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LETTER

Greenhouse gas emissions of hydropower in the Mekong River Basin

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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 CO_2e MWh^{-1} over a 100 year lifetime with a median of 26 kg CO_2e MWh^{-1}. Hydropower reservoirs facilitating irrigation (22) had generally higher emissions reaching over 22 000 kg CO_2e MWh^{-1}. The emission fluxes for all reservoirs (141) had a range of 26–1813 000 t CO_2e yr^{-1} over a 100 year lifetime with a median of 28 000 t CO_2e yr^{-1}. Altogether, 82% of hydropower reservoirs (119) and 45% of reservoirs also facilitating irrigation (22) have emissions comparable to other renewable energy sources ($<$190 kg CO_2e MWh^{-1}), while the rest have higher emissions equalling even the emission from fossil fuel power plants ($>$380 kg CO_2e 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 (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_20) (Demarty 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 (Demarty 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 CO_2 and CH_4 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 CO_2 MWh^{-1} and 3 kg CH_4 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 CO_2 MWh^{-1} and 2.95 kg CH_4 MWh^{-1}. Both estimates are below the emissions from fossil fuel power plants (380–1300 kg CO_2e 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 CO_2e 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 CO_2 and CH_4 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 CO_2 and CH_4 and their combined CO_2 equivalent (CO_2e) through the reservoir water-air interface. We excluded other emission sources such as degassing and diffusion from the reservoir tail water,

