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LETTER

Greenhouse gas emissions of hydropower in the Mekong River Basin

Timo A Räsänen1, Olli Varis1, Laura Scherer2 and Matti Kummu1,3

1 Water and Development Research Group, Aalto University, PO Box, 15200, Tietotie 1 E, 02150 Espoo, Finland
2 Institute of Environmental Sciences (CML), Leiden University, PO Box 9518, 2300 RA Leiden, Netherlands
3 Author to whom any correspondence should be addressed.

E-mail: timo.a.rasanen@gmail.com and matti.kummu@aalto.fi

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Supplementary material for this article is available online

Abstract

The Mekong River Basin in Southeast Asia is undergoing extensive hydropower development, but the magnitudes of related greenhouse gas emissions (GHG) are not well known. We provide the first screening of GHG emissions of 141 existing and planned reservoirs in the basin, with a focus on atmospheric gross emissions through the reservoir water surface. The emissions were estimated using statistical models that are based on global emission measurements. The hydropower reservoirs (119) were found to have an emission range of 0.2–1994 kg CO₂e MWh⁻¹ over a 100 year lifetime with a median of 26 kg CO₂e MWh⁻¹. Hydropower reservoirs facilitating irrigation (22) had generally higher emissions reaching over 22 000 kg CO₂e MWh⁻¹. The emission fluxes for all reservoirs (141) had a range of 26–1813 000 t CO₂e yr⁻¹ over a 100 year lifetime with a median of 28 000 t CO₂e yr⁻¹. Altogether, 82% of hydropower reservoirs (119) and 45% of reservoirs also facilitating irrigation (22) have emissions comparable to other renewable energy sources (<190 kg CO₂e MWh⁻¹), while the rest have higher emissions equalling even the emission from fossil fuel power plants (>380 kg CO₂e MWh⁻¹). These results are tentative and they suggest that hydropower in the Mekong Region cannot be considered categorically as low-emission energy. Instead, the GHG emissions of hydropower should be carefully considered case-by-case together with the other impacts on the natural and social environment.

1. Introduction

The Mekong River region in Southeast Asia is undergoing rapid social and economic development (Grumbine et al 2012), which has led to increasing demand for energy. The region is abundant in water resources and therefore hydropower is seen as an attractive energy source. Although hydropower is often considered as a climate-friendly energy option (Kaygusuz 2004, Edenhofer et al 2011, Dincer and Acar 2015), reservoirs are known to produce greenhouse gases (GHG), such as methane (CH₄), carbon dioxide (CO₂) and nitrous oxide (N₂O) (Demory and Bastien 2011).

These emissions originate from the degradation of organic matter in the reservoir and they enter the atmosphere via diffusive flux and bubbling through the reservoir water surface, via degassing and diffusion from the reservoir tail waters, and via the reservoir drawdown area (Demory and Bastien 2011, Varis et al 2012). The emissions depend on the characteristics of the natural systems that are inundated, on organic matter entering the reservoir from the catchment, and on reservoir characteristics and climate conditions. The emissions are further distinguished between gross and net emissions. Gross emissions are those that are directly measurable from existing reservoirs and net emission consider also the emissions from the reservoir area before inundation, which can act as a GHG source (e.g. natural waters) or sink (e.g. forests).

In the Mekong, the construction of large dams (dam height >15 m) for hydropower and irrigation started in the 1960s, and became more intensive in the late 1990s. Currently the basin has at least 64 large dams...
and more than 100 are planned (MRC 2015, WLE 2015). The total hydropower capacity of all the existing and planned large dams is over 60,000 MW.

The impacts of hydropower development on various aspects are increasingly well understood in the Mekong River Basin; these include impacts on hydrology (Lauri et al 2012, Cochrane et al 2014, Räsänen et al 2017), ecosystems (Ziv et al 2012, Arias et al 2014), sediment (Kummu et al 2010, Kondolf et al 2014, Manh et al 2015), fisheries (Baran and Myschowoda 2009, Stone 2016) and riparian people (Wyatt and Baird 2007, Keskinen et al 2016). At the same time, the hydropower’s GHG emissions have received less attention and are not systematically assessed, although concerns on potentially high emissions have been raised (Yang and Flower 2012).

Globally, GHG emission measurements have been reported since the 1990s. Barros et al (2011) collected existing CO₂ and CH₄ gross emission data from 85 reservoirs worldwide and found that emissions varied considerably between regions, being highest in the tropics. They estimate that the reservoir emissions correspond to 4% of the global carbon emissions from inland waters.

Hertwich (2013) estimated that the global average emission is 85 kg CO₂ MWh⁻¹ and 3 kg CH₄ MWh⁻¹, the most important predictor for emissions being reservoir area per kWh. Scherer and Pfister (2016) developed another statistical model, which they applied to ∼1500 reservoirs, estimating the global average emissions to be 173 kg CO₂ MWh⁻¹ and 295 kg CH₄ MWh⁻¹. Both estimates are below the emissions from fossil fuel power plants (380–1300 kg CO₂e MWh⁻¹) (Turconi et al 2013), but there is a high variability between reservoirs.

