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Review

Hydropower Reservoir Greenhouse Gas Emissions: State of the Science and Roadmap for Further Research to Improve Emission Accounting and Mitigation

Surabhi Karambelkar *, Maryalice Fischer and Shannon Ames

Low Impact Hydropower Institute, Boston, MA 02111, USA
* Correspondence: skarambelkar@lowimpacthydro.org

Abstract

Rapidly decarbonizing the electricity grid is crucial for achieving net-zero greenhouse gas (GHG) emissions by mid-century and mitigating climate change impacts. Hydropower facilities can directly support grid decarbonization; however, like all energy systems, they emit GHGs throughout their lifecycle, with reservoirs being an important source. Further research is urgently needed to improve the accounting and mitigation of hydropower reservoir GHG emissions to ensure that this technology is accurately considered in decarbonization policies and to allow project owners and energy buyers to make credible emission claims regarding this energy source. To this end, this paper reviews over seven dozen studies and emerging research to synthesize the current state of the science on reservoir GHG emission pathways as well as advancements in emission measurement tools to identify areas where further research is needed. This paper presents a research roadmap for government agencies, research institutions, and funding organizations covering four action areas: understanding and reducing uncertainties in reservoir GHG estimation and associated publicly accessible estimation tools; reducing the technical and economic barriers for reservoir managers to use GHG estimation tools; setting common standards to enable consistent monitoring, allocation, and reporting of reservoir GHG emissions; and supporting work on reservoir GHG emission mitigation strategies, including watershed-scale strategies. Progress in these areas will enable robust accounting of hydropower reservoir GHG emissions and targeted mitigation efforts to advance grid decarbonization.

Keywords: hydropower; reservoirs; greenhouse gas emissions; methane; mitigation; policy

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Academic Editor: Pallav Purohit

Received: 16 May 2025
Revised: 17 June 2025
Accepted: 23 June 2025
Published: 24 June 2025

Citation: Karambelkar, S.; Fischer, M.; Ames, S. Hydropower Reservoir Greenhouse Gas Emissions: State of the Science and Roadmap for Further Research to Improve Emission Accounting and Mitigation. *Sustainability* **2025**, *17*, 5794. https://doi.org/10.3390/su17135794

1. Introduction

The climate challenge is an energy challenge: the energy sector accounts for approximately two-thirds of the global greenhouse gas (GHG) emissions [1,2]. Limiting and avoiding GHG emissions from the energy sector is at the heart of the solution to avoiding dangerous increases in global temperatures and some of the most catastrophic impacts of climate change. Globally, the public and private sectors have stepped up efforts to mitigate climate change by addressing the energy sector's GHG emissions [3,4]. Since the adoption of the Paris Agreement in 2015, scores of nations have adopted pledges in either law or in policy documents to decarbonize their electricity grids—and lower their dependence on traditional fossil-based generation—and reach economy-wide net-zero emissions by mid-century [4]. Over the last decade, private sector entities have also adopted ambitious net-zero emissions goals and have committed to shifting their electricity sourcing from fossil-based resources to renewable sources [3].

Hydropower provides essential services that can directly support grid decarbonization goals. This resource can provide storage and flexible grid support services that are vital for integrating increasing amounts of intermittent renewable resources and enhancing grid resiliency and reliability [5]. Hydropower's strategic value is more important than ever in a 24/7 clean generation scenario: this resource can serve in the historical role of fossil-fuel based generation given its ability to operate at all hours of the day and ramp up when wind and solar generation are unavailable [6,7].

However, hydropower facilities, like all energy systems, can emit GHG emissions over their entire lifecycle [8,9]. The Intergovernmental Panel on Climate Change (IPCC) estimates that the median lifecycle GHG emission intensity for hydropower is 24 gCO_2eq/kWh, which equates to the grams of carbon dioxide equivalent generated per kilowatt-hour of electricity produced, allocated over the life of a hydropower project [9]. The IPCC-estimated hydropower median lifecycle GHG emission intensity is lower than power plants fueled by coal (820 gCO_2eq/kWh) and natural gas (490 gCO_2eq/kWh) [9]. However, it is worth noting that an individual hydropower facility may have a lifecycle GHG emission intensity that is vastly different than the IPCC median value [10]. Human-made reservoirs can emit GHGs [2,11–14], and for hydropower facilities with a reservoir—regardless of whether hydropower generation is the primary purpose of the reservoir—the creation and unique characteristics of the reservoir along with its ongoing operation plays a key role in influencing the overall rate of GHG emissions from individual facilities [15–19].

Crafting policies to advance decarbonization goals as well as tracking progress towards achieving those goals requires accurate accounting of GHG emissions. Given hydropower's value in enabling a renewable energy transition, it is vital to support further research to help improve the assessment, ongoing monitoring, and reporting of GHG emissions linked to hydropower facilities. While some existing regulatory and market-based policies consider the carbon emission intensity of hydropower [20–24], these policies rely on general thresholds of carbon emission intensity or assumptions around the GHG emissions at individual projects that may be inaccurate or imprecise in practice. Further research on GHG emission accounting at hydropower facilities is therefore needed to help better understand the complexity of GHG emissions at individual projects and identify where targeted action may be needed to minimize or mitigate GHG emissions. Crucially, this research will be vital in ensuring that policies and financial incentives truly advance grid decarbonization. With the emerging focus on GHG emission disclosure [25,26], research on improving GHG emission accounting will also be important for hydropower owners and energy buyers in making credible claims regarding the emission intensity of their power source.

