoirs using the All-Res Modeling Tool. https://tellthedamtruth.com/wp-content/uploads/2025/11/Englebright-All-Res-Final-3-31-2025.pdf Sis
[9] Wockner, G., M. Easter, and G. McCurry. 2023. Estimate of Greenhouse Gas Emissions for the proposed Sites Reservoir using the All-Res Modeling Tool. https://tellthedamtruth.com/wp-content/uploads/2023/08/Sites-Reservoir-Projectect-Emissions-V4.pdf
[10] Jackson, Rob. Global Carbon Project. 2024. *Into the Clear Blue Sky*. Scribner, New York.
[11] *Ibid*.

This report includes an estimate of surface methane emissions from reservoirs located within the state of California that have been identified in a consolidated public database of lakes and reservoirs worldwide[12]. While this estimate includes only reservoirs within the State's boundaries, it is important to note that the State of California currently includes in its statewide inventory the emissions from energy imported to the state. California's water supply is stored and delivered from highly-interconnected dam and reservoir systems in multiple other states, including Colorado, Arizona, Utah, New Mexico, Nevada, and Wyoming; however, those emissions are not included in this report. The surface emissions from reservoirs on the Colorado and Green Rivers that are involved in storing and delivering water and electricity for use in California have a total surface area, and likely emissions, comparable to the California reservoirs analyzed in this study. A significant amount of the water stored behind and delivered from these systems, and the electricity they generate, is dedicated to the State of California. Accounting for those emissions from imported water and electricity would significantly increase the emissions from dams and reservoirs in the statewide inventory.

Methods

Surface Methane Emissions

Both methane and carbon dioxide are significant emissions from reservoir surfaces. However, it is unclear to what degree carbon dioxide emissions from reservoir surfaces are simply displaced from some other location in the watershed[13]. Surface methane emissions from reservoirs, in contrast, have been identified as unlikely to have occurred under baseline conditions in watersheds without reservoirs[14]. Surface emissions were estimated using greenhouse gas inventory methods developed by the Intergovernmental Panel on Climate Change (IPCC)[15], consistent with the approach used in the California Air Resources Board greenhouse gas inventory. The GWP_{100} global warming potential for

[12] Lehner, Bernhard; Beames, Penny; Mulligan, Mark; Zarfl, Christiane; De Felice, Luca; van Soesbergen, Arnout; et al. (2024). Global Dam Watch database version 1.0. figshare. Dataset. https://doi.org/10.6084/m9.figshare.25988293.v1
[13] Prairie, Yves T., Jukka Alm, Jake Beaulieu, et al. "Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See?" Ecosystems 21, no. 5 (2018): 1058–71. https://doi.org/10.1007/s10021-017-0198-9.
[14] Deemer, BR, JA Harrison, SY Li, JJ Beaulieu, T Delsontro, N Barros, JF Bezerra-Neto, SM Powers, MA dos Santos, and JA Vonk. "Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis." BIOSCIENCE 66, no. 11 (November 2016): 949–64. https://doi.org/10.1093/biosci/biw117
[15] *Ibid*.

methane[16] was utilized in the modeling, per CARB policy for inventory purposes. For surface methane emissions, the inventory method depends upon three physical attributes of the reservoirs: 1) reservoir surface area; 2) reservoir trophic status; and 3) IPCC Climate region where the reservoir is located.

Reservoir Surface Area

This report utilized the spatial data provided by the Global Dam Watch Consensus database (GDWdb)[17]. The database provides the spatial delineation of global waterbodies approximately larger than four hectares in size within the Continental United States. The database identified 368 reservoirs wholly within the state of California with an area of approximately four hectares (10 acres) or larger in size, which represents more than 95% of the surface area and volume of the total number of reservoirs (>1,200) in the state of California[18]. The USGS National Hydrography database[19] and the LT[20] database have similar capabilities; however, those datasets do not distinguish between reservoirs and natural lakes with the accuracy of the GDWdb.