A review of emission measurements from tropical and equatorial reservoirs by Demarty and Bastien (2011) suggests that emissions can be large in warm climates particularly in cases in which vegetation and other easily degradable matter such as peat was not cleared and thus submerged by a reservoir. They used measurements from 18 equatorial and tropical reservoirs in which emissions varied between 2 and 4100 kg CO₂e MWh⁻¹. Demarty and Bastien (2011) further note that the emission measurements are too limited to take global position on the emissions of tropical reservoirs, given that there is a large number of dams in the tropics, and that there is a need to develop unified measurement protocols (see also Goldenfum 2012).

In the case of the Mekong, the research on GHG emissions from the reservoirs is very limited. To our knowledge, there exist published GHG emission measurements only from three reservoirs in Lao PDR, namely Nam Ngum 1 and Nam Leuk reservoirs (Chanudet et al 2011) and Nam Theun 2 reservoir (Deshmukh et al 2012, Deshmukh et al 2013). These three cases provide an important starting point for quantifying reservoir GHG emissions in the Mekong Basin, but there is no basin-wide understanding of the potential emissions.

The methods for estimating the GHG emissions from reservoirs on regional scale are limited, particularly in situations when GHG measurements are scarce or not available. UNESCO/IHA (2012) developed a GHG risk assessment tool that provides an estimate of the vulnerability of a reservoir on GHG emissions. The tool is based on existing global reservoir emission measurements and used, for example, by Kumar and Sharma (2016) for analysing the Tehri hydropower project in India. Another approach was developed by de Faria et al (2015), who applied a combination of models and existing measurements from the Amazon region to estimate emissions for planned reservoirs. More detailed modelling methods also exist (e.g. Weissenberger et al 2010), but those are often data intensive and not feasible for regional scale studies with limited measurements.

The quantification of GHG emissions in the Mekong has clearly major research gaps, and scientific information to support decision-making is lacking. Therefore, in this paper we aim to conduct the first assessment of the gross GHG emissions of the hydropower development in the basin, with focus on gross emissions of CO₂ and CH₄ through the reservoir water surface. Our aim can be divided further into two objectives: to estimate emissions of hydropower per energy unit, and to estimate emission fluxes from the reservoirs.

We decided to achieve our objectives by estimating the GHG emissions of 141 existing and planned hydropower reservoirs in the Mekong Basin using global statistical models from Hertwich (2013) and Scherer and Pfister (2016), considering them the most robust and well-documented methods for data scarce area with climate zones ranging from cool continental to tropics. Further, in contrast to the global assessments for a single year, this is the first large-scale study to assess emissions over a lifetime of 100 years.

With this we aim to provide an improved understanding of the GHG emissions of the hydropower development in the Mekong and thus provide information for directing future research efforts and for climate-smart decision making. Since we are analysing GHG emissions of hydropower generation, our analysis includes only the reservoirs that have documented to be equipped for power generation, and leave other reservoirs for further studies.

2. Materials and methods

In this study, we focus on the atmospheric gross emissions of CO₂ and CH₄ and their combined CO₂ equivalent (CO₂e) through the reservoir water-air interface. We excluded other emission sources such as degassing and diffusion from the reservoir tail water,
Figure 1. Estimated greenhouse gas emissions and power densities of 141 existing and planned reservoirs in the Mekong River Basin. CDM stands for the Clean Development Mechanism of the Kyoto Protocol (UN 2017) for implementing emission-reduction projects.

as well as dam construction. The results are reported as emissions per energy unit \([\text{CO}_2 \text{e kg MWh}^{-1}]\) and emission fluxes \([\text{t CO}_2 \text{e yr}^{-1}]\) averaged over a 100 year lifetime. In the Discussion section, we also provide results averaged over a 10 year lifetime for the purpose of comparison with emission estimates presented in the literature. Below, the data and methods used for estimations are described.

2.1. Reservoirs

The reservoirs selected for our analysis were taken from the dam databases of the Mekong River Commission (MRC) and the CGIAR Research Program on Water, Land Ecosystem (WLE) (MRC 2015, WLE 2015). The MRC and WLE databases contain 154 and 394 dams and reservoirs, respectively. The WLE database contains a larger number of small dams compared to the MRC database. We screened both databases for large dams (height over 15 m) with sufficient data for our analysis, and ended up with a dataset of 141 reservoirs (figure 1). At least 64 of these reservoirs are already built.

For each reservoir, we collected the following parameters from the two databases: location (decimal degrees), dam height (m), purpose (hydropower, irrigation etc.), annual energy (GWh yr\(^{-1}\)), installed capacity (MW), and reservoir surface area (km\(^2\)). For 22 (out of 141) reservoirs, mainly on the Chinese side of the basin, we had to estimate the reservoir surface area using the dam location, the dam height and a digital elevation model (DEM, see table 1) (Jarvis and Reuter 2008).

For estimating the emissions of hydropower, the purpose of the reservoirs needed to be considered. In the Mekong, reservoirs are built mainly for electricity generation and irrigation purposes, and therefore, we divided the reservoirs into three groups: (i) all reservoirs (141), (ii) hydropower reservoirs (119 of 141) and (iii) hydropower reservoirs with irrigation (22 of 141). Irrigation has potentially large effects on
reservoir and power plant design as well as operations, which in turn impact estimates of emissions per energy unit. For example, in irrigation reservoirs the power capacity of the power plant is often smaller than in those designed primarily for power generation, and the water available for power generation can be affected by irrigation demands. Thus, the emission estimates of the first group with 119 reservoirs are considered to reflect the emissions of hydropower in the Mekong Basin. The reservoir and hydropower data with key parameters are given in the supplement 2 available at stacks.iop.org/ERL/13/034030/mmedia.

