DOI: 10.7251/QOL2501048S
UDC: 635.918:621.311.21-7
Professional paper

Hydropower as a Hidden Source of Greenhouse Gases

Marko Supić[1], Dajana Cvijetić[2]
[1]*Faculty of Health Sciences, Apeiron Pan-European University, Banja Luka, Bosnia and Herzegovina, mrksupic@gmail.com*
[2]*Faculty of Health Sciences, Apeiron Pan-European University, Banja Luka, Bosnia and Herzegovina, dajacvijetic1307@gmail.com*

ABSTRACT: Hydropower is widely considered one of the cleanest forms of renewable energy, but recent research highlights its contribution to greenhouse gas (GHG) emissions, challenging this perception. This study quantifies the indirect emissions of carbon dioxide (CO_2) and methane (CH_4) linked to hydropower facilities, focusing on emissions from the anaerobic decomposition of organic matter in reservoirs. The findings reveal that hydropower reservoirs emit approximately 1 billion tonnes of GHGs annually, which accounts for 1.3% of global anthropogenic emissions. Notably, methane, a greenhouse gas with a global warming potential 28 times greater than CO_2 over a 100-year period, represents a substantial part of these emissions. Around 22 million tonnes of CH_4 are released annually from reservoirs due to the decay of submerged vegetation and organic material from inflowing rivers. To assess these emissions, methodologies such as floating chamber measurements and remote sensing techniques were employed, providing accurate, site-specific emission data across various geographic regions. The study also explores mitigation strategies, including optimizing reservoir design and enhancing water management practices to reduce methane production. These results highlight the need to address the environmental impacts of hydropower and suggest that, without such interventions, hydropower's role in climate change mitigation could be undermined by its contribution to GHG emissions. Therefore, achieving true sustainability in hydropower development requires integrating these findings into policy and design frameworks.

Key words: greenhouse gases, methane, carbon dioxide,mitigation strategies

INTRODUCTION

Often referred to as one of the cleaner and more dependable renewable energy resources, hydropower does not use fossil fuel directly but rather the natural water cycle to generate electrical power. Its carbon emissions are, therefore, not emitted at the facility itself, which has positioned it as one of the keys to the worldwide transition into sustainable energy. However, broader environmental impacts of hydropower, most particularly its contribution to GHG emissions, are increasingly coming under scrutiny. While there is broad consensus that the generation of electricity by hydropower does not emit CO_2 directly, there is an increasing amount of research that suggests hydropower may not be as environmentally benign as has often been assumed, particularly in the case of CH_4 emissions from reservoirs.

Methane is an extremely powerful greenhouse gas, 28 times more effective at trapping heat in the atmosphere than CO_2 over a 100-year period. Methane emissions from hydropower reservoirs are mainly given out through anaerobic decomposition of organic matter in reservoir water, including submerged vegetation and sediment. Since this organic material decomposes without oxygen, large amounts of methane are emitted into the atmosphere. This process is increased in tropical and subtropical regions because of increasing temperatures, which again increase the rate of decomposition. Indeed, recent studies have estimated that methane emissions from hydropower reservoirs could have the potential to compose a significant portion of total GHG emissions attributed to the hydropower sector, going as far as 30% of the contribution responsible for the current rise in global temperatures.

Despite increased awareness of methane production associated with hydropower, the issue remains unaddressed by policy or in environmental impact assessments. Methane is a "short-lived" GHG because it stays in the atmosphere for about 12 years, whereas CO_2 can be present in the atmosphere even after centuries. (Doğan et al. 2020) This feature makes the reduction of methane emission an effective and crucial strategy toward near-term climate mitigation. It is possible that significant reduction of methane emission from hydropower reservoirs can provide measurable impacts on global warming in several decades. On the other hand, much of the current discourse on hydropower continues to be based on low-carbon profiles, failing to take into account considerable GHG emissions concerning reservoir management and organic matter decomposition.

This is a literature gap, and the full environmental impact of hydropower is hardly understood, especially as the world increasingly looks at renewable energy sources to meet climate goals. Hydropower is most likely to form part of any strategy that seeks to reduce reliance on fossil fuels, but not being accountable for its hidden emissions means that the actual price of this source of energy remains obfuscated. Therefore, one of the research gaps that this study tries to address is the emission of greenhouse gases, especially methane, from hydropower reservoirs. This study attempts to quantify the emissions, based on which factors influence the magnitude of emissions, and accordingly proposes mitigation strategies to reduce their impact.