Reservoir Trophic Status

Attempts have been made to estimate the trophic status of reservoirs using satellite-based sensors that detect the chlorophyll concentration at the reservoir surface[21]. Reservoir surface methane emissions are correlated with reservoir trophic status, and surface chlorophyll a concentrations in reservoirs are correlated with reservoir trophic status[22]. At the present time, no aggregated, reliable spatial database has been built that reliability

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[16] Intergovernmental Panel on Climate Change (IPCC). (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Shukla, P. R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley (eds.)]. Cambridge University Press. doi:10.1017/9781009157926

[17] Lehner, Bernhard; Beames, Penny; Mulligan, Mark; Zarfl, Christiane; De Felice, Luca; van Soesbergen, Arnout; et al. (2024). Global Dam Watch database version 1.0. figshare. Dataset. https://doi.org/10.6084/m9.figshare.25988293.v1

[18] https://water.ca.gov/programs/all-programs/division-of-safety-of-dams

[19] USGS 2023. National Hydrography Dataset. https://www.usgs.gov/national-hydrography/national-hydrography-dataset

[20] Meyer, M.F., S.N. Topp, T.V. King, R. Ladwig, R.M. Pilla, H.A. Dugan, J.R. Eggleston, S.E. Hampton, D.M. Leech, I.A. Oleksy, J.C. Ross, M.R. Ross, R.I. Woolway, X. Yang, M.R. Brousil, K.C. Fickas, J.C. Padowski, A.I. Pollard, J. Ren, and J.A. Zwart. 2023. National-scale, remotely sensed lake trophic state (LTS-US) 1984-2020 ver 1. Environmental Data Initiative. https://doi.org/10.6073/pasta/212a3172ac36e8dc6e1862f9c2522fa4 (Accessed 2025-10-06)

[21] Hanly, Patrick J., Katherine E. Webster, and Patricia A. Soranno. 2025. “LAGOS-US LANDSAT: Remotely Sensed Water Quality Estimates for U.S. Lakes over 4 Ha from 1984 to 2020.” https://doi.org/10.1101/2024.05.10.593626

[22] Deemer, B. R., and M. A. Holgerson. Drivers of Methane Flux Differ Between Lakes and Reservoirs, Complicating Global Upscaling Efforts. Journal of Geophysical Research: Biogeosciences 126, no. 4 (2021): e2019JG005600. https://doi.org/10.1029/2019JG005600.

reports these data for reservoirs[23],[24]. Therefore, the trophic status of a subsample of reservoirs in California was used for this report and extended to the entire state, with estimates of associated uncertainty[25]. The report indicated that 40% of reservoirs were eutrophic or hypereutrophic, and 60% of reservoirs were oligotrophic or mesotrophic. For the purposes of this project, 20% of reservoirs were assumed to be hypereutrophic, 20% were eutrophic, 30% were mesotrophic, and 30% were oligotrophic. The uncertainty of these estimates was not quantified in the study, so an uncertainty of 33% was applied to these proportions for modeling purposes.

IPCC Climate Region

Lewis (2022) created a spatial delineation of IPCC climate regions[26] based on the CRU world climate database[27]. This map was utilized to determine the IPCC climate region for each reservoir modeled for this project.

The data from these three datasets were combined to create the data in Table 1 for modeling purposes.

Table 1. Combined input data used to estimate surface methane emissions in California Reservoirs.

Climate Region	**Trophic Status**	**Reservoir Surface Area (hectares)**
warm temperate dry	Oligotrophic	24,532 +/- 8,096
warm temperate dry	Mesotrophic	24,532 +/- 8,096
warm temperate dry	Eutrophic	16,355 +/- 5,397
warm temperate dry	Hypereutrophic	16,355 +/- 5,397
warm temperate moist	Oligotrophic	2,290 +/- 756
warm temperate moist	Mesotrophic	2,290 +/- 756
warm temperate moist	Eutrophic	1,527 +/- 504
warm temperate moist	Hypereutrophic	1,527 +/- 504
cool temperate moist	Oligotrophic	129 +/- 42
cool temperate moist	Mesotrophic	129 +/- 42