### 2.2. Emission models

The GHG emissions were estimated using the models from Scherer and Pfister (2016) and Hertwich (2013). Both are based on linear statistical models for CO$_2$ and CH$_4$ that are fitted against emission data from about 100 reservoirs worldwide. For estimating emissions per energy unit we used the equation from Hertwich (2013) for CO$_2$ and the equation from Scherer and Pfister (2016) for CH$_4$, and for estimating emission fluxes we used the equations from Scherer and Pfister (2016) for both CO$_2$ and CH$_4$. There were two reasons for using a combination of models. First, the model from Scherer and Pfister (2016) for CO$_2$ emissions per energy unit lacks an age factor and thus considers the CO$_2$ emissions per energy unit to be constant in time. The constant CO$_2$ emissions, however, do not fit to the general understanding of reservoir emissions (St Louis et al 2000, Abril et al 2005, Barros et al 2011, Demarty and Bastien 2011, Miller et al 2011, Hertwich 2013). Second, Scherer and Pfister (2016) compare their model to the model of Hertwich (2013) using various indicators and found that their model outperformed the model of Hertwich (2013) in the case of CH$_4$ emissions. For further model comparison see Scherer and Pfister (2016).

The model, we used for estimating emissions per energy unit (EpEU model, kg MWh$^{-1}$), is based on the following equations:

\[
\log_{10}(CO_2) = 0.8 + 0.97 \cdot \log_{10}(ATE) - 0.006 \cdot AGE + 0.737 \cdot \log_{10}(NPP) \quad (1)
\]

\[
\ln(CH_4) = -9.81 - 0.75 \cdot \ln(AGE) + 1.18 \cdot \ln(ATE) + 4.50 \cdot \ln(TMAX) \quad (2)
\]

where ATE [km$^2$ GWh yr$^{-1}$] is the reservoir area-to-electricity ratio, NPP [g C m$^{-2}$ yr$^{-1}$] is the net primary production, AGE [yr] is the reservoir age, and TMAX [°C] is the temperature of the warmest month.

The model for estimating emission fluxes (EF model, mg C m$^{-2}$ d$^{-1}$) is based on the following equations:

\[
CO_2 = 494.46 - 4.07 \cdot \ln(AGE) + 8.09 \cdot \ln(TMAM) \quad (3)
\]

\[
\ln(CH_4) = -12.84 - 0.03 \cdot \ln(AGE) + 0.21 \cdot \ln(A) - 0.01 \cdot \ln(TMAM) + 4.88 \cdot \ln(TMAM) \quad (4)
\]

where ERR [t ha yr$^{-1}$] is the annual erosion per hectare, A [km$^2$] is the surface area of the reservoir.

The spatial data used in the equations are listed in table 1, and the reservoir specific values derived from spatial data are given in online supplement 2. The NPP, ERR and TMAX were estimated using 5 km buffers at the dam location, if the reservoir area was not available. The calculated emissions were further corrected as in Scherer and Pfister (2016): the CO$_2$ emissions were reduced by multiplying with a factor of 0.87 and the CH$_4$ emission increased by multiplying with factor of 1.4. to consider the neglection of carbon burial and methane ebullition (bubbling) in the measurements.

In this paper, we present the results as combined CO$_2$e, and as averages of EpEU and EF models. The emission fluxes were further converted from mg C m$^{-2}$ d$^{-1}$ to t CO$_2$e yr$^{-1}$. For transforming CH$_4$ to CO$_2$e we used a Global Warming Potential (GWP) of 34 over 100 years. As a comparison, we also calculated power densities (W m$^{-2}$) for each reservoir. Power densities are used in the Clean Development Mechanism (CDM) of the Kyoto Protocol (UN 2017) for implementing emission-reduction projects in developing countries that can earn saleable certified emission reduction credits. Hydropower projects with power densities above 4 W m$^{-2}$ are eligible for the CDM.

We further provide 20–80 percentile uncertainty intervals for emission estimates. These intervals were derived by comparing here estimated emissions of