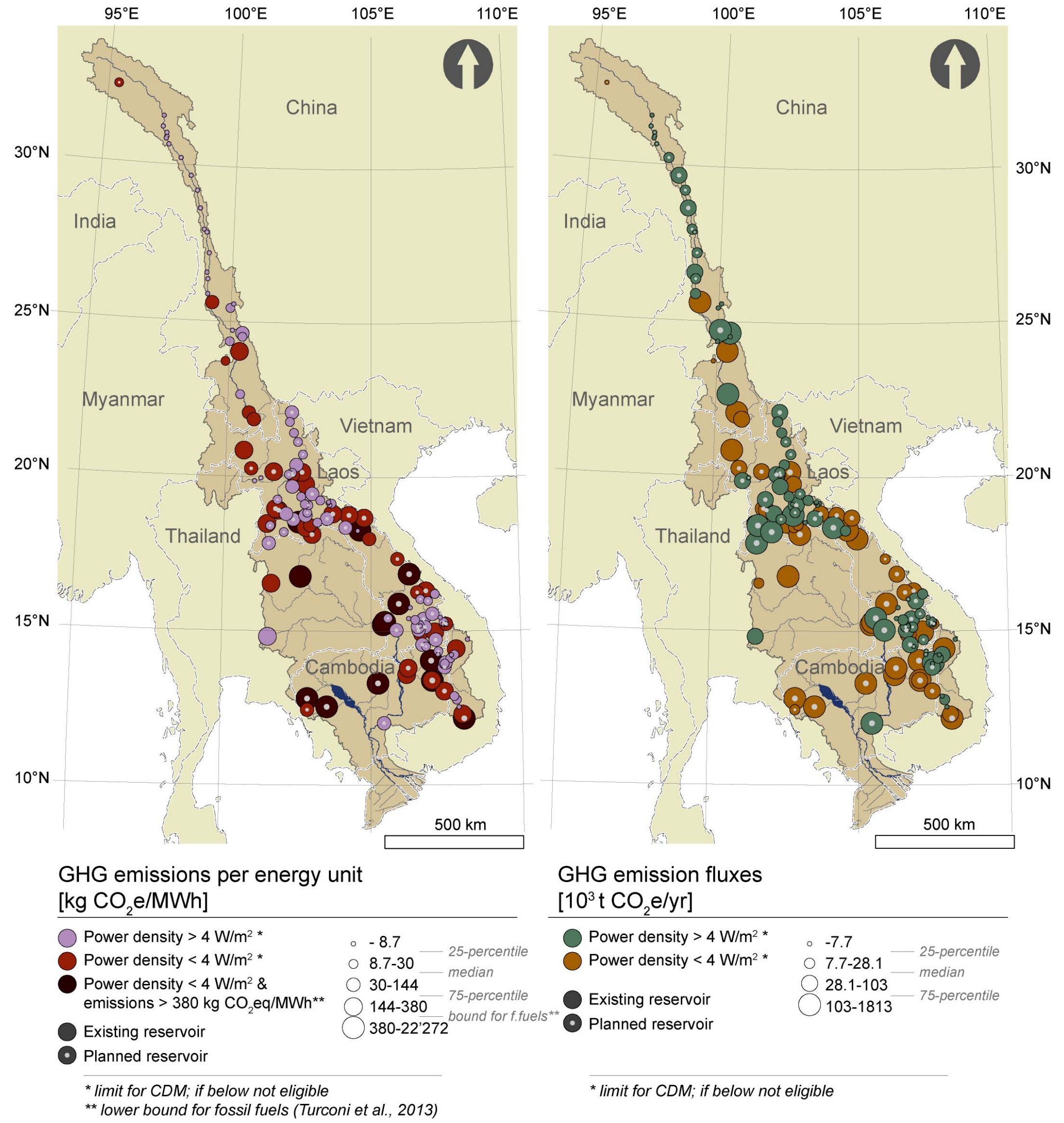

Figure 1. Estimated greenhouse gas emissions and power densities of 141 existing and planned reservoirs in the Mekong River Basin. CDM stands for the Clean Development Mechanism of the Kyoto Protocol (UN 2017) for implementing emission-reduction projects.

as well as dam construction. The results are reported as emissions per energy unit [$CO_2e\,kg\,MWh^{-1}$] and emission fluxes [$t\,CO_2e\,yr^{-1}$] 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 ($GWh\,y^{-1}$), 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

Table 1. Spatial data used in estimation of reservoir greenhouse gas emissions.

Data	Source	Description	Unit
Net primary production (NPP)	Haberl *et al* (2007)	Potential vegetation (NPP0); Coverage/resolution: globe, 5 arc min. (∼10 km at the equator)	$\mathrm{g\,C\,m^2\,yr^{-1}}$
Erosion (ERR)	Scherer and Pfister (2015)	Global soil erosion, based on Universal Soil Loss equation (USLE); Coverage/resolution: globe, 5 arc min. (∼10 km at the equator)	$\mathrm{t\,ha\,yr^{-1}}$
Temperature of warmest month (TMAX)	Hijmans *et al* (2005)	Maximum temperature of the warmest month (BIO5); Coverage/resolution: globe, 30 arc sec. (∼1 km at the equator)	°C
Digital elevation model (DEM) used to estimate the reservoir surface area for 22 reservoirs	Jarvis and Reuter (2008)	Hole-filled Shuttle Radar Topology Mission for the globe Version 4.1; Coverage/resolution: globe, 3 arc sec. (∼90 m at the equator)	m

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, $\mathrm{kg\,MWh^{-1}}$), is based on the following equations

$$\log_{10}(\mathrm{CO_2}) = 0.8 + 0.97 \cdot \log_{10}(\mathrm{ATE}) - 0.006 \cdot \mathrm{AGE} + 0.737 \cdot \log_{10}(\mathrm{NPP})\ \text{(Hertwich 2013)} \tag{1}$$

$$\ln(\mathrm{CH_4}) = -9.81 - 0.75 \cdot \ln(\mathrm{AGE}) + 1.18 \cdot \ln(\mathrm{ATE}) + 4.50 \cdot \ln(\mathrm{TMAX})\ \text{(Scherer and Pfister 2016)} \tag{2}$$

where ATE $[\mathrm{km^2\,GWh\,yr^{-1}}]$ is the reservoir area-to-electricity ratio, NPP $[\mathrm{g\,C\,m^2\,yr^{-1}}]$ 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, $\mathrm{mg\,C\,m^2\,d^{-1}}$) is based on the following equations

$$\mathrm{CO_2} = 494.46 - 4.07 \cdot \mathrm{AGE} + 8.09 \cdot \mathrm{ERR}\ \text{(Scherer and Pfister 2016)} \tag{3}$$

$$\ln(\mathrm{CH_4}) = -12.84 - 0.03 \cdot \mathrm{AGE} + 0.21 \cdot \ln(\mathrm{A}) - 0.01 \cdot \mathrm{ERR} + 4.88 \cdot \ln(\mathrm{TMAX})\ \text{(Scherer and Pfister 2016)} \tag{4}$$

where ERR $[\mathrm{t\,ha\,yr^{-1}}]$ is the annual erosion per hectare, A $[\mathrm{km^2}]$ 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 multpying with a factor of 0.87 and the CH_4 emission increased by multipying with factor of 1.4. to consider the negligence of carbon burial and methane ebullition (bubbling) in the measurements.