This research goes against conventional wisdom, which has positioned hydropower as a source of purely clean energy, by examining the indirect GHG emissions from hydropower. Beyond this, it also aims to emphasize the need for embedding reservoir-related methane emission into environmental impact assessments for hydropower projects. In so doing, this study provides a wide perspective into the role of hydropower in climate change and underlines enhanced management as necessary to make sure hydropower aligns with global sustainability goals.

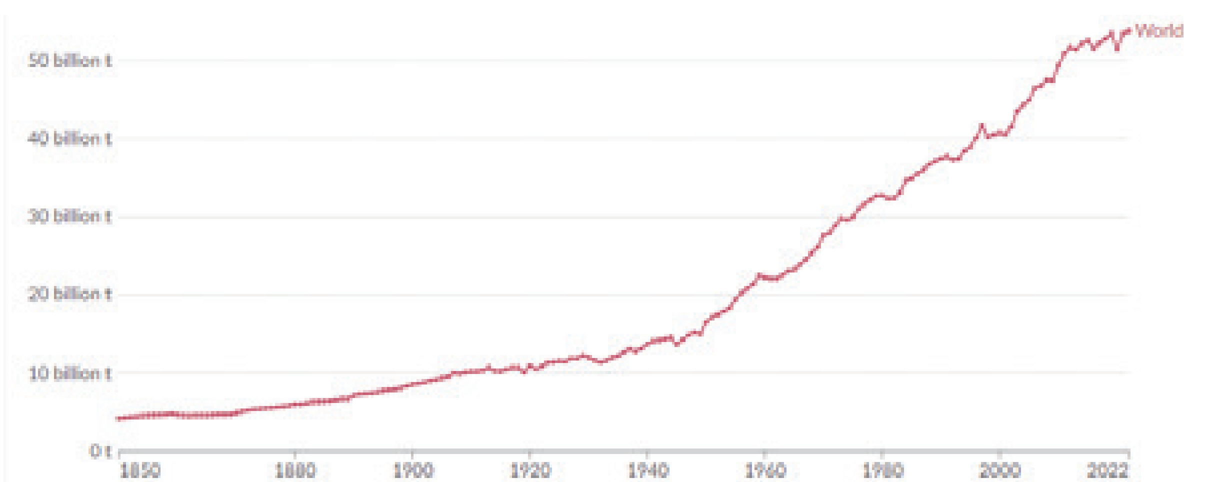


Figure 1. Greenhouse gas emissions include carbon dioxide, methane and nitrous oxide from all sources

MATERIALS AND METHODS

Factors that determine the quantity of methane and CO2 Reservoir Emissions

A key source of GHG emissions from hydropower is through artificial reservoirs created by dams. Flooding of land to create a reservoir submerges organic material like plants and soils, which begin anoxic decomposition. This process follows the pathway of CH_4 and CO_2 generation. Methane is itself an extremely GHG gas with global warming potential of about 28-36 times higher than that of CO_2 over a period of 100 years.

Methane dissolved in the water can be released into the atmosphere when water passes through turbines or over spillways. This process is known as degassing and can significantly contribute to a hydropower plant's total GHG emissions (Abril et al., 2005).

Factors that determine the quantity of methane and CO_2 emissions from these systems include the type of vegetation submerged, depth of water, water temperature, and age of the reservoir. Together, for instance, tropical reservoirs are high producers of methane because of the warm temperatures and an increase in organic content in the submerged biomass. Some articles have reported that tropical reservoirs can emit as much methane as a fossil fuel power plant with comparable capacity.