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net primary production (NPP)</td>
<td>Haberl et al (2007)</td>
<td>Potential vegetation (NPP0); Coverage/resolution: globe, 5 arc min. (&lt;10 km at the equator)</td>
<td>g C m$^{-2}$ yr$^{-1}$</td>
</tr>
<tr>
<td>Erosion (ERR)</td>
<td>Scherer and Pfister (2015)</td>
<td>Global soil erosion, based on Universal Soil Loss equation (USLE); Coverage/resolution: globe, 5 arc min. (&lt;10 km at the equator)</td>
<td>t ha$^{-1}$</td>
</tr>
<tr>
<td>Temperature of warmest month (TMAX)</td>
<td>Hijmans et al (2005)</td>
<td>Maximum temperature of the warmest month (BIO5); Coverage/resolution: globe, 30 arc sec. (&lt;1 km at the equator)</td>
<td>°C</td>
</tr>
<tr>
<td>Digital elevation model (DEM)</td>
<td>Jarvis and Reuter (2008)</td>
<td>Hole-filled Shuttle Radar Topology Mission (SRTM) for the globe Version 4.1; Coverage/resolution: globe, 3 arc sec. (&lt;90 m at the equator)</td>
<td>m</td>
</tr>
</tbody>
</table>
22 global low-latitude (33°N–33°S) reservoirs with measured emissions. In the comparison, we calculated relative errors and fitted a log-normal probability distribution to those. This was then used to characterize the uncertainty of the emission estimates in the Mekong according to probability quantiles of 0.2 and 0.8. The global low-latitude reservoirs were considered to provide a reasonable reference for model errors for the Mekong, as it is located in similar latitudes (33°N–8°N). The measurement data were collected from Scherer and Pfister (2016) and was supplemented with six reservoirs from Asia of which three are located in the Mekong Basin (Chanudet et al 2011, Deshmukh et al 2013, Zhao et al 2013, Kumar and Sharma 2016). The emission range of these Asian reservoirs (10–336 kg CO$_2$e MWh$^{-1}$) is close and on both sides of global average (187–273 kg CO$_2$e MWh$^{-1}$) and median (84 kg CO$_2$e MWh$^{-1}$) emissions (Hertwich 2013, Scherer and Pfister 2016), which further supports the use of global emission models in the Mekong Basin. The uncertainty analysis method is presented in detail in supplement 1, while uncertainty intervals given in results section in appropriate place and for all reservoirs in supplement 2.

3. Results

We estimated the unweighted average and median emissions per energy unit of all 141 reservoirs to be 419 and 30 (where 20–80 percentile uncertainty intervals for emissions are 1–161) kg CO$_2$e MWh$^{-1}$, respectively. For 119 hydropower reservoirs, the average and median emissions are 122 and 26 (1–114) kg CO$_2$e MWh$^{-1}$, respectively, while for the 22 hydropower reservoirs with irrigation those are 2031 and 85 (8–634) kg CO$_2$e MWh$^{-1}$, respectively. The emissions for individual reservoirs vary considerably, ranging from 0.2–22,272 kg CO$_2$e MWh$^{-1}$ (figure 1).

The frequency distribution of the emissions is highly skewed (figure 2(a)). Thus, a median, instead of a mean, provides a better description for the central tendency of the emissions. The skewed emission distribution suggests that a large number of the reservoirs have relatively low emissions per energy unit, but there are a number of reservoirs with high emissions, too. In the case of hydropower reservoirs, the ten highest emissions per energy unit range 322–1994 kg CO$_2$e MWh$^{-1}$ (table 2). The reservoirs with high emissions tend to have a large reservoir surface area in relation to power capacity and are located in the warmer parts of the basin (table 2).

The emission fluxes of all reservoirs (figures 1(b) and 2(b)) indicate that the emissions vary considerably, too. The average emission flux for all reservoirs is 133,000 t CO$_2$e yr$^{-1}$ with median of 28,000 (587–109,100) t CO$_2$e yr$^{-1}$. The range of the ten highest emission fluxes is 700,000–1,800,000 t CO$_2$e yr$^{-1}$ (100 yr) (table 2b). All of these ten reservoirs have a very large surface area.

The results further suggest that existing reservoirs have lower emissions than the planned reservoirs (figure 2). The median emission per energy unit for existing hydropower reservoirs (53 of 119) is 18 kg CO$_2$e MWh$^{-1}$ and for planned hydropower reservoirs (66 of 119) 31 kg CO$_2$e MWh$^{-1}$. There is, however, a large uncertainty in the characteristics of the planned reservoirs.

The comparison of emission estimates to power densities shows that they have a strong correlation ($r=−0.96$; p-value <0.01) (figure 5). The average and median power densities for the 119 hydropower reservoirs are 54.3 and 10.9 W m$^{-2}$, while for 22 hydropower reservoirs with irrigation those are 6.0 and 2.3 W m$^{-2}$, respectively. Altogether 84 out of 119 hydropower reservoirs and 8 out of 22 hydropower reservoirs with irrigation have a higher power density than the CDM threshold of 4 W m$^{-2}$ (figure 1). Out of the 77 planned reservoirs 27 are above the 4 W m$^{-2}$ threshold. This threshold corresponds to emissions per energy unit of 87 kg CO$_2$e MWh$^{-1}$.

Total reservoir emissions (figures 3(a)–(b)) illustrate well the different phases of hydropower construction in the basin. First reservoirs were
completed in 1966 and 1971, and the second, very intensive construction phase started in the early 2000s. According to the used databases and our analysis, the growth in emissions will continue at least until the year 2023 when altogether 111 reservoirs are built, should all existing plans be implemented. There are plans for 30 more large dams for which commission years are not known—their emissions are not included in figure 3. The 111 reservoirs, with known commission year, continue to emit GHGs in the post-2023 era with a rather high rate but decreasing trend.