Against this background, this paper aims to: (1.) provide a review of the current state of the science on the sources and patterns of GHG emissions at reservoirs; (2.) highlight advances in GHG emission measurement tools and techniques; and (3.) present a roadmap of research areas where further work is needed to advance the accounting and mitigation of hydropower reservoir GHG emissions. This paper is organized as follows: Section 2 outlines the materials and methods used in this review. Section 3 provides an overview of what we know today about reservoir GHG emissions, including those with hydropower facilities. Section 4 outlines the advances in both direct measurement techniques and modeling tools for estimating reservoir GHG emissions. Section 5 builds on the state of the science to present a roadmap of further research areas for assessing and addressing hydropower reservoir GHG emissions, which in turn, can help move policy forward. Section 6 presents the concluding remarks.

2. Materials and Methods

This paper seeks to help advance research on the accounting and mitigation of hydropower reservoir GHG emissions. While many notable scholarly studies on the topic of reservoir GHG emissions and hydropower reservoir GHG emissions have been published (as will be discussed in Sections 3 and 4), this paper contributes to the body of existing knowledge by not only synthesizing what we know today from the various studies but also identifying research gaps and developing a roadmap of action areas where more work is needed to drive climate policy forward. To this end, this paper synthesizes findings from the review of over seven dozen scholarly publications, government reports, and other studies on the topic of reservoir GHG emissions. The relevant articles were primarily identified using Google Scholar using permutations of the keywords 'hydropower', 'hydroelectric', 'reservoir', 'greenhouse gas emissions', 'emissions', and 'methane.' Since the authors are engaged in the Uncommon Dialogue on Hydropower, River Restoration, and Public Safety—a leading group of non-governmental organizations, hydropower companies, trade associations, government agencies, universities, and investors working on dam-related issues in the United States [27]—a few studies and advancements in tools and techniques were shared in and by members in this group. As such, the relevant articles include global scholarly studies on GHG emissions from reservoirs generally and hydropower reservoirs specifically [13,17–19,28,29], including the latest published research from the United States [30,31].

The relevant studies were analyzed to identify: (1.) the drivers and pathways of reservoir GHG emissions, including specific trends for hydropower reservoirs; (2.) the current available tools and techniques for measuring and estimating reservoir GHG emissions; and (3.) gaps in our scientific understanding of reservoir emissions and available GHG estimation tools. As this paper has been written by science-policy practitioners based in the United States, it takes into account the specific U.S. context where less than 3% of the over 90,000 dams have hydropower and most of these dams were built decades ago [32]. As a result, this paper presents findings on reservoir GHG emissions broadly since the conclusions around areas for further research will equally apply to improving the accounting and mitigation of the anthropogenic emissions from water reservoirs, with or without hydropower. Furthermore, while this paper is grounded in a U.S. perspective, the research recommendations are equally applicable globally.

3. Reservoir Greenhouse Gas Emissions: What We Know Today

Humans have altered river systems for millennia, and the construction of dams and reservoirs has often been considered an important driver of human development, given their role in supporting critical functions of water management and energy generation [33]. However, the development of human-made reservoirs also has a long history of conflicts and socio-ecological impacts [33–36].

Beginning with influential studies in the 1990s, there has been growing attention and debate about the impact of human-made reservoirs, including those with hydropower generation, on GHG emissions [11,12,37–41]. Human-made reservoirs change the way carbon moves through fluvial systems [17,19,41]. Scientific studies have highlighted that human-made reservoirs are distinct from natural systems in several key ways that may amplify their GHG emissions [11,17]. Deemer et al. [17] have synthesized these distinctions noting that the process of flooding large tracts of land for reservoir creation may add to microbial decomposition and the release of GHG emissions, that the high catchment area-to-surface area ratios of reservoirs and proximity to human activities can increase nutrient loading (compared to natural lakes) that can in turn fuel productivity and resulting decomposition, and that the fluctuations in water levels in human-made reservoirs can enhance methane bubbling. Over the years, studies have documented that human-made reservoirs can emit GHGs including carbon dioxide, nitrous oxide, and the potent climate-warming gas, methane [2,11–14,16,42], and have highlighted the need to better understand the drivers of GHG emissions at individual reservoirs.

With this context, this section provides an overview of the state of the science on what we know today about the drivers and pathways of GHG emissions at reservoirs as well as key ongoing studies in the United States that aim to improve our understanding of reservoir GHG emissions.

3.1. Known Pathways of Reservoir GHG Emission

Emerging research is adding to our understanding of the key GHG emission pathways at reservoirs, including those with hydropower facilities. Studies highlight four main pathways which include continuous diffusion across the surface of the reservoir, bubbling or 'ebullition' from sediments, vascular transport in emergent and floating-leaved aquatic plants, and degassing caused by pressure change at the outlet of turbines and spillways [13,14,17–19,28,42–44]. In addition, researchers have identified drawdown emissions as an important pathway. Drawdown emissions occur when fluctuating water levels in a reservoir cause large changes in hydrostatic pressure and create conditions where sediments are periodically inundated with water and then exposed to the atmosphere [17,43,45,46]. Some of these known pathways—such as drawdown emissions and degassing—are either nonexistent or of marginal importance in natural lakes [17].