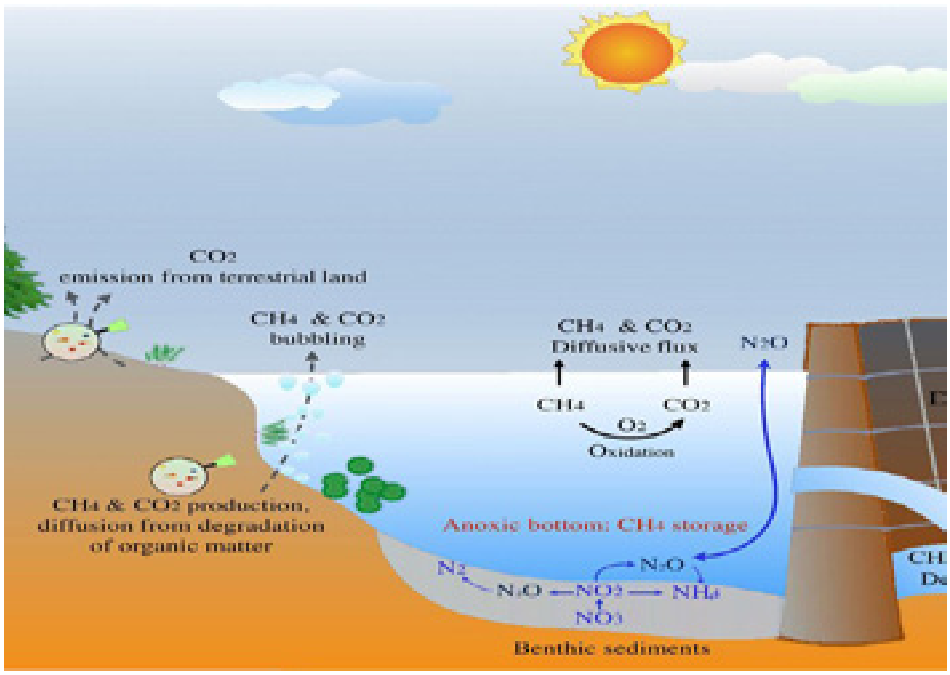


Figure 2. GHG emission pathways from hydropower

GHG emissions are also related to the construction of hydropower plants. Huge quantities of concrete and steel are required for the process, both are polluting, in terms of carbon emission, at their production sites. Extraction activities, machine operations, and transportation of materials, etc. result in the emission of CO_2 and other GHG. Though these are one-time evolutions and not continuous as in the case of fossil fuel plants, still emissions can be quite considerable. Also, maintenance activities during the life cycle contribute to GHG emissions from the hydropower plant. Needless to say, infrastructure upkeep, equipment replacement, and periodic dredging of sediment from reservoirs require energy and materials, which add to the overall GHG envisaged. (Yiming et al. 2024)

Maintenance activities during the life cycle also contribute to GHG emissions from the hydropower plant. Needless to say, infrastructure upkeep, equipment replacement, and periodic dredging of sediment from reservoirs require energy and materials, which add to the overall GHG envisaged.

MEASSURING GHG EMISSIONS

Due to the difficulty in correctly estimating actual GHG emissions from the hydropower plant, measuring procedures are complex. There are many methodologies dependent on the nature of gas emissions as:

Floating Chambers

Testing for GHG in water bodies, including hydropower reservoirs, is done by one of the most common techniques: floating chambers. It is a technique well-suited to measuring the two most important GHG constituents, that is, carbon dioxide and methane, considered critical to climate change. The technique involves placing a sealed chamber in contact with the water surface to capture the gases diffusing from the water into the chamber. In this context, application of floating chambers for measurement of hydropower-related GHG emissions is overviewed, discussing their advantages, limitations, and application (Fearnside and Pueyo, 2012).

Floating chambers are usually simple, cost-effective devices used to measure gas fluxes between water surfaces (e.g., reservoirs) and the atmosphere. Typically made from materials like PVC or other lightweight plastics, these chambers float on the water surface and capture a known volume of gas over a set period.

Deployment: A floating chamber is placed on the water surface at the measurement site.

Gas capture: The chamber traps a sample of the gases emitted from the water surface.

Sampling: Gas samples are periodically collected from the chamber using syringes or sampling ports.

Analysis: The collected gas samples are analyzed in a laboratory to determine concentrations of target GHGs (e.g., CH_4, CO_2).

Flux calculation: By measuring the rate of gas accumulation within the chamber over time, researchers calculate the flux (e.g., mg CH_4 m^{-2} day^{-1})

The headspace of the incubation vessels are sampled with a syringe or any other appropriate sampling device for gas samples after a selected incubation time. Multiple sampling can be done to develop a curve for the rate of accumulation of gases. It is then possible to determine the concentrations of CO2 and CH4 using gas chromatography or other analytical procedures from the collected gas samples.