The median emission per energy unit for the hydropower reservoirs varies over time (figure 3(c)). In 2000–2005, when several new reservoirs were built, the median emission was 120 (1–344) kg CO$_2$e MWh$^{-1}$, while for 2015–2020 the median emission decreases to 41 (1–134) kg CO$_2$e MWh$^{-1}$. If no more reservoirs are built after 2023, the median emission is estimated to decrease to 26 (1–113) kg CO$_2$e MWh$^{-1}$ by the 2050s (see figure S4 for results for a situation where no more reservoirs are built after 2017).

### 4. Discussion

In this article, we provide the first GHG emission estimates for hydropower in the Mekong Basin. We found that the emissions range from 0.2–1994 kg CO$_2$e MWh$^{-1}$ over a 100 year lifetime with a median of 26 (1–114) kg CO$_2$e MWh$^{-1}$. The emissions per energy unit and emission fluxes were most strongly related to the following model predictors: area-to-electricity ratio, surface area and air temperature (table S3). The power density (W m$^{-2}$)—used in CDM—also showed a strong relationship with our estimated emissions per energy unit (figure S3).

### 4.1. Comparison to global, low-latitude and local emission estimates

Our average and median emissions for the Mekong reservoirs have similar orders of magnitude than the estimated global emissions, the global median being slightly higher (table 3). The global low-latitude reservoirs (33°N–33°S) (table S1), in turn, have one order of magnitude higher measured emissions than our estimates for the Mekong (table 3). The high-emission reservoirs from the Amazonian region increases the average derived from that dataset. The comparison to measured emissions from the tropical reservoirs in Brazil and French Guiana shows that the average and median emissions in the Mekong are generally lower but have a similarly high variability in emissions (table 3). In addition, when our estimates are compared with measurements from low-latitude reservoirs in India (Tehri), China (Three Gorges) and Taiwan (Tsengwen) and Lao PDR (Nam Theun 2, Nam Leuk), our results are in the same order of magnitude (table 3 and table S1). These comparisons are, however,

### Table 2. Estimates of highest CO$_2$e emissions per energy unit and largest CO$_2$-e fluxes of the reservoirs in the Mekong River Basin. Emission estimates are given as averages over a 100 year lifetime. The 60% uncertainty interval is given in parentheses.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Country</th>
<th>Commission year</th>
<th>Annual energy [GWh]</th>
<th>Reservoir area [km$^2$]</th>
<th>CO$_2$e emission per energy unit [kg CO$_2$e MWh$^{-1}$]</th>
<th>CO$_2$e fluxes [10$^3$ t CO$_2$e y$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Highest CO$_2$e emissions per energy unit (119 hydropower reservoirs, reservoirs with irrigation excluded)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average/median of 119 reservoirs</td>
<td>—</td>
<td>—</td>
<td>1735/507</td>
<td>69/16</td>
<td>120/26 (1–114)</td>
<td></td>
</tr>
<tr>
<td>Xe Bang Nouan</td>
<td>Lao PDR</td>
<td>2021</td>
<td>79</td>
<td>87</td>
<td>1990 (299–3449)</td>
<td></td>
</tr>
<tr>
<td>Lower Sre Pok 3 (3A)</td>
<td>Cambodia</td>
<td>TBD</td>
<td>1201</td>
<td>721</td>
<td>1400 (210–2423)</td>
<td></td>
</tr>
<tr>
<td>Lower Sesan 3</td>
<td>Cambodia</td>
<td>TBD</td>
<td>1310</td>
<td>727</td>
<td>1380 (209–2394)</td>
<td></td>
</tr>
<tr>
<td>Xe Bang Hieng 2</td>
<td>Lao PDR</td>
<td>2022</td>
<td>73</td>
<td>46</td>
<td>1030 (154–1778)</td>
<td></td>
</tr>
<tr>
<td>Nam Ngum 1</td>
<td>Lao PDR</td>
<td>1971</td>
<td>1025</td>
<td>369</td>
<td>670 (100–1154)</td>
<td></td>
</tr>
<tr>
<td>Duc Xuyen</td>
<td>Vietnam</td>
<td>TBD</td>
<td>181</td>
<td>334</td>
<td>370 (55–632)</td>
<td></td>
</tr>
<tr>
<td>Lower Sesan 2</td>
<td>Cambodia</td>
<td>2019</td>
<td>1310</td>
<td>113</td>
<td>360 (54–622)</td>
<td></td>
</tr>
<tr>
<td>Nam Feuang 1</td>
<td>Lao PDR</td>
<td>2022</td>
<td>73</td>
<td>46</td>
<td>1330 (200–2307)</td>
<td></td>
</tr>
<tr>
<td>Lower Sre Pok 4</td>
<td>Cambodia</td>
<td>TBD</td>
<td>221</td>
<td>33</td>
<td>350 (53–606)</td>
<td></td>
</tr>
<tr>
<td>Sekong</td>
<td>Cambodia</td>
<td>TBD</td>
<td>557</td>
<td>94</td>
<td>320 (48–557)</td>
<td></td>
</tr>
</tbody>
</table>