Studies looking at reservoirs globally have noted that some flux pathways may be more important than others in contributing GHGs, specifically methane, to the atmosphere. For example, Harrison et al. [13] found that methane fluxes via degassing and ebullition are much larger than previously estimated, that diffusive methane fluxes are lower than previously recognized, while carbon dioxide emissions are similar to those related in past work. Keller et al. [45] used satellite observations to analyze over 6700 reservoirs globally and found that drawdown emissions were an important source of GHG emissions from these reservoirs and, when drawdown emissions were taken into account, these reservoirs were net GHG emitters. Soued et al. [28] analyzed reservoirs globally and found that although carbon dioxide emissions have been declining as reservoirs age, reservoir-induced radiative forcing has continued to rise because of ongoing increases in reservoir methane emissions; this study highlights that, in the future, methane ebullition and degassing fluxes will be key emission pathways from reservoirs. Looking at hydropower reservoirs specifically, studies have found that turbine degassing and downstream emissions can be comparable to methane emissions from ebullition [14,47] and that these downstream emissions have the potential to exceed diffusive emissions if turbines pull water from stratified, anoxic water (i.e., from greater depths) [14].

Despite the advances in our understanding of reservoir GHG emission pathways, there remains considerable uncertainty and variability in the findings around the pattern of GHG emissions at individual reservoirs. Recent studies from the United States are a case in point. Pilla et al. [30] studied six large hydropower reservoirs in the Southeastern U.S. and found a high variability in carbon emissions within and across the six reservoirs; this study found that carbon dioxide diffusion was the dominant flux pathway. Compared to other studies in temperate reservoirs using similar field measurement methods, Pilla et al. also found that the methane ebullition rate at the six Southeastern reservoirs was relatively low [30]. Focusing on thirty-two reservoirs in the Mid-west U.S., Beaulieu et al. [2] found that all reservoirs were a source of methane to the atmosphere, with ebullition being the dominant pathway; this study also found that 65% of the sampled reservoirs were a net carbon dioxide sink. In a study of six Pacific Northwestern U.S. reservoirs, Harrison et al.

found that water level drawdowns could, at least temporarily, greatly increase per-area reservoir methane fluxes to the atmosphere [46]. Collectively, the variability across these studies illustrates the complexity in the pattern of GHG emission across reservoirs and the need to better understand the role that individual reservoir characteristics and dynamics play in influencing GHG fluxes, as will be discussed next.

3.2. Individual Reservoir Characteristics and Dynamics

A growing body of literature has documented that GHG emissions at individual reservoirs, including those with hydropower facilities, can vary based on a wide range of factors. Studies focused on hydropower reservoirs have found that carbon emissions may be correlated with reservoir latitude (i.e., location) [15,16,44], with tropical reservoirs being of particular concern given the amount of their GHG emissions [15,16]. Studies that have reviewed reservoirs globally have echoed this finding in part [13,28], yet one study found that temperate and sub-tropical reservoirs can emit as much methane as tropical systems [17]. Studies have also found that carbon emissions can vary based on a reservoir's age and that emissions can increase immediately following the creation of a reservoir and may decrease as reservoirs age [15,16], though certain emission pathways may persist and become important as reservoirs age (e.g., methane degassing) [28]. Several studies have also found that reservoir size and morphology, surrounding watershed characteristics, land use and patterns of nutrient discharge, as well as water quality characteristics including productivity (e.g., chlorophyll a concentration) and vertical stratification (e.g., minimum water column temperature and maximum dissolved oxygen) can influence the rate and pathways of GHG emissions from reservoirs [2,13,17,19,30,42,48–52]. Additionally, researchers have also found that reservoir GHG emissions vary by season and time of day [30,51,53].

Several major studies have underscored that GHG emissions can vary throughout the life of a dam–reservoir complex, with or without hydropower [8,10]. At the beginning and the end of a project's life, the design and materials used for constructing dams [10,54] as well as decommissioning processes [54,55], respectively, can influence the amount of GHGs emitted to the atmosphere. Additionally, during the useful life of a project, researchers have found that reservoir operational patterns, especially for hydropower reservoirs (e.g., run-of-river, storage/peaking), can affect GHG emissions [17,19,42,43,48,56]. The IPCC considered some of these lifecycle emission factors, including some biogenic emission pathways from reservoirs, in its estimate of median lifecycle GHG emission intensity of hydropower (24 gCO_2eq/kWh) [9,57]. That said, individual reservoir characteristics, as discussed in the previous paragraph, can have substantial influence over the GHG emission intensity at individual hydropower facilities as illustrated by studies involving hydropower projects in the United States that have estimated the GHG emission intensity to be both lower than the IPCC median value [10] as well as considerably higher than the IPCC median value, indicating that reservoirs may be major emitters of GHGs [58].