[23] The LAGOS-LANDSAT database has been reported to under-report the uncertainty of its estimates, and was not selected for this project.
[24] The LTS-US dataset has emerged as a potential vehicle for this purpose, however at the time the modeling for this work was completed, it had not been applied in this way. (Meyer, Michael F., Simon N. Topp, Tyler V. King, et al. National-Scale Remotely Sensed Lake Trophic State from 1984 through 2020. Scientific Data 11, no. 1 (2024): 77. https://doi.org/10.1038/s41597-024-02921-0)
[25] Smith, J. et al. 2025. Central Valley Lakes and Reservoirs Eutrophication Assessment. California Surface Water Ambient Monitoring Program. https://www.waterboards.ca.gov/centralvalley/water_issues/swamp/cv_lakes_eutrophication_techrpt.pdf
[26] Lewis, M. (2022). IPCC Climate Zones (from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories) (0.1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7303808
[27] Harris, I., Jones, P., Osborn, T. and Lister, D. (2014), Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. Int. J. Climatol., 34: 623-642. https://doi.org/10.1002/joc.3711

cool temperate moist	Eutrophic	86 +/- 28
cool temperate moist	Hypereutrophic	86 +/- 28
cool temperate dry	Oligotrophic	27,531 +/- 9,085
cool temperate dry	Mesotrophic	27,531 +/- 9,085
cool temperate dry	Eutrophic	18,354 +/- 6,057
cool temperate dry	Hypereutrophic	18,354 +/- 6,057

A Monte Carlo simulation of 1,000 iterations was used to randomly combine uncertainties in emission factors, trophic status, and global warming potential, as recommended by the IPCC[28]. Simulations made random draws on probability density functions or ranges for each variable or input activity data item, whichever was applicable. Emissions factors within equations were assumed to be independent and uncorrelated, as no correlation coefficients have been published in the IPCC method for the emissions factors and the input activity data.

Turbine Degassing Methane Emissions

Turbine degassing has been identified as a significant source of methane in hydropower facilities throughout the world[29]. The IPCC method for these emissions quantifies those emissions simply as 8% of the reservoir surface methane emissions[30]. However, the authors of that IPCC method identified this estimate as a significant undercounting of likely actual degassing emissions in a paper by Harrison *et al*. (2021)[31]. In that paper, those authors identified turbine degassing as likely totaling 55% of total reservoir methane emissions from facilities with hydropower turbines. The paper did not provide an updated equation for turbine degassing emissions, but that estimate of 55% implies that turbine degassing emissions are likely at least the same as surface methane emissions. A subsequent paper by Delwiche *et al*. (2022) conservatively estimated turbine degassing

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[28] Frey, Christopher, Jim Penman, Lisa Hanle, Suvi Monni, and Stephen Ogle. 2003. Chapter 3: Uncertainties, in 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_3_Ch3_Uncertainties.pdf

[29] Deemer, BR, JA Harrison, SY Li, JJ Beaulieu, T Delsontro, N Barros, JF Bezerra-Neto, SM Powers, MA dos Santos, and JA Vonk. "Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis." BIOSCIENCE 66, no. 11 (November 2016): 949–64. https://doi.org/10.1093/biosci/biw117

[30] Lovelock *et* al. 2019. Chapter 7: Wetlands, in 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch07_Wetlands.pdf