| B. Largest CO$_2$e fluxes (all 141 reservoirs) |
|-----|-----|-----|-----|-----|-----|
| Average/median of 141 reservoirs | — | — | 1713/485 | 77/22 | 133/28 (<1–109) | |
| Lower Sesan 3 | Cambodia | TBD | 1310 | 727 | 1810 (272–3136) | |
| Lower Sre Pok 3 (3A) | Cambodia | TBD | 1201 | 721 | 1680 (252–2911) | |
| Samnor | Cambodia | TBD | 11 740 | 620 | 1150 (73–1992) | |
| Stung Sen | Cambodia | TBD | 124 | 434 | 1250 (187–2158) | |
| Ubol Ratana | Thailand | 1966 | 56 | 401 | 760 (113–1307) | |
| Dachashan | China | 2003 | 5500 | 826 | 970 (145–1673) | |
| Sirindhorn | Thailand | 1971 | 90 | 289 | 740 (110–1272) | |
| Inghong | China | 2009 | 5570 | 510 | 710 (107–1236) | |
| Lower Sesan 2 | Cambodia | 2019 | 1954 | 334 | 700 (105–1213) | |
| Nam Theun 2 | Lao PDR | 2010 | 6000 | 450 | 410 (209–2394) | |
Figure 3. Estimated CO$_2$e emission of reservoirs in the Mekong River Basin: (a) total annual emissions, (b) cumulative total emissions and (c) median emission per energy unit. The estimates in tiles A and B include 111 reservoirs with known or planned commission years until the year 2023 and excludes 30 planned reservoirs with unknown commission year. The estimate in tile (c) includes 97 hydropower reservoirs of these 111 reservoirs (i.e. includes only hydropower reservoirs and excludes reservoirs also serving irrigation). The grey shading is the 20–80 percentile uncertainty interval for emissions. Note: in tile (c) the emission data is out of range from the 1970s to the early 1990s due to estimated high emissions of Nam Ngum 1, the small number of hydropower reservoirs in early years of analysis, and the use of the median as metric.

only indicative, as the global emissions were estimated for the year 2009, the low-latitude and tropical reservoir datasets contain measurements from reservoirs with different ages, whereas our results for the Mekong Basin are estimates over 100- and 10 year periods.

Comparison in the Mekong Basin shows that our estimates are higher than measured emissions. Nam Leuk and Nam Ngum 1 reservoirs measured emissions of 78 kg CO$_2$e MWh$^{-1}$ and $\sim$30 300 t CO$_2$e y$^{-1}$ (Chanudet et al 2011), respectively, whereas our estimates for the same years are 183 (28–317) kg CO$_2$e MWh$^{-1}$ and 623 800 (93 750–1 079 174) t CO$_2$e y$^{-1}$. The large negative emissions from 1971 commissioned Nam Ngum 1 dam are exceptional when compared to measured emission elsewhere in low latitudes (Barros et al 2011). Nam Theun 2 reservoir had a measured emission range from 216–336 kg CO$_2$e MWh$^{-1}$ for the two first years of operation (Deshmukh et al 2012, Deshmukh et al 2013), being close to our estimate of 381 (60–659) kg CO$_2$e MWh$^{-1}$ for the same years. Thus, our estimates for reservoirs in the Mekong are in the same order of magnitude, and within the uncertainty range, when compared to the measurements in the basin and low-latitude reservoirs in Asia. Some differences exist but they could not
Table 3. Comparison of emission estimates from the Mekong to global, low latitude and local measurements. For the Mekong, only reservoirs with hydropower as main purpose are included.

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of reservoirs</th>
<th>Reservoir age/estimate year</th>
<th>Source</th>
<th>Average [kg CO$_2$e MWh$^{-1}$]</th>
<th>Median [kg CO$_2$e MWh$^{-1}$]</th>
<th>Range [kg CO$_2$e MWh$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil and French Guiana$^a$</td>
<td>12</td>
<td>1–36 yr</td>
<td>Demarty and Bastien (2011)</td>
<td>1548</td>
<td>1381</td>
<td>2–4100</td>
</tr>
<tr>
<td>Mekong$^b$</td>
<td>119</td>
<td>Average over 100 year lifetime</td>
<td>This study</td>
<td>122 (1–114)</td>
<td>26 (1–114)</td>
<td>0.2–1994</td>
</tr>
<tr>
<td>Mekong$^b$</td>
<td>119</td>
<td>Average over 10 year lifetime</td>
<td>This study</td>
<td>251 (2–269)</td>
<td>46 (2–269)</td>
<td>0.2–4354</td>
</tr>
</tbody>
</table>

$^a$ Measurement-based estimate.

$^b$ Model estimate.

Figure 4. Estimated 100 year lifetime emissions of 119 hydropower reservoirs in the Mekong River Basin compared to life cycle emissions of other energy forms (Turconi et al 2013). We added, on top of the GHG emissions reported elsewhere in the paper, construction emissions of 19 kg CO$_2$e MWh$^{-1}$ (Schlömer et al 2014) for each reservoir, while manufacturing, maintenance and decommissioning emissions were not included.

be explained within this study as it would require more detailed measurements and modelling. The reservoir emission measurements themselves have also uncertainties mainly due to a lack of standard measurement techniques and varying consideration of emission sources (Goldenfum 2012, Deemer et al 2016). For further comparison of measured and estimated reservoir emissions according to climate zones and per surface unit area see table S4.