3.3. Key Ongoing Studies in the United States

Given the critical need to understand dynamics at individual reservoirs in specific geographic contexts, as discussed in Section 3.2, efforts are underway to improve understanding of GHG emission pathways at U.S. reservoirs specifically. For example, scientists at the United States Environmental Protection Agency (U.S. EPA) are collaborating with researchers at the United States Geological Survey and Oak Ridge National Laboratory (ORNL) as part of the Survey of Reservoir Greenhouse Gas Emissions (known as SuRGE) project to measure diffusive and ebullitive GHG emissions from 108 U.S. reservoirs, mostly without hydropower [59]. A primary motivation for this project has been to generate data that will be used to develop country-specific emission factors for U.S. reservoirs in order to help improve the representation of reservoirs in U.S. EPA's annual 'Inventory of U.S. Greenhouse Gas Emissions and Sinks' report (GHG Inventory Report) to the Conference of the Parties under Article 4.1a of the United Nations Framework Convention on Climate Change (UNFCCC) [60]. The findings from this project are expected to be published in the near term and will help improve our understanding of both the rate of GHGs emitted from U.S. reservoirs and the environmental factors that affect those rates. ORNL scientists are also collecting data from six hydropower reservoirs in Southeastern U.S. states to assess the spatial and temporal patterns in GHG emissions with the long-term goal of informing potential mitigation strategies [61]. The results from this study are expected to provide a greater understanding of hydropower reservoir GHG emissions. This study is noteworthy given that it is one of the few studies of its kind that focuses on assessing and estimating hydropower reservoir GHG emissions across three pathways: diffusion, ebullition, and the presently less-studied pathway, degassing [19,61].

4. Estimating Hydropower Reservoir Greenhouse Gas Emissions: Advances in Measurement Techniques and Modeling Tools

Reservoirs are biogeochemically dynamic and since reservoir GHG emissions have strong spatial and temporal variability, measuring and estimating these emissions is challenging [19,30,41,42,62,63]. On the measurement side, techniques have seen considerable advancement from the early 2010s when the International Energy Agency [64,65] and the International Hydropower Association [66] issued guidelines on measuring hydropower reservoir GHG emissions. Over the last decade, increasingly sophisticated tools have also become available to quantify reservoir GHG emissions. This section highlights some of the important advancements in reservoir GHG measurement and estimation techniques and tools, as well as planned improvements to help provide context for the research roadmap in Section 5. It is worth noting that while this section discusses direct measurement techniques and modeling tools separately, they are often used in tandem in practice.

4.1. Advances in Direct Measurement

Direct measurements and field sampling campaigns on reservoirs have been foundational for advancing our understanding of both the rate of GHGs emitted from reservoirs and the environmental factors that influence the rate [17,30,42,53]. However, traditional direct measurement and monitoring techniques have had several implementation challenges. Traditional techniques require researchers to deploy measurement instruments for short periods of time at different locations within a water body; these methods can be costly, labor intensive, [31,67] and may often be limited to daylight hours during warmer months for safety reasons, which in turn, may result in gaps in year-round data [17,19] and potential over- or underestimation of GHG emissions.

Several advances are being tested to address the implementation challenges with traditional measurement techniques and improve data collection. For example, U.S. EPA scientists adapted a monitoring technique from terrestrial ecosystems called eddy covariance, in conjunction with traditional techniques, to continuously measure emissions from a reservoir over a two-year period [63]. Unlike traditional 'snapshot in time methods,' the eddy covariance method provided a 'high-resolution movie' of seasonal and daily patterns in methane emissions from one area in the reservoir [63,67]; even though spatially limited, this technique presents an important advancement to measure emissions temporally. The application of satellite instruments like NASA's EMIT system [68] and GHGSat [69] is also being explored for assessing reservoir emissions; while these satellite instruments may not be able to detect low levels of GHG emissions currently, future instrument refinements, including advances in sensor technologies, may make this technology useful in detecting emissions, especially point source degassing emissions.

For hydropower reservoirs specifically, the testing of several new GHG emission measurement technologies is underway. Scientists at ORNL are using aquatic drones in addition to traditional tools to measure ebullitive GHG emissions [61]. Scientists are also testing a custom automated carbon dioxide and methane monitoring system—called SAGES—at several hydropower generating stations in Québec, Canada [70]. The SAGES monitoring system was designed specifically for long-term surveys at hydropower facilities, with a focus on low maintenance requirements [70]. This tool is being tested to collect real-time emission data, especially from the degassing pathway [71]. The scientists working on this tool are continuing traditional field sampling campaigns in conjunction with using the automated system to validate results and calibrate the automated GHG measuring system with an eye towards primarily using this system for GHG emission measurement and reducing the need for field measurement campaigns in the future [71].

4.2. Advances in Modeling

Over the last decade, sophisticated models and publicly accessible web-based tools have become available to help estimate reservoir GHG emissions, especially in the absence of direct measurements. In 2017, a World Bank-funded team of scientists led by the International Hydropower Association and the UNESCO Chair in Global Environmental Change published the first publicly accessible web-based tool for estimating and reporting GHG emissions: the GHG Reservoir Tool (G-res Tool) [72]. The G-res Tool relies on a series of empirical models developed from a synthesis of pre-2016 published literature and data on reservoir emissions [62]. The G-res Tool is designed to estimate the lifetime, net GHG footprint of reservoirs based on user provided data on the characteristics of the reservoir and adjoining environment (e.g., land use), as well as user input on the allocation of net GHG emissions to one or more uses of the reservoir [72]. It distinguishes the contribution of four specific GHG emission pathways as follows: diffusive carbon dioxide emissions, diffusive methane emissions, ebullitive methane emissions, and degassing methane emissions [62]. It differentiates between pre- and post-impoundment emissions—i.e., emissions before and after the creation of a dam and reservoir—enabling a granular estimation of GHG emissions resulting from the creation and operation of individual reservoirs, including hydropower reservoirs [72]. The G-res Tool is applicable globally [62] and, since its release, a growing number of studies have estimated GHG emissions at reservoirs (with and without hydropower) using this tool [13,28,31,73,74].