Although the material expenditure for their construction and deployment is minimal, and they can be used in inaccessible areas, they do have certain drawbacks. For instance, they are limited to specific points and may not capture spatial variations in large reservoirs. Primarily, they are used for measuring CH_4 and CO_2, while being less effective at measuring other GHG gases, and their physical presence can disturb natural gas flows.

Ebullition measurements

Ebullition is the process by which gas bubbles are emitted from sediments into the water column, eventually reaching the atmosphere. It is one of the important pathways for emissions of methane (CH4) from aquatic systems, including hydropower reservoirs. For this reason, measuring ebullition is necessary for correctly quantifying total GHG emissions from these environments. (Tremblay et al. 2005) The present paper aims to give a general view on the methodology of ebullition measurements for estimated GHG emission assessments in hydropower reservoirs, together with their advantages, limitations, and areas of application. (DelSontro et al. 2015)

The rate of methane ebullition depends on various factors, including:

- Sediment type and organic matter content
- Water depth and temperature
- Seasonal variations (ebullition tends to be higher during warmer periods)

Instrumentation and Setup:

1. **Bubble Trap Design**:

Methane ebullition is captured and quantified by deploying what is variously called bubble traps, gas traps, or ebullition collectors on the reservoir bed. These traps capture rising methane bubbles and allow the researcher to quantify volume and rate of bubble release over time.

These are usually devices, funnel-shaped, made of transparent or opaque material such as plastic or glass. The funnel directs the rising bubbles into a collection chamber where they are stored for later measurement.

A typical trap is a floating inverted funnel commonly ranging between 20–50 cm in diameter, attached to a collection tube or chamber. It is fastened strongly to the sediment in order not to wobble during long deployments.

2. Trap Deployment:

The bubble traps are set in depth in the hydropower reservoirs, taking into account the character of the reservoir and different study objectives. This might be zones with high accumulation of organic matter or deeper zones where methane production is expected to be high. Depth and number of traps are selected to capture changes in sediment type and environmental conditions throughout the reservoir.

3. **Data Collection Process:**

a) Methane Collection:

The bubbles rise through the water column and are captured by the funnel trap into a gas-tight chamber.

This gas accumulates in the chamber over time, usually over periods ranging from hours up to several days. The periodic retrieval of gas samples by the researcher is done by drawing with a syringe or through tubing the accumulated gas in the trap. (**Bastviken et al. 2020)**

b) Gas Volume and Concentration Measurement:

The volume of gas collected in each trap is measured, and the gas is analyzed to determine the methane concentration. This is done using gas chromatography or portable gas analyzers.

Knowing the volume of gas and methane concentration, rates of methane ebullition can be determined on a mass per unit area per unit time basis, for example mg $CH4\ m^2\ day^{-1}$, by the researcher.

Collected data can then be used to extrapolate the rates of ebullition measured at each trap to estimate total methane emissions from ebullition over the entire reservoir surface. (Prairie and Mercier-Blais ,2021)

Several factors influence the rate of methane ebullition from the reservoir sediments: temperature, water level changes in the reservoir, sediment characteristics and reservoir management practices.

Remote sensing

Remote sensing is an advanced method for monitoring greenhouse gas (GHG) emissions from hydropower reservoirs. This technique involves the use of satellite, aerial, and ground-based sensors to detect and measure GHG emissions over large spatial scales and extended time periods. Remote sensing offers a powerful tool for assessing the environmental impact of hydropower projects by providing comprehensive and continuous data. Next part provides an overview of the application of remote sensing in measuring hydropower-related GHG emissions, discussing the methodology, advantages, limitations, and applications (Harrison et al., 2021).