4.2. Comparison to other energy forms

The full comparison between Mekong hydropower GHG emissions and other energy forms would require a life cycle emission analysis, which considers the emissions from manufacturing, construction, maintenance and decommissioning. In addition, net emissions, and emissions from the reservoir drawdown area and tail waters should also be considered. This is outside the scope of this paper, but for a simplified comparison we include an estimate of the construction emissions of 19 kg CO$_2$e MWh$^{-1}$ (Schlömer et al 2014) to our estimates of gross reservoir emissions.

When the construction related emissions are included, the estimated median of hydropower emissions is 49 kg CO$_2$e MWh$^{-1}$, ranging from 19–2013 kg CO$_2$e MWh$^{-1}$ (figure 4). Altogether 97/119 hydropower reservoirs and 10/22 of hydropower reservoirs with irrigation are within the range of other renewable energy forms (<190 kg CO$_2$e MWh$^{-1}$; based on Turconi et al (2013)) during a 100 year lifetime. The rest of the reservoirs had higher emissions and emissions of 14 reservoir equalled the emissions from fossil fuel power plants (>380 kg CO$_2$e MWh$^{-1}$; Turconi et al 2013)).
4.3. High-emission future hydropower projects

Over half of the assessed reservoirs are under construction or in planning. These reservoirs have higher median emission estimates than existing ones. Our estimates help to identify reservoirs that are potentially high GHG emitters and would thus require special attention prior to the commission of building them. For example, 15 future reservoirs were found to have emission range of 278–9271 kg CO$_2$e makes hydropower projects eligible for the CDM (UN 2017). Table 4. Fifteen future reservoirs with highest estimated CO$_2$e emissions over a 100 year lifetime in the Mekong River Basin. The table also shows power densities for each reservoir. A power density above 4 W m$^{-2}$ makes hydropower projects eligible for the CDM (UN 2017).

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Country</th>
<th>Purpose$^a$</th>
<th>Commission year</th>
<th>Annual energy [GWh]</th>
<th>Reservoir area [km$^2$]</th>
<th>CO$_2$e emission [kg CO$_2$e MWh$^{-1}$]</th>
<th>Power density [W m$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average/median of 141 res.</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1715/485</td>
<td>77/22</td>
<td>420/30 (1–161)</td>
<td>46.8/8.2</td>
</tr>
<tr>
<td>Stung Sen</td>
<td>Cambodia</td>
<td>PCA</td>
<td>TBD</td>
<td>124</td>
<td>434</td>
<td>9270</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>77</td>
<td>22</td>
<td>(1391–16 039)</td>
<td></td>
</tr>
<tr>
<td>Xe Bang Nouan</td>
<td>Lao PDR</td>
<td>P</td>
<td>2021</td>
<td>79</td>
<td>87</td>
<td>1990</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>79</td>
<td>87</td>
<td>(239–3419)</td>
<td></td>
</tr>
<tr>
<td>Battambang 1</td>
<td>Cambodia</td>
<td>PCAF</td>
<td>TBD</td>
<td>120</td>
<td>92</td>
<td>1510</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>120</td>
<td>92</td>
<td>(227–2616)</td>
<td></td>
</tr>
<tr>
<td>Lower Sre Pok 3 (3A)</td>
<td>Cambodia</td>
<td>PCF</td>
<td>TBD</td>
<td>1201</td>
<td>721</td>
<td>1400</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>1201</td>
<td>721</td>
<td>(227–2616)</td>
<td></td>
</tr>
<tr>
<td>Lower Sesan 3</td>
<td>Cambodia</td>
<td>PCF</td>
<td>TBD</td>
<td>1310</td>
<td>727</td>
<td>1380</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>1310</td>
<td>727</td>
<td>(210–2423)</td>
<td></td>
</tr>
<tr>
<td>Xe Bang Hieng 2</td>
<td>Lao PDR</td>
<td>P</td>
<td>2022</td>
<td>73</td>
<td>46</td>
<td>1030</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>73</td>
<td>46</td>
<td>(154–1778)</td>
<td></td>
</tr>
<tr>
<td>Duc Xuyen</td>
<td>Vietnam</td>
<td>PAF</td>
<td>TBD</td>
<td>181</td>
<td>77</td>
<td>600 (89–1031)</td>
<td>0.7</td>
</tr>
<tr>
<td>Stung Pursat 1</td>
<td>Cambodia</td>
<td>PCAF</td>
<td>TBD</td>
<td>335</td>
<td>81</td>
<td>400 (59–685)</td>
<td>0.3</td>
</tr>
<tr>
<td>Lower Sesan 2$^a$</td>
<td>Cambodia</td>
<td>PCF</td>
<td>2019</td>
<td>1954</td>
<td>334</td>
<td>370 (55–652)</td>
<td>1.2</td>
</tr>
<tr>
<td>Nam Feuang 1</td>
<td>Lao PDR</td>
<td>P</td>
<td>2022</td>
<td>113</td>
<td>26</td>
<td>360 (54–622)</td>
<td>1.1</td>
</tr>
<tr>
<td>Lower Sre Pok 4</td>
<td>Cambodia</td>
<td>PC</td>
<td>TBD</td>
<td>221</td>
<td>33</td>
<td>350 (53–606)</td>
<td>1.5</td>
</tr>
<tr>
<td>Sekong</td>
<td>Cambodia</td>
<td>P</td>
<td>TBD</td>
<td>557</td>
<td>94</td>
<td>320 (48–557)</td>
<td>2</td>
</tr>
<tr>
<td>Xe Pon 3</td>
<td>Lao PDR</td>
<td>P</td>
<td>2020</td>
<td>164</td>
<td>30</td>
<td>310 (46–527)</td>
<td>1.6</td>
</tr>
<tr>
<td>Nam Ngum Lower dam</td>
<td>Lao PDR</td>
<td>PAR</td>
<td>2022</td>
<td>526</td>
<td>80</td>
<td>290 (43–492)</td>
<td>1.4</td>
</tr>
<tr>
<td>Nam Theun 4</td>
<td>Lao PDR</td>
<td>P</td>
<td>2022</td>
<td>130</td>
<td>29</td>
<td>280 (42–482)</td>
<td>2.8</td>
</tr>
</tbody>
</table>