In this paper, we present the results as combined CO_2e, and as averages of EpEU and EF models. The emission fluxes were further converted from $\mathrm{mg\,C\,m^2\,d^{-1}}$ to t $\mathrm{CO_2e\,yr^{-1}}$. For transforming CH_4 to CO_2e we used a Global Warming Potential (GWP) of 34 over 100 years. As a comparison, we also calculated power densities ($\mathrm{W\,m^{-2}}$) 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 $\mathrm{W\,m^{-2}}$ 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

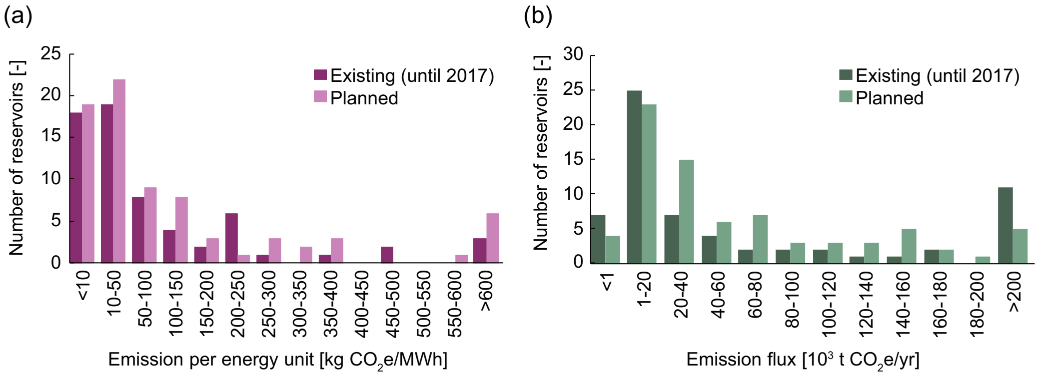

Figure 2. Estimated frequency distribution of (*a*) emissions per energy unit and (*b*) emission flux of 141 existing and future reservoirs in the Mekong Basin. Emissions are given as averages over a100 year lifetime.

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, Wang *et al* 2013, Zhao *et al* 2013, Kumar and Sharma 2016). The emission range of these Asian reservoirs (10–336 kg CO_2e MWh^{-1}) is close and on both sides of global average (187–273 kg CO_2e MWh^{-1}) and median (84 kg CO_2e 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_2e MWh^{-1}, respectively. For 119 hydropower reservoirs, the average and median emissions are 122 and 26 (1–114) kg CO_2e MWh^{-1}, respectively, while for the 22 hydropower reservoirs with irrigation those are 2031 and 85 (8–634) kg CO_2e MWh^{-1}, respectively. The emissions for individual reservoirs vary considerably, ranging from 0.2–22 272 kg CO_2e 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_2e 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_2e yr^{-1} with median of 28 000 (587–109 100) t CO_2e yr^{-1}. The range of the ten highest emission fluxes is 700 000–1 800 000 t CO_2e yr^{-1} (100 yr) (table 2*b*). 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_2e MWh^{-1} and for planned hydropower reservoirs (66 of 119) 31 kg CO_2e 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 S3). 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_2e MWh^{-1}.

Total reservoir emissions (figures 3(*a*)–(*b*)) illustrate well the different phases of hydropower construction in the basin. First reservoirs were

Table 2. Estimates of highest CO_2e emissions per energy unit and largest CO_2e 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.