Instrumentation and Platforms:

1. Satellite-Based Sensors:

- Satellite platforms are equipped with sophisticated instruments designed to detect and measure atmospheric gases from space. Satellites allow for the monitoring of GHG emissions on a global scale and provide repeated measurements over time.
- Key satellite instruments used for GHG measurements include:

- **Greenhouse Gases Observing Satellite (GOSAT):** Launched by the Japan Aerospace Exploration Agency (JAXA), GOSAT monitors concentrations of CO_2 and CH_4 in the Earth's atmosphere. The satellite uses **Fourier Transform Spectrometers** (FTS) to detect gas absorption of solar radiation reflected by the Earth's surface.
- **Orbiting Carbon Observatory-2 (OCO-2):** Managed by NASA, OCO-2 provides high-resolution measurements of CO_2 concentrations. It uses spectrometers to measure the absorption of sunlight by CO_2 molecules.
- **TROPOspheric Monitoring Instrument (TROPOMI):** Onboard the European Space Agency's Sentinel-5P satellite, TROPOMI detects atmospheric trace gases, including CH_4 and CO_2, with high spatial resolution. It uses spectrometers to measure gas concentrations based on their absorption spectra.

Figure 3. Greenhouse Gases Observing Satellite (GOSAT)

2. Aerial-Based Sensors:

Aerial platforms like drones, planes, or helicopters equipped with sensors-can be used for ground-truthing valuable data on GHG emissions at high resolution and spatially focused over areas of interest. (Prairie, Y.T. and Mercier-Blais S. ,2021)

These platforms are very useful in reservoir monitoring where the satellite data may not be effective due to cloud cover or limitation of spatial resolution. These aerial sensors often are equipped with infrared gas analyzers or lidar systems that can detect methane plumes or CO_2 concentrations directly above the reservoir.

METHODOLOGY:

Satellites, aerial platforms, or ground-based sensors gather the spectral data over the hydropower reservoir. The sensors measure the absorption and scattering of sunlight-or other sources of radiation-by GHGs in the atmosphere.

This spectral data of sensors is converted into concentration values, such as CH_4 and CO_2, with the help of algorithms that utilize atmospheric conditions, surface reflectance, and sensor calibration data.

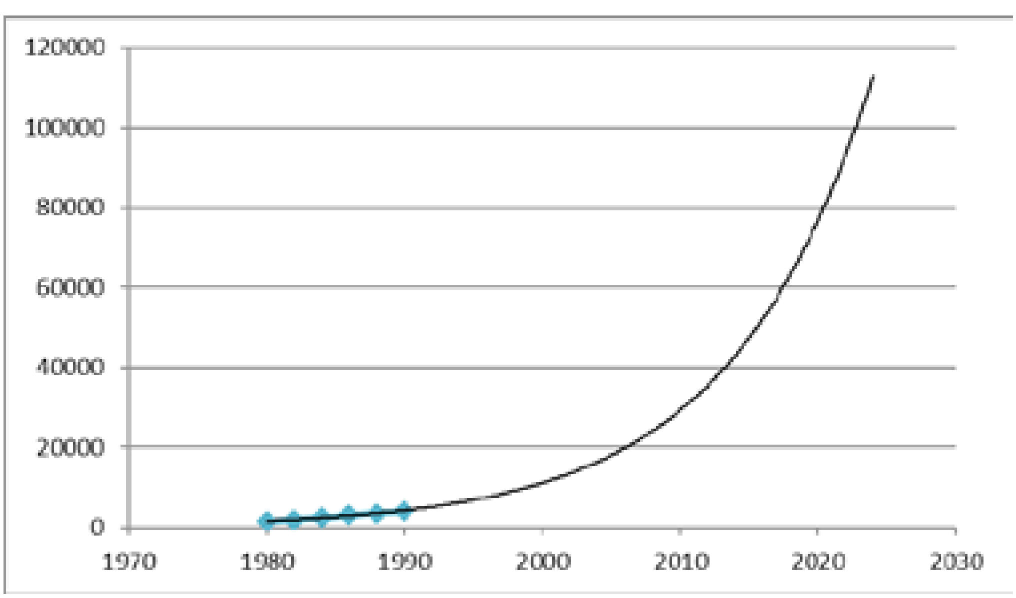
The raw spectral data collected by the sensors go through algorithmic processing, which corrects for the interfering factors-cloud cover, water vapor, and aerosols-standing in the way of the GHG detection. (Pavelko R. G. 2012)

Advanced models, such as radiative transfer models, then model the absorption and scattering of light as it passes through the atmosphere. These allow only the GHG signal to be separated from background noise and give accurate estimates of gas concentration.