For hydropower reservoirs specifically, the G-res Tool remains the most well-known and widely used tool for estimating GHG emissions, despite its current shortcomings. A key shortcoming is numerical uncertainty in the predicted results [19]. The G-res Tool is based on a global dataset of reservoir emissions [72]. While the dataset covers all climate zones, boreal reservoirs—and to a lesser extent sub-tropical and tropical reservoirs—are somewhat over-represented [19,62]; consequently, the underlying modeling dataset may not always be representative of local conditions. Two recent studies on hydropower reservoir emissions in the U.S. are a case in point where scientists found high variability in the G-res modeled results compared to field conditions and surveys [31,74]. In one of the studies, there was inconsistency in the carbon dioxide diffusion estimate: field surveys indicated negative diffusion (i.e., uptake) whereas the G-res Tool estimated positive diffusion [31]. Some other shortcomings of the G-res Tool include static inputs for information categories that may have long-term changes (e.g., human population around a reservoir or the pattern of thermal stratification or trophic state of the reservoir), seasonal drawdown changes, simplified consideration of littoral area or reservoir morphology, and lack of accounting of all GHG flux pathways (e.g., carbon burial) [19]. Efforts are underway to help improve the accuracy of the G-res Tool in the coming years, such as through the Reservoir Methane Measurement Project that will generate new data on reservoir GHG emissions worldwide [75]. Notwithstanding the need for improvements, the G-res Tool continues to be widely used in international settings. For instance, the European Union Taxonomy for Sustainable Activities that defines criteria for economic activities that are aligned with a net-zero trajectory by 2050, supports the use of the G-res Tool for calculating hydropower's lifecycle GHG emissions [20]. The Hydropower Sustainability Assessment Protocol and the Hydropower Criteria for the Climate Bonds Standard and Certification Scheme also support the use of the G-res Tool for net GHG emission estimation [21,22]. Similarly, the IPCC's guidelines for the National Greenhouse Gas Inventories—discussed later in this sub-section—also support the use of the G-res Tool for estimating methane emissions from individual reservoirs under the guideline's tiered approach, specifically Tier 3 [76].

Since the launch of the G-res Tool in 2017, several other modeling and reservoir GHG estimation tool development initiatives have been underway. For example, new models such as ResME ([Res]ervoir [M]ethane [E]missions) [14] have been developed for assessing GHG emissions at hydropower reservoirs. ResME is a mechanistic model, which estimates carbon inputs and methanogenesis to predict methane release via ebullition and diffusion, plant emissions, and downstream emissions [14]. Another tool called Open Hydro has also recently been released [77], but it remains to be tested through peer-reviewed studies.

The emerging body of research on GHGs emitted from human-made reservoirs led to growing policy calls to include reservoirs in global inventories of anthropogenic GHG emissions [38]. In 2019, the IPCC provided guidance on estimating carbon dioxide and methane emissions for flooded land (i.e., reservoirs) in national GHG inventory reporting under Article 4.1a of the UNFCCC [76]. In 2022, the U.S. EPA began including, for the first time, reservoir emissions in its annual GHG Inventory Report to the Conference of the Parties under Article 4.1a of the UNFCCC [78]. The U.S. EPA has used the IPCC guidance to report reservoir methane emission estimates as part of the annual GHG Inventory Reports wherein managed waterbodies are defined as reservoirs if they have a surface area of over 8 hectares and are over 20 years old [79]. The reservoir methane emission estimate is calculated as the product of flooded land surface area and a climate-specific emission factor [79]. The climate-specific emission factors are derived using the G-res Tool-predicted emission rates [79]. In its 2023 GHG Inventory Report, the U.S. EPA observed methane emissions from reservoirs (with and without hydropower) across all states in the country and estimated the aggregate methane emission from reservoirs (with and without hydropower) nationally at 1033 kilotons (compared to 6962 kilotons from enteric fermentation, which was the largest source of methane emissions) [79], underscoring the prevalence of anthropogenic reservoir GHG emissions.

It is worth noting that in the U.S. EPA's annual GHG Inventory Reports, the climate-specific emission factors used in calculating the reservoir methane emissions estimate are derived using the G-res Tool-predicted emission rates [79]. As discussed earlier in this sub-section, there are known shortcomings with the representativeness of the underlying reservoir database used in the G-res Tool that creates uncertainty around the default emission factors for U.S. reservoirs specifically. There are planned improvements to address this uncertainty: the data from U.S. EPA's SuRGE project, discussed in Section 3.3, will be used to develop country-specific emission factors for U.S. reservoirs with GHG Inventory reporting using these factors beginning in 2026 [60]. U.S. EPA scientists also plan to develop a predictive model to estimate reservoir emissions for the GHG Inventory [80].