A. Highest CO_2e emissions per energy unit (119 hydropower reservoirs, reservoirs with irrigation excluded)

Reservoir	Country	Commission year	Annual energy [GWh]	Reservoir area [km^2]	CO_2e emission per energy unit [kg CO_2e MWh^{-1}]
Average/median of 119 reservoirs	—	—	1735/507	69/16	120/26 (1–114)
Xe Bang Nouan	Lao PDR	2021	79	87	1990 (299–3449)
Lower Sre Pok 3 (3A)	Cambodia	TBD	1201	721	1400 (210–2423)
Lower Sesan 3	Cambodia	TBD	1310	727	1380 (209–2394)
Xe Bang Hieng 2	Lao PDR	2022	73	46	1030 (154–1778)
Nam Ngum 1	Lao PDR	1971	1025	369	670 (100–1154)
Duc Xuyen	Vietnam	TBD	181	77	600 (89–1031)
Lower Sesan 2	Cambodia	2019	1954	334	370 (55–632)
Nam Feuang 1	Lao PDR	2022	113	26	360 (54–622)
Lower Sre Pok 4	Cambodia	TBD	221	33	350 (53–606)
Sekong	Cambodia	TBD	557	94	320 (48–557)

B. Largest CO_2e fluxes (all 141 reservoirs)

Reservoir	Country	Commission year	Annual energy [GWh]	Reservoir area [km^2]	CO_2e fluxes [10^3 t CO_2e y^{-1}]
Average/median of 141 reservoirs	—	—	1715/485	77/22	133/28 (<1–109)
Lower Sesan 3	Cambodia	TBD	1310	727	1810 (272–3136)
Lower Srepok 3 (3A)	Cambodia	TBD	1201	721	1680 (252–2911)
Sambor	Cambodia	TBD	11 740	620	1 330 (200–2307)
Stung Sen	Cambodia	TBD	124	434	1150 (173–1992)
Ubol Ratana	Thailand	1966	56	401	1250 (187–2158)
Dachaoshan	China	2003	5500	826	970 (145–1673)
Sirindhorn	Thailand	1971	90	289	760 (113–1307)
Jinghong	China	2009	5570	510	740 (110–1272)
Lower Sesan 2	Cambodia	2019	1954	334	710 (107–1236)
Nam Theun 2	Lao PDR	2010	6000	450	700 (105–1213)

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_2e MWh^{-1}, while for 2015–2020 the median emission decreases to 41 (1–134) kg CO_2e MWh^{-1}. If no more reservoirs are built after 2023, the median emission is estimated to decrease to 26 (1–113) kg CO_2e 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_2e MWh^{-1} over a 100 year lifetime with a median of 26 (1–114) kg CO_2e 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,