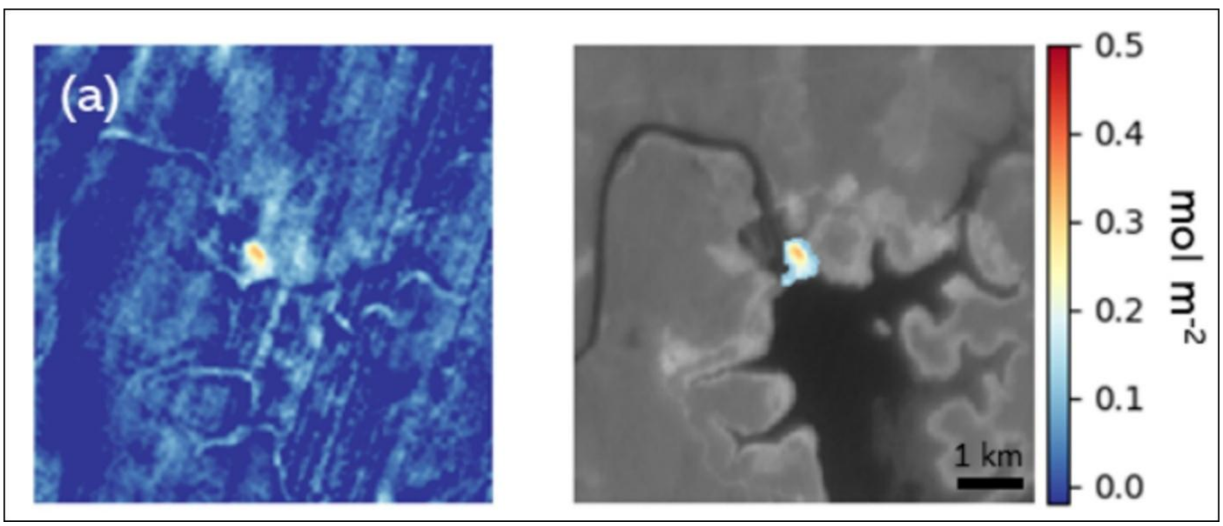
[31] Harrison, John A., Yves T. Prairie, Sara Mercier-Blais, and Cynthia Soued. "Year-2020 Global Distribution and Pathways of Reservoir Methane and Carbon Dioxide Emissions According to the Greenhouse Gas From Reservoirs (G-res) Model." Global Biogeochemical Cycles 35, no. 6 (2021): e2020GB006888. https://doi.org/10.1029/2020GB006888.

emissions to be 80-100% of surface methane emissions[32], while noting that measured emissions in many facilities were much higher[33].

In light of the correction provided by the authors of the IPCC method, and based on their published research and that of others, this analysis does not utilize the emissions factor of 8% of surface emissions as recommended by the IPCC method. This paper uses the estimate that turbine emissions are 80% of surface methane emissions. Despite increasing the percentage from the previous IPCC methodology, it is important to note that 80% is still a conservative emission factor that is unlikely to overstate the actual emissions.

The uncertainty of the emissions are propagated in the equations using Monte Carlo simulation methods recommended by the IPCC, as with the surface methane emissions[34].

Turbine methane emissions are a type of facility emission that can actually be seen on satellite images. Below is an example of a methane plume emitting from a hydropower turbine, in one of the very few cases where a satellite was trained on a dam to test the technology, in Cameroon. In the peer-reviewed paper, the authors wrote, *"On 20 April 2017 we observed a methane plume over the dam vanes of the Lom Pangar hydro-electric reservoir in eastern Cameroon that was flooded the previous year. Hydro-electric reservoirs are a known source of methane and carbon dioxide emissions."*[35]



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[32] Delwiche, Kyle B., John A. Harrison, Joannes D. Maasakkers, et al. "Estimating Drivers and Pathways for Hydroelectric Reservoir Methane Emissions Using a New Mechanistic Model." Journal of Geophysical Research: Biogeosciences 127, no. 8 (2022). https://doi.org/10.1029/2022JG006908
[33] Delwiche, Kyle. 2024. Personal Communication.
[34] *Ibid*.
[35] IMAGE FROM: Jervis, D, J McKeever, BOA Durak, et al. **"The GHGSat-D Imaging Spectrometer."** *ATMOSPHERIC MEASUREMENT TECHNIQUES* 14, no. 3 (2021): 2127–40. WOS:000631085800001. https://doi.org/10.5194/amt-14-2127-2021.

AI-Assistance in the Modeling Effort

We utilized the Gemini large language model[36] to optimize the multiple disparate datasets needed for modeling both the surface methane emissions and turbine degassing emissions. Gemini constructed code in both Python and R that were utilized to conduct both spatial and non-spatial joins needed to combine datasets, to identify subsets of the input datasets for use in quality control and quality assurance, and in the greenhouse gas emissions modeling itself. Queries conducted in Gemini assisted in ruling out unhelpful datasets while identifying the optimum datasets necessary for this modeling effort. The results of Gemini queries, after independent verification, aided in identifying dam facilities bordering on and outside of the state of California that are used to store, manage, and deliver water and generate hydroelectricity utilized within the state of California.