5. Discussion and Roadmap for Further Research on Assessing and Addressing Hydropower Reservoir Greenhouse Gas Emissions

Human-made reservoirs, including those with hydropower generation, are known sources of GHG emissions; however, current scientific studies highlighted in Section 3 underscore the uncertainty and strong spatial and temporal variability in GHG emissions at individual reservoirs, including those with hydropower facilities [13,14]. Studies also note that GHG fluxes are sensitive to input parameters that may be influenced by climate change in the years ahead; as a result, there is a critical need to better understand the environmental and climate-related drivers of GHG emissions [13]. Additionally, studies note that while GHG emissions from some pathways may decrease in the future as reservoirs age, some GHG emission pathways—methane ebullition and degassing—may be more important than others in the coming decades due to methane's global warming potential [28]. For hydropower reservoirs, turbine degassing and downstream emissions can be comparable to methane emissions from ebullition [14,47]. Yet, studies also note the paucity of data on some of these pathways, particularly degassing, when it comes to hydropower projects [19]. They also stress the need to better quantify GHG emissions via these specific pathways, notably methane ebullition and degassing [13,31]. While tools to quantify GHG emissions are improving, as Section 4 illustrated, more work remains to reduce modeled uncertainty and improve the accuracy of results.

From a policy perspective, tracking progress towards decarbonization and addressing anthropogenic sources of GHG emissions will require accurate accounting and reporting of reservoir GHG emissions as well as implementation of mitigation measures. For hydropower facilities specifically, it will be crucial to support further research and investment in understanding and addressing their reservoir GHG emissions to assess their effectiveness in supporting grid decarbonization and climate mitigation efforts. As discussed in the introduction, research on improving GHG emission accounting for hydropower will also be important for project owners and energy buyers in making credible claims regarding the emission intensity of their power source.

Given this context, this section outlines a roadmap of action areas to advance the assessment and reporting of reservoir GHG emissions, including those linked to hydropower facilities, with the ultimate goal of minimizing and mitigating these emissions to aid decarbonization efforts. As government agencies, research institutions, and funding organizations craft strategies to support decarbonization and climate mitigation research, they should prioritize and invest in these action areas.

5.1. Understanding and Reducing Uncertainties in Existing Reservoir GHG Estimation and Associated Publicly Accessible Estimation Tools

Accurate, publicly accessible modeling tools are vital for expanding our efforts to estimate and improve our understanding of reservoir GHG emissions, including those linked to hydropower facilities. Compared to direct field measurement approaches, GHG estimation modeling tools may be easier to use for a non-technical audience, especially reservoir owners and operators, since they are neither as labor intensive nor require extensive logistical planning as field measurements. Given the value of publicly accessible modeling tools, there is an urgent need to reduce the uncertainty in their estimates and improve their accuracy that will require bolstering the data underlying the models. To this end, further scientific field research and funding is needed to expand taking direct measurements on a wide range and diversity of reservoirs (with and without hydropower) across the world and over time [18,19,31]. Scientists underscore the need to focus future field efforts on capturing the variability in carbon dioxide diffusion as well as methane ebullition and degassing to improve current models [19,31]. Additionally, further field sampling is needed to understand the fate of carbon in undammed catchments compared to dammed catchments [18], including carbon dioxide sequestration [30], to improve the inclusion of all flux pathways in currently available reservoir modeling tools such as the G-res Tool [30,62], which in turn could be especially valuable in regions that are exploring new dam development where improved modeling tools can inform development and siting-related decision-making. In the U.S. and other regions where most dams have already been built, improving the accounting of GHG emissions via specific flux pathways will be critical to target mitigation measures.

In the United States, ORNL and U.S. EPA's research projects discussed in Section 3.3 are expected to provide enhanced understanding of GHG emissions from U.S. reservoirs specifically. The U.S. EPA's project is also slated to develop a predictive model to estimate those emissions for reservoirs across the country as noted in Section 4.2. It will be critical to continue to support and fund research efforts such as these or others that may be complementary. Government agencies and national laboratories in the United States should consider making the resulting predictive models accessible as publicly usable tools to encourage broad use and allow a knowledgeable audience that may include non-scientists to conduct robust GHG emissions estimations with fewer barriers (see next research action area). Additionally, data and findings from these U.S. studies should be shared to aid ongoing international efforts to reduce the uncertainty in and improve the accuracy of the only existing publicly accessible GHG estimation tool, the G-res Tool. Lastly, research on how climate change may affect emissions from reservoirs in the future will also be important.

A special note is worth highlighting with respect to pumped storage hydropower (PSH), which is a century-old energy storage technology that is witnessing a resurgence in the United States [81]. PSH systems act as large water batteries and are net energy consumers [81]. The few PSH lifecycle assessment studies that examine GHG emissions note that the grid mix of the electricity used for pumping water during the operational stage is a predominant factor in influencing PSH's GHG emissions [82]. Focusing on the U.S. specifically, Simon et al. [82] found that closed-loop PSH projects had lower lifecycle GHG emissions compared to other energy storage technologies; however, since no closed-loop project has begun construction in the U.S., the actual GHG emissions of these projects remains unknown. Drawing on data and methods from Simon et al. [82], the National Renewable Energy Laboratory has developed a publicly accessible tool to evaluate the lifecycle GHG emissions of new closed-loop PSH facilities in the U.S. [83]. This is an important tool for estimating PSH GHG emissions; however, it can be improved further to include a robust accounting of reservoir GHG emissions (e.g., for existing brownfield reservoirs), as well as granular estimation of the electricity source used for pumping water to allow for a nuanced assessment of this storage technology in grid decarbonization policies.