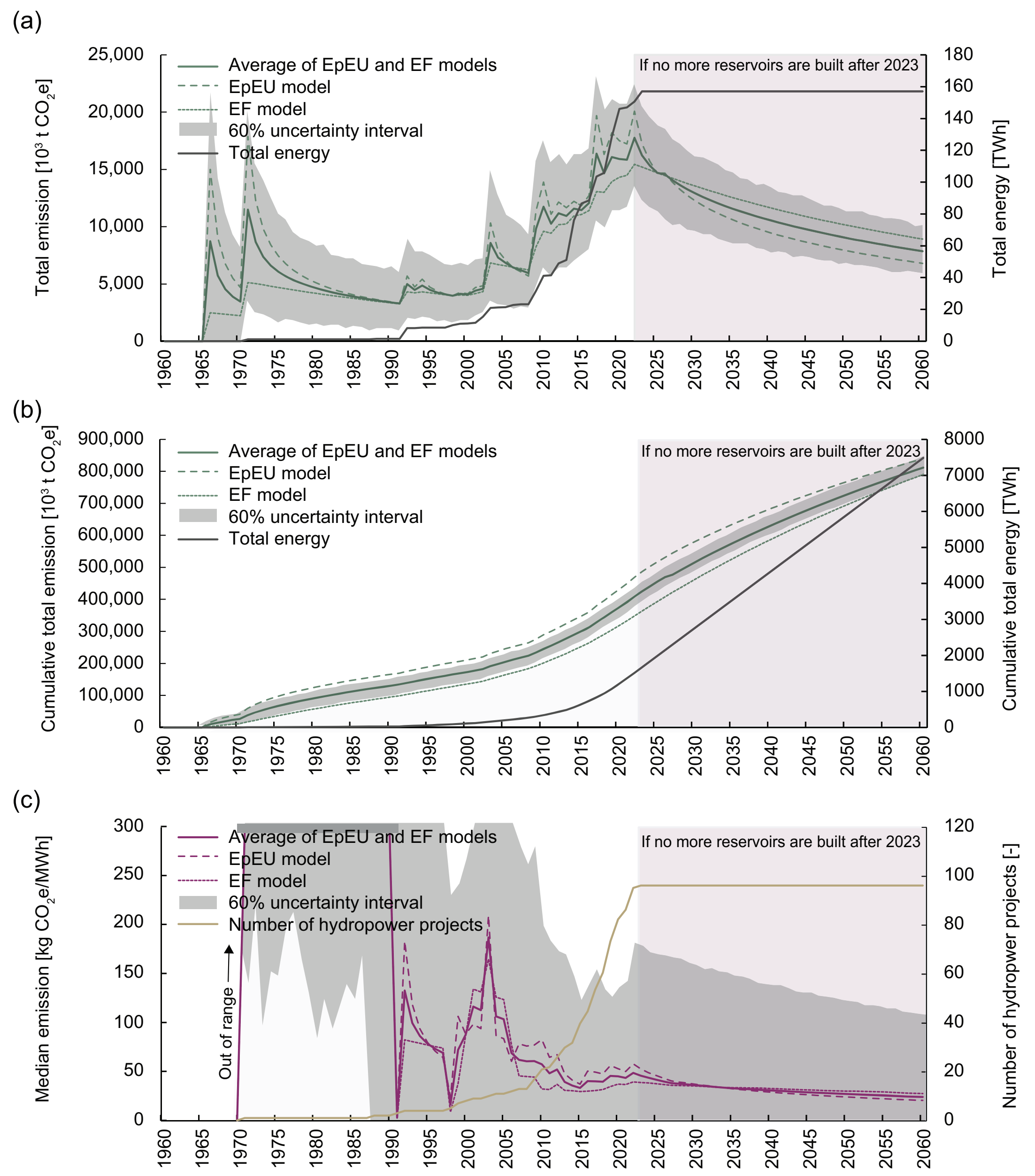

Figure 3. Estimated CO_2e emission of reservoirs in the Mekong River Basin: (*a*) total annual emissions, (*b*) cumulative total emissions and (*c*) median emission per energy unit. The estimates in tiles A and B include 111 reservoirs with known or planned commission years until the year 2023 and excludes 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 had measured emissions of 78 kg CO_2e MWh^{-1} and −30 300 t CO_2e y^{-1} (Chanudet *et al* 2011), respectively, whereas our estimates for the same years are 183 (28–317) kg CO_{2e} MWh^{-1} and 623 800 (93 750–1 079 174) t CO_2e 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_2e 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_2e 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.

Region	Number of reservoirs	Reservoir age/ estimate year	Source	Average [kg CO_2e MWh^{-1}]	Median [kg CO_2e MWh^{-1}]	Range [kg CO_2e MWh^{-1}]
Global[b]	85	2009	Hertwich (2013)	187	—	—
Global[b]	1473	2009	Scherer and Pfister (2016)	273	84	—
Low latitude (33°N-33°S)[a]	22	1–90 yr	Scherer and Pfister (2016), Chanudet *et al* 2011, Deshmuk *et al* 2013, Zhao *et al* 2013, Wang *et al* 2013, Kumar and Sharma 2016	2334	334	10–20 624
Brazil and French Guiana[a]	12	1–36 yr	Demarty and Bastien (2011)	1548	1381	2–4 100
China, Taiwan, India and Lao PDR[a]	5	1–38 yr	Chanudet *et al* 2011, Deshmuk *et al* 2013, Zhao *et al* 2013, Wang *et al* 2013, Kumar and Sharma 2016	90	18	10–336
Mekong[b]	119	Average over 100 year lifetime	This study	122 (1–114)	26 (1–114)	0.2–1994
Mekong[b]	119	Average over 10 year lifetime	This study	251 (2–269)	46 (2–269)	0.2–4354

[a] Measurement-based estimate.

[b] Model estimate.