Results

The results of the analysis of reservoir surface and turbine degassing methane emissions from the GDWdb dataset for California reservoirs are shown in Figure 1 below.

[36] Anil et al. 2023. Gemini: A family of highly capable multimodal models. https://doi.org/10.48550/arXiv.2312.11805

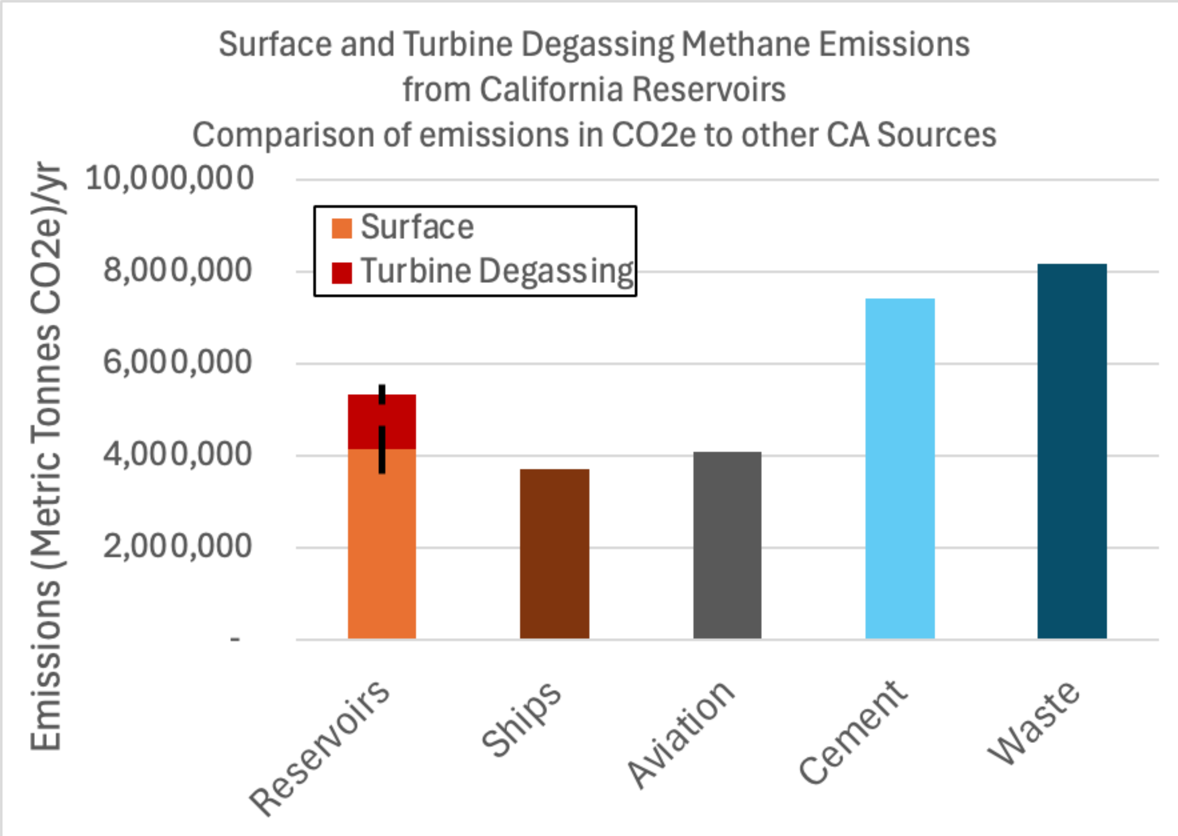

Figure 1. Surface and turbine methane emissions from California reservoirs, compared with other emissions sources.

The estimated reservoir surface methane emissions are approximately half those from the waste sector, half those from the cement manufacturing sector, and comparable to emissions from fuel burned by ships, or fuel burned in aviation. **Importantly, shipping, large-scale aviation, cement manufacturing, and waste facilities are all currently included in the State's inventory.**

Emissions from turbine degassing from the 96 hydropower facilities included in this analysis are approximately a quarter of the total surface methane emissions from the 368 reservoirs examined in this study.