5.2. Reducing the Technical and Economic Barriers for Reservoir Managers to Use GHG Estimation Tools and Measurement Techniques

To promote widespread uptake of publicly accessible reservoir GHG emission estimation tools, they need to be easy to use by a non-technical audience. Reservoir managers, including owners and operators of hydropower projects, are a key target audience in this regard since they are closely familiar with the details and context for their own reservoirs.

Studies that use the G-res Tool highlight its ease of use and clear technical documentation; yet they also state that certain input data may not be readily available [58]. Drawing on the example of the G-res Tool, publicly accessible reservoir GHG estimation tools developed in the future, such as through a U.S. agency effort, should create plain language technical documentation and accompanying webinars for a non-technical audience that explain how these tools should be used correctly, their assumptions and limitations, and how to interpret results. In addition, if tool users require additional support to complete reservoir GHG emission assessments, such as when user-input data are not readily available, government agencies could create programs to provide technical assistance to improve know-how for using the tools and related activities such as for data gathering, curation, addressing data gaps, and validation. In the United States for instance, the Department of Energy frequently offers technical assistance to the hydropower industry through its national laboratories [84]. Government agencies should also invest in creating consistent datasets through data collection or modeling to address data gaps. Additionally, agencies should build their own capacity to validate the results of publicly accessible reservoir GHG estimation tools to rigorously assess user-provided inputs and assumptions to verify the accuracy of results; such validation will be necessary to implement policies around the assessment, reporting, and mitigation of reservoir GHG emissions.

In addition to lowering the barriers for reservoir managers to use modeling tools, it will be important to invest in training them to take direct field measurements to validate modeling results. Until recently, field sampling campaigns have been conducted primarily by trained researchers. To expand direct measurements, it will be critical to improve the technical know-how and reduce costs for reservoir managers associated with field sampling. On the technical know-how side, organizations such as Bluemethane are working with Canadian university researchers to help expand field measurements by offering training to hydropower owners on how to take measurements, and providing detailed measurement protocols and equipment; they are also offering services for laboratory analysis of samples and sharing results of measurements with owners [75]. As government agencies such as the U.S. Department of Energy's Water Power Technologies Office contemplate initiatives around understanding hydropower emissions [85], they should consider providing funding for and scaling such direct measurement efforts in partnership with reservoir managers, including hydropower owners and national laboratories. In addition, government agencies should explore pathways to improve the accuracy and lower the costs of automated systems for measuring emissions discussed in Section 4.2. Anecdotally, researchers have shared that these systems, specifically SAGES, can typically cost $30,000 for their acquisition and installation, which may be cost-prohibitive for owners and operators of smaller reservoirs and hydropower projects. In the United States, agencies may consider piloting such automated systems at federal reservoirs initially to test and improve their accuracy and then scale their use by providing funding to reservoir owners and operators to install these systems.

5.3. Setting Common Standards to Enable Consistent Monitoring, Allocation, and Reporting of Reservoir GHG Emissions

Consistent and ongoing monitoring and reporting of reservoir GHG emissions will be critical to understand GHG emission trends over time and facilitate targeted and timely action to help address emissions. An important first step in this regard will be the development of common standards for reservoir managers to conduct ongoing monitoring and reporting of reservoir GHG emissions. Given the role that government agencies play in crafting and implementing policies, they should lead the effort to develop common standards that are credible and nationally applicable. In the United States, government agencies can work with experts from national laboratories and research institutions to develop common standards and include opportunities for robust stakeholder input.

The common standards should provide guidance that is understandable and implementable by a non-technical audience on how to conduct ongoing monitoring assessments of GHG emissions, report results, and allocate GHG emissions to various water uses of a reservoir based on reporting needs. Scientists have highlighted the need for clarity and consistency in defining reservoir characteristics (such as littoral zones that contribute to GHG emissions) to help estimate emissions [31,86], standardization of measurement methods [87], and guidance on the use of various data sources. The common standards should address topics such as these to enable consistent and robust monitoring assessments of GHG emissions. The common standards should consider including guidance on reporting year-over-year changes in GHG emissions to help track and compare temporal trends at individual reservoirs. Additionally, if available, year-over-year changes in emissions via each relevant flux pathway should be reported since this information can help identify where targeted mitigation intervention is needed. Furthermore, common standards on reporting should provide guidance on how to allocate (or attribute) GHG emissions to the different functions of a reservoir, including hydropower generation, navigation, flood control, water supply, etc. Several approaches exist for attributing reservoir GHG emissions [72], however there is no consensus on when each approach should be applied. The question around the allocation of GHG emissions is particularly relevant for hydropower in the United States since less than 3% of the over 90,000 dams generate electricity and dams frequently serve multiple purposes [32]. Depending on the policy context, guidance on emission attribution will be important to measure and model GHG emissions that are directly tied to hydropower operations [19] in order to enable comparability with other energy sources, estimate grid emission impacts, and craft decarbonization strategies and incentive programs. Reporting guidance on GHG emission attribution will also help advance hydropower's inclusion in GHG reporting and inventory programs in the future.