This finally allows development of high-resolution GHG concentration maps for the reservoir area at given time and space, revealing methane or carbon dioxide emissions.

Awareness of GHG emissions from hydropower

Research from 2022 by L. Parlons Bentata and N. Rueda-Vallejo of Bluemethane, UK, found that despite the relatively high awareness of methane and other GHG emissions from hydropower among energy companies (including dam owners, operators, and integrated energy companies), environmentalists, engineers, academics, and government officials, these emissions are not widely measured.



Hydropower generation (TW-h)

Figure 4. The evolution of world hydropower generation since 1980

Mitigation Strategies

Since we cannot yet avoid or reduce all greenhouse gases (GHG) emissions from reservoirs, carbon capture and utilization (CCU) offers an alternative solution. Many carbon capture technologies are already in use or being developed. These technologies are primarily designed to remove carbon dioxide (CO_2) from the atmosphere, which is challenging and costly because CO_2 is present in low concentrations.

However, unlike CO_2, methane is an energy source that reservoirs continuously produce. This means capturing and using methane could provide significant environmental and financial advantages.

There are several strategies that can help mitigate the GHG emissions associated with hydropower:

1. Smaller reservoir sizes: Run-of-river systems and those with small reservoirs have less land area being flooded; therefore, there is reduced organic material decomposing to form GHG.

Small-sized reservoirs submerge less organic matter, hence directly limiting the amount of material available for decomposition. This reduces methane production at its very source. With the surface area of water being small, it presents a reduced area through which methane could escape into the atmosphere. This further limits diffusive and bubble emissions that might be prominent in large tropical reservoirs. (Doğan et al., 2020)

Also, smaller reservoirs are normally shallower, and oxygenation is better, and anoxic conditions can hardly appear-developing, which are the most favorable conditions for methane-producing microorganisms.

2. Vegetation management: **Vegetation management** is a key mitigation strategy to reduce greenhouse gas (GHG) emissions, particularly methane, from hydropower reservoirs. When vegetation is removed from areas about to be flooded, it will immensely reduce methane emissions. However, this process is labor-intensive and costly.

Probably the most efficient technique to minimize the amount of methane production in reservoirs is with preimpoundment clearing-vegetation removal before the land is flooded. This reduces the carbon available for microbial breakdown by removing biomass that would have otherwise decomposed underwater and thus directly limits methane emissions.

Studies such as those of Fearnside (2005) and the more recent work by Deemer et al. (2016) have shown that reservoirs where vegetation was cleared before flooding produced significantly less methane than those where vegetation was left to decay in place. Clearing reduces the substrate available for methane-producing microbes.

In most cases, selective or partial vegetation removal can be employed, usually in portions most prone to methane generation. It can be the removal of highly dense biomass only or large woody vegetations while leaving behind residual natural vegetation.

The cost-benefit balance in this approach means lower methane emission, while the costs remain lower than in the case of full clearing. Besides, selective clearing helps to preserve a part of the ecological functions of the landscape, which may be quite important for biodiversity.

3. Aeration Methods: Intrusion of oxygen in water to enhance aerobic decomposition of organic matter resulting in CO_2 rather than methane. Mechanical aeration or induced mixing procedures may be used to enhance the natural mixed circulation of the water body.

Artificial Aeration (Mechanical)

- Plume aerators or diffusers: This is one of the most common techniques; it uses bubble diffusers that release the air or oxygen along the bottom of the reservoir. The rising bubbles oxygenate the water by breaking down methane through oxidation and preventing its formation by creating aerobic conditions.

- Mixing Vertically: This involves pumps that move water between the surface and the layers at depth to make sure oxygen-rich surface water reaches the bottom of the reservoir. Vertical mixing reduces stratification of water, resulting in minimal production of methane by maintaining oxygen levels throughout the reservoir.

Surface Aerators

These are devices that function from the surface of the reservoir, causing ripples and mixing the uppermost layers of the water. Although their influence is generally confined to the top layers of a reservoir, surface aerators can prevent the formation of stagnant zones of water in which anaerobic conditions might otherwise develop.