The estimated emissions from the eight largest emitters of turbine degassing methane emissions in California are shown in Figure 2 below.

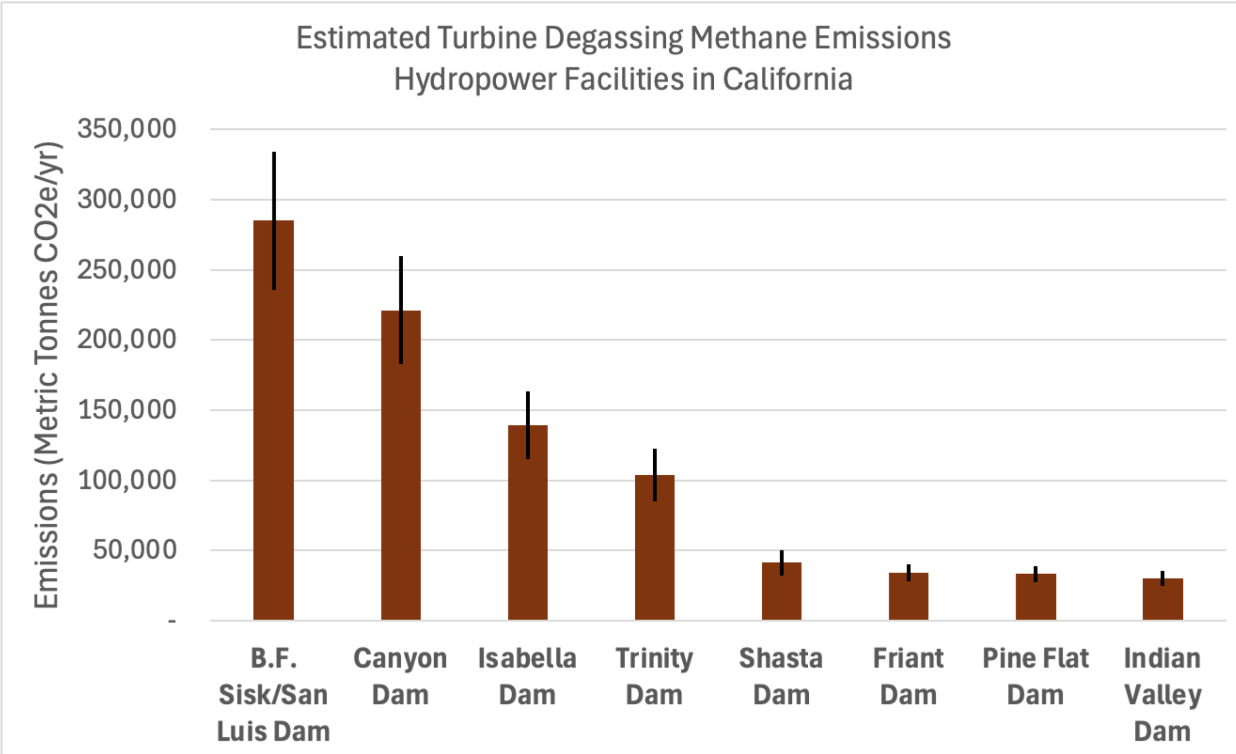

Figure 2. Estimates of turbine degassing emissions from the eight largest emitters in California, as derived from attributes in the GDWdb consensus database.

Discussion

This paper describes an emissions estimate approach for reservoir surface and turbine degassing methane emissions in the state of California. The major drivers of surface methane emissions from reservoirs, and associated turbine emissions, are the size of reservoirs, and the trophic status of reservoirs. Large reservoirs that are identified to be oligotrophic or mesotrophic are likely to have lower overall emissions than smaller reservoirs that are eutrophic or hypereutrophic. This comparison is apparent in the difference in emissions in Figure 2. This is primarily due to the effect that eutrophication has on reservoir methane emissions. A eutrophic reservoir is estimated to have 3.3 times greater emissions than a mesotrophic reservoir of the same characteristics. Similarly, a hypereutrophic reservoir of the same characteristics would have 2.7 times more emissions than a eutrophic reservoir, and 9 times greater emissions than a comparable mesotrophic reservoir. The reasons for this are summarized in a literature review in the IPCC methods document[37]. As noted in the earlier description of methods, 40% of California reservoirs are estimated to be eutrophic or hypereutrophic, which matches analysis in the USEPA National Lakes Assessment[38]. Of the factors included in this modeling effort, eutrophication of reservoirs is the greatest driver of surface methane and turbine degassing emissions.