Lastly, common standards should include guidance on the verification of reported GHG emissions. As discussed in Section 5.2, it will be crucial to build capacity within government agencies to rigorously verify the accuracy of reported data and results. Additionally, it will be vital to make verified reports publicly viewable to allow interested stakeholders to examine and use this data, such as for assessing progress towards our societal goal of decarbonizing the grid and the economy by the middle of this century.

5.4. Supporting Research and Implementation of Reservoir GHG Mitigation Strategies, Including Watershed-Scale Strategies

Once we improve the quantification of GHG emissions at reservoirs (including those linked to hydropower facilities) and our understanding of the factors that influence GHG emissions, implementing mitigation strategies to address these GHG emissions will be paramount. Over the last decade, researchers have proposed several strategies to help reduce reservoir GHG emissions at existing dams and hydropower projects, including by changing operational patterns and modifying the turbine intake depth [14,88]. It will be important to continue research and field testing of these mitigation strategies. In a recent study, scientists published a conceptual model to clarify the causal linkages between water level fluctuations from hydropower operations and methane emissions [43]. This study identified a range of strategies for reducing methane emissions beyond flow management that merit further attention. For example, forebay oxygenation is one approach discussed for mitigating seasonal and diurnal peaks in degassing [43] and researchers have previously recommended a similar strategy of installing aerating devices to increase dissolved oxygen in the water [88]; these concepts require further field testing to examine if effects are measurable in practice and assess their technical and economic feasibility. Similarly, further research is needed to test the effectiveness, cost, and scalability barriers of managing sediments, water quality, and biological productivity as strategies to address GHG emissions [30,43].

Recent studies have also discussed basin-wide coordination of reservoir operations as a potential strategy for reducing methane emissions [19,43,89,90]. Reservoirs often exist in cascades within a single watershed/river basin; however, few studies have assessed cumulative or basin-scale emissions [91]. In the United States where most dams have already been built [10], basin-scale studies can help identify reservoir operation patterns that could minimize GHG emissions. Beyond the United States, basin-scale studies can help evaluate trade-offs in siting dams across multiple objectives, including for building new hydropower projects [89,90].

Conducting research on mitigation strategies will be a key step towards their implementation. Once we identify effective strategies, government agencies should develop supportive policies and incentive programs to encourage hydropower and reservoir owners to mitigate GHG emissions.

6. Conclusions

Rapidly decarbonizing the electricity grid is a critical strategy to achieve the goal of net-zero GHG emissions by mid-century and to help mitigate the worst impacts of climate change. Hydropower facilities can support grid decarbonization efforts but, like all energy systems, they can emit GHG emissions over their entire lifecycle. Reservoirs that form an integral part of a hydropower generation system are known sources of GHG emissions and influence the overall rate of GHG emissions from individual facilities. However, current scientific studies discussed in Section 3 highlight the uncertainty and strong spatial and temporal variability in GHG emissions at individual reservoirs, including those with hydropower facilities. Studies note that some reservoir GHG emission pathways—methane ebullition and degassing—may be more important than others in the coming decades, yet there also remains a paucity of data on some of these pathways, particularly degassing associated with hydropower operations. A growing body of scholarship has underscored the need to better quantify GHG emissions via these specific pathways, notably methane ebullition and degassing. While tools to quantify GHG emissions are improving, as Section 4 illustrated, more work remains to reduce modeled uncertainty and improve the accuracy of results.

From a policy perspective, crafting policies to advance decarbonization goals, tracking progress towards achieving those goals, and ultimately addressing anthropogenic sources of GHG emissions will require accurate accounting and reporting of GHG emissions as well as implementation of mitigation measures. To this end, investing in research to improve the accounting and mitigation of hydropower reservoir GHG emissions is urgently needed to ensure that this technology is accurately considered and incentivized in decarbonization policies. With the growing global focus on GHG emission disclosure, improving GHG emission accounting for hydropower will also be important for project owners and energy buyers in making credible claims regarding the emission intensity of their power source.

Drawing on the current state of the science on the drivers and pathways of reservoir GHG emissions as well as advancements in GHG estimation tools and techniques, this paper presented a roadmap for government agencies, research institutions, and funding organizations to support and fund research in the following action areas:

- Understanding and reducing uncertainties in existing reservoir GHG estimation and associated publicly accessible estimation tools;
- Reducing the technical and economic barriers for reservoir managers to use GHG estimation tools and measurement techniques;
- Setting common standards to enable consistent monitoring, allocation, and reporting of reservoir GHG emissions; and
- Supporting research and implementation of reservoir GHG mitigation strategies, including watershed-scale strategies.

Progress on these research areas will be critical in enabling robust, credible, and consistent accounting of hydropower reservoir GHG emissions, directing targeted mitigation efforts, and ultimately advancing our societal goal of decarbonizing the electricity grid in the near future.

Author Contributions: Conceptualization, S.K.; investigation, S.K.; data curation, S.K.; writing—original draft preparation, S.K.; writing—review and editing, S.K. (lead), M.F. and S.A. (supporting); project administration, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable.

Acknowledgments: Thank you to Brenda Pracheil, Rick Glick, Kelly Catlett, and the Low Impact Hydropower Institute Board and Advisory Members for their thoughtful feedback.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
U.S. EPA	United States Environmental Protection Agency
UNFCCC	United Nations Framework Convention on Climate Change
ORNL	Oak Ridge National Laboratory
G-res Tool	GHG Reservoir Tool
PSH	Pumped Storage Hydropower

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