Aeration prevents the production of methane by the decomposition of organic materials by oxygenating the water. Moreover, since these bacteria are aerobic that make this conversion of methane to carbon dioxide, it means less potent GHGs are being released to the atmosphere, since CO_2 has a very low global warming potential compared with methane. Aeration can improve the general quality of the water in reservoirs by reducing the development of hydrogen sulfide (H_2S) and other toxic materials that develop under anoxic conditions.

4. Water Level Management: Stabilization of water levels, without frequent drying and reflooding, will reduce methane production.

Water level manipulation, for example, at different times of the year, can disrupt the conditions under which methane is produced.

Periodically, the operators should draw down the water level to expose submerged organic matter to air. This will lead to an aerobic decomposition of organic material by means of aerobic bacteria, producing much less harmful CO_2 instead of methane.

For example, in cases of high organic input, such as after heavy rains or flooding, operators can lower the water level to reduce the inundation of organic matter. This practice can decrease the development of anaerobic conditions and, consequently, methane production (Yiming et al. 2024).

5. Enhanced Monitoring: Advanced monitoring and modeling to project and manage GHG emissions, including continued water quality and GHG level monitoring activities to identify and address points of high GHG emission.

CO_2 and methane gas can even be utilized in hydropower plants as part of an original idea in reducing greenhouse gases and producing energy. A few ways in which CO_2 and methane could be utilized are as follows:

Biological sequestration of CO_2:

Microalgae use: Microalgae have the ability to absorb CO2 either from the atmosphere or directly from the emissions of hydroelectric power plants. Such algae can be used in the production of biofuels or other bioproducts. (Fearnside, 2002)

Plant use: CO_2 – gaseous can be consumed from the atmosphere by fast-growing plants planted close to a hydroelectric power plant. Later trees and plants produced can be used for producing biomass.

Chemical CO_2 Sequestration:

Mineralization: In this, stable mineral carbonates are produced by reacting CO_2 with certain minerals like basalt or serpentine.

Solutions: Water may be used to dissolve CO_2, which results in carbonic acid which again can be neutralized using bases.

Methane Utilization

Combustion of methane: CH4 methane recovered from hydroelectric reservoirs can be used as fuel to produce electricity.

Biofuels: Through methanogenesis methane is converted into liquid or gaseous biofuels

Gas-to-Liquid, GTL: Methane can be processed into liquid fuels with liquefaction in what is referred to as GTL. Sometimes this occurs through Fischer-Tropsch synthesis.

CCS technology devices for CO2 capture and storage in hydroelectric power stations contribute to reducing the emissions of greenhouse gases. This makes such plants more sustainable, it decreases GHG emissions and extra production is allowed by reusing waste gases. The requirement for further investigation and development in this line cannot be underestimated for further prospective application. (Giles, J. 2006)

RESULTS AND DISCUSSIONS

Region	Energy emissions (MT CO_2e) in 2023	Share	YoY Change
Asia Pacific	21,057.6	52.1%	+4.9%
North America	6,289.3	15.6%	-1.8%
Europe	3,775.8	9.3%	-5.3%
CIS	3,008.4	7.4%	+3.0%
Middle East	2,899.5	7.2%	+0.4%
Africa	1,788.3	4.4%	+1.1%
South & Central America	1,599.1	4.0%	+4.3%
Global Total	**40,417.9**	**100.0%**	**+6.4%**

Figure 5. Energy emissions worldwide in 2023

1. Methane Released from Hydropower Storage Facilities

The hydrpower reservoirs have emerged as a leading methane culprit in research over the last few years, especially for tropics. Decades of investigation worldwide have found that, in certain reservoirs at least, methane emissions exceed those due to some other greenhouse gases emitted during plant decomposition and this has significance when we take into account the warming potential of carbon dioxide. To cite just one example, some large tropical reservoirs emit methane in amounts up to the order of 104 mg CH_4/m^2/day (i.e., comparable with or even exceeding per kilowatt-hour emissions from fossil fuel-based energy generation).