There are reasons to believe that these emissions estimates, utilizing methods recommended by the IPCC, could be significantly lower than the actual emissions. A summary of recommended modeling improvements follows:

- The method developed by the IPCC utilizes a metamodel approach that in the opinion of this author is inadequately constrained by actual measurements of reservoir surface emissions. Deemer *et al*. (2016,2020) developed a worldwide dataset of reservoir surface emissions with emissions by climate region approximately twice as large as the emission factors recommended by the IPCC[39]. In the opinion of this author, using empirically-derived emissions factors is a more accurate reflection of the actual emissions, and would likely increase the emissions estimates by 80-100%.

- Because of the resolution of the satellite sensors used, reservoir surface estimates are constrained to water bodies greater than approximately 4 hectares (10 acres) in size. Reservoir shape and geometry can also limit their ability to be accurately detected from space, meaning somewhat larger reservoirs up to 10 hectares (25 acres) that exist may not be included in the databases used. There are a significant number of small reservoirs in the state of California smaller than that baseline threshold. Small reservoirs are reported to be prone to eutrophication and have much higher methane emissions/hectare than larger water bodies[40]. There are likely to be hundreds to thousands of uncatalogued small agricultural reservoirs in the state that are significant sources of emissions. Estimating the emissions from those

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[37] Lovelock *et* al. 2019. Chapter 7: Wetlands, in 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch07_Wetlands.pdf

[38] U.S. Environmental Protection Agency. 2024. National Lake Assessment 2022. EPA 841-R-24-006. U.S. Environmental Protection Agency, Office of Water and Office of Research and Development. https://www.epa.gov/national-aquatic-resource-surveys/reports-and-data-national-lakes-assessment-2022

[39] Deemer, BR, JA Harrison, SY Li, JJ Beaulieu, T Delsontro, N Barros, JF Bezerra-Neto, SM Powers, MA dos Santos, and JA Vonk. “Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis.” BIOSCIENCE 66, no. 11 (November 2016): 949–64. https://doi.org/10.1093/biosci/biw117

[40] Malerba, Martino E., Tertius De Kluyver, Nicholas Wright, Lukas Schuster, and Peter I. Macreadie. “Methane Emissions from Agricultural Ponds Are Underestimated in National Greenhouse Gas Inventories.” Communications Earth & Environment 3, no. 1 (2022): 306. https://doi.org/10.1038/s43247-022-00638-9

water bodies was not possible for this study. In the opinion of this author, including these water bodies could lead to an increase in estimated surface emissions of 15-25%, or approximately 750,000 – 1,000,000 metric tonnes of CO_2e /yr.

- Imported energy generated outside the state is identified as a significant source of greenhouse gas emissions in the California greenhouse gas inventory. Reservoirs and infrastructure on the Colorado River in adjoining states upstream impound water for delivery to and use within California. For Example, Lake Powell and Lake Mead (reservoirs) on the Colorado River have more surface area than all of the combined reservoirs identified in the GDWdb database within California, and they deliver significant portions of their reservoir volume to the state. Emissions apportioned from those reservoirs and others associated with delivering water to California could roughly double the state's surface methane emissions.

- Uncertainty in estimates of the turbine emissions is likely underestimated, as no basis for estimating variance of the emission factor of 80% of surface methane emissions is available in the literature. Consulting with experts in developing an emissions method for the state of California may lead to a useful probability density function, or range of likely emissions, that would improve the uncertainty estimate.

If the IPCC methods were improved to address the above issues, reservoir surface area for reservoirs < 4 ha in size were available for use, and emissions from reservoirs used to store water imported from other states were incorporated, the total surface methane emissions from reservoirs could be comparable to multiple other emissions sources in California, on a CO_2e basis, including refrigerants, commercial buildings, general fuel use, or livestock.