$^a$ Power generation, C = flood control, A = Agriculture/irrigation, F = fisheries, R = recreation.

$^b$ Reservoir filling started during the writing of the paper.

4.4. Limitations and ways forward

The reservoir emission estimates presented in this paper provide the first screening of the GHG emissions of the hydropower reservoirs in the Mekong. However, there are three important limitations that need to be considered when interpreting the results. First, the used methodology is based on global statistical models that are calibrated on reservoir emissions worldwide and not specifically for the reservoirs located in the Southeast Asian climate zones and conditions. However, detailed model calibration for the Mekong, as done by de Faria et al (2015) in the Amazon, is not currently an option due to lack of emission measurements. Second, the applied models may not be able to adequately capture the local factors that influence emissions of individual reservoirs. This can potentially cause inaccuracies to the emission estimates. Third, our assessment focuses on gross emissions from the reservoir surface, not accounting for net emissions or emissions from other sources such as the reservoir tail waters and drawdown areas. Our estimated gross emissions are likely to be higher than net emissions, but the inclusion of emissions from degassing would have increased our emission estimates, as it was only partially considered in our models (not all measurements underlying the regression models included CH$_4$ bubbles). For example, in the case of two tropical reservoirs, Balbina and Petit Saut, the degassing of CH$_4$ is considered to account for 35% and 60% of the total CH$_4$ emissions, respectively (Demarty and Bastien 2011), and in Nam Theun 2 reservoir the gross emissions were estimated to be 23%–27% larger than the net emissions (Deshmukh et al 2014, Serča et al 2016, Deshmukh et al 2016).

Our findings emphasize the need to further investigate the GHG emissions of hydropower in the Mekong, particularly in case of planned future reservoirs that were here identified to potentially have high emissions. There is a growing number of emission measurements in Asia (Deemer et al 2016), but there still an urgent need for further measurement across the climate zones and reservoir types of the Mekong Basin. These measurements would enable development of improved regional emission models and increase the
5. Conclusions

This paper provides the first assessment of the GHG emissions of hydropower reservoirs in the Mekong Basin. The basin is undergoing extensive hydropower development, yet the understanding of hydropower’s GHG emissions is limited. We estimated the emissions of 141 existing and planned reservoirs using statistical global emission models, with focus on gross CO$_2$ and CH$_4$ emissions through the reservoir water surface.

Our results show considerable variation in the estimated hydropower emissions. The hydropower was found to have an emission range of 0.2–1994 kg CO$_2$e MWh$^{-1}$ over a 100 year lifetime with a median of 26 (1–114) kg CO$_2$e MWh$^{-1}$. Altogether, 82% of hydropower reservoirs (119) and 45% of reservoirs facilitating also irrigation (22) have emissions comparable to other renewable energy sources (<190 kg CO$_2$e MWh$^{-1}$), while the rest have higher emissions equalling even the emissions from fossil fuel power plants (>380 kg CO$_2$e MWh$^{-1}$). Several of these high-emission reservoirs are still in the planning phase. The results further show that the total basin-wide emissions (t CO$_2$e) of the hydropower development are considerable.

Our findings indicate that, although the reservoir emissions per produced energy may be low in the Mekong, hydropower cannot be considered categorically as low-emission energy. The emissions can reach the emission levels from fossil fuel power plants, depending on the characteristics and location of the hydropower project. High emissions were related most strongly to low area-to-electricity ratios, large reservoir surface areas and high air temperature. Therefore, each hydropower project should be carefully analysed for its GHG emissions. It is also obvious that careful removal of vegetation and other easily degradable organic matter from the inundated area of a reservoir is fundamental in minimizing GHG emissions from it.

Our findings should be considered as tentative, given that they are based on global models with high uncertainty. To improve the estimates, more measurements and better models are needed. Besides geophysical, ecological and social impacts, this paper highlights the importance of considering the climate impacts of hydropower development.

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ORCID IDs

Timo Räsänen @ https://orcid.org/0000-0003-0839-3155
Olli Varis https://orcid.org/0000-0001-9231-4549
Laura Scherer https://orcid.org/0000-0002-0194-9942
Matti Kummu https://orcid.org/0000-0001-5096-0163

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