2. Influences factors on methane emission

There are numerous influences on how much and at what rate the methane enters hydropower reservoirs, among them:

Temperature and Climate – Reservoirs in warm climates, such as tropical areas where organic material decomposes rapidly, often emit substantial amounts of methane (because it is a by-product of decomposition), whereas reservoirs from temperate or colder regions tend to release less methane. The substantial methane emissions observed in tropical reservoirs can be attributed to several key mechanisms related to the tropical climate and reservoir characteristics. (**Abril & Guérin (2005))** Warm temperatures in tropical regions accelerate the decomposition of organic matter within reservoirs. In these conditions, organic material such as plant matter, vegetation, and soil, submerged during reservoir creation, decomposes more rapidly under anaerobic conditions, producing methane. The lack of oxygen in deeper waters, combined with higher temperatures, creates an ideal environment for methane generation, particularly through microbial activity (methanogenesis).

Young reservoirs, particularly in the early flooding stage due to a lot of organic matter present for decay -- greater amounts of methane being released —higher flow rates. Even so, older reservoirs may remain a source of methane if they are shallow or have large amounts of organic material decaying photogenically.

Latest data also point to the importance of pre-impoundment land management in mitigating methane emissions. Methane outputs were considerably lower for those reservoirs whose vegetation was removed before impoundment in comparison with those reservoirs that were impounded without such interventions. This would, therefore, suggest that appropriate management of biomass-for example, removal or burning of vegetation-reduces the quantity of organic matter available for decomposition and hence minimizes the overall production of methane.

These findings thus hold considerable implications for the global assessment of hydropower's environmental impact. Given that there are already a great and increasing number of hydropower projects in the tropics, any calculation of their carbon footprint should definitely take methane emissions from these reservoirs into consideration. Mitigation strategies, such as technologies for aeration or organic matter removal, should therefore be targeted at tropical hydropower projects with a view to offsetting the great GHG emissions these systems produce.

CONCLUSION

This study highlights the significant, but largely overlooked, contribution of hydropower reservoirs to global emissions of the most potent greenhouse gases, methane and CO_2. Hydropower is a valuable renewable energy source that offers significant benefits in terms of reducing direct GHG emissions compared to fossil fuels. However, the full environmental impact, particularly concerning GHG emissions from reservoirs, construction, and maintenance, must be carefully considered and managed. Our estimates indicate that methane emission from tropical reservoirs could match or even outpace that of fossil fuel-based energy sources when measured on a per-kilowatt-hour basis. These are mostly mediated by increased decomposition of organic matter in anoxic, warm-water conditions and is compounded in most tropical regions due to lack of pre-impoundment land management practices.

By employing mitigation strategies, advancing technology, and implementing supportive policies, it is possible to reduce the carbon footprint of hydropower and ensure its role in a sustainable energy future.

Strategies like pre-impoundment vegetation clearing, better management of reservoirs, and various technologies, oxygenation or methane capture, could significantly mitigate those emissions. It shows that pre-impoundment vegetation clearing before flooding drastically reduces methane emission in some reservoirs. For this reason, this study is fundamental to designing and building future hydropower projects, particularly those in tropical regions with high potentials for methane release.

The policy implications of the study are clear: governments and energy stakeholders across the world have to go back to the drawing board and reconsider the environmental costs of hydropower. Policymakers should make sure that methane mitigation strategies are inserted into licensing procedures for new hydropower projects, especially for those involving new reservoirs to be constructed. Requirements for pre-impoundment vegetation removal, regular monitoring of reservoirs, and the introduction of methane-capture technologies would go a long way toward reducing the emissions of this gas.

Governments and hydropower operators should mandate vegetation management as part of the environmental assessment and approval processes for new reservoirs, especially in tropical regions where methane emissions are highest. Requiring pre-impoundment clearing or harvesting as a condition for project approval would help ensure that hydropower projects minimize their carbon footprint.

Future research should focus on refining methane measurement techniques in reservoirs, particularly those in tropical regions, to better understand the seasonal and operational variables that affect emission rates. Additionally, research into innovative methane mitigation technologies for existing reservoirs is essential to reduce the climate impact of hydropower without undermining its energy potential.

In conclusion, while hydropower remains an essential component of the global energy mix, this study highlights the urgent need for more nuanced assessments of its environmental footprint. With targeted interventions and robust policy frameworks, the negative climate impacts of hydropower in tropical regions can be mitigated, ensuring that it truly contributes to sustainable energy goals.

Understanding the complexities and challenges associated with hydropower emissions is essential for making informed decisions and promoting a balanced approach to renewable energy development.

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Recived: September 1, 2024

Accepted: November 18, 2024