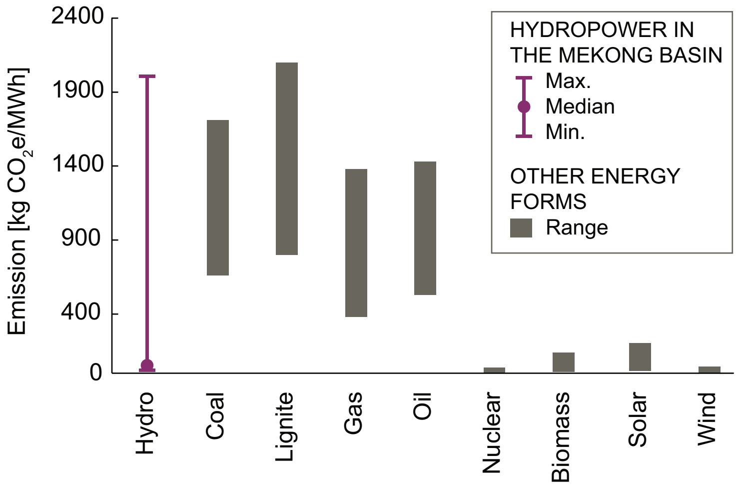

Figure 4. Estimated 100 year lifetime emissions of 119 hydropower reservoirs in the Mekong River Basin compared to life cycle emissions of other energy forms (Turconi *et al* 2013). We added, on top of the GHG emissions reported elsewhere in the paper, construction emissions of 19 kg CO_2e MWh^{-1} (Schlömer *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_2e 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_2e MWh^{-1}, ranging from 19–2013 kg CO_2e 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_2e 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_2e MWh^{-1}; Turconi *et al* (2013)).

Table 4. Fifteen future reservoirs with highest estimated CO_2e 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).

Reservoir	Country	Purpose[a]	Commission year	Annual energy [GWh]	Reservoir area [km^2]	CO_2e emission [kg CO_2e MWh^{-1}]	Power density [W m^{-2}]
Average/median of 141 res.	—	—	—	1715/485	77/22	420/30 (1–161)	46.8/8.2
Stung Sen	Cambodia	PCA	TBD	124	434	9270 (1391–16 039)	0.1
Xe Bang Nouan	Lao PDR	P	2021	79	87	1990 (299–3449)	0.4
Battambang 1	Cambodia	PCAF	TBD	120	92	1510 (227–2616)	0.3
Lower Sre Pok 3 (3A)	Cambodia	PCF	TBD	1201	721	1400 (227–2616)	0.4
Lower Sesan 3	Cambodia	PCF	TBD	1310	727	1380 (210–2423)	0.4
Xe Bang Hieng 2	Lao PDR	P	2022	73	46	1030 (154–1778)	1.9
Duc Xuyen	Vietnam	PAF	TBD	181	77	600 (89–1031)	0.7
Stung Pursat 1	Cambodia	PCAF	TBD	335	81	400 (59–685)	0.5
Lower Sesan 2[b]	Cambodia	PCF	2019	1954	334	370 (55–632)	1.2
Nam Feuang 1	Lao PDR	P	2022	113	26	360 (54–622)	1.1
Lower Sre Pok 4	Cambodia	PC	TBD	221	33	350 (53–606)	1.5
Sekong	Cambodia	P	TBD	557	94	320 (48–557)	2
Xe Pon 3	Lao PDR	P	2020	164	30	310 (46–527)	1.6
Nam Ngum Lower dam	Lao PDR	PAR	2022	526	80	290 (43–492)	1.4
Nam Theun 4	Lao PDR	P	2022	130	29	280 (42–482)	2.8

[a] *P* = power generation, *C* = flood control, *A* = Agriculture/irrigation, *F* = fisheries, *R* = recreation.

[b] Reservoir filling started during the writing of the paper.

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_2e MWh^{-1}, while the median for all analysed reservoirs is 30 kg CO_2e MWh^{-1} (table 4). The power densities of these 15 reservoirs are also below the CDM threshold of 4 W m^{-2} (UN 2017) (table 4). Our analyses indicate that the high emissions of these reservoirs are partly explained by high surface area-to electricity ratios, their location in a warm climate zone and high erosion rates. The GHG emissions and power densities of all analysed reservoirs are given in supplement 2.

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, Serça *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 accuracy of the emission estimates of existing and future reservoirs.

Finally, we did not include the emissions of other GHGs such as N_2O in our study, being also a shortcoming. Inclusion of other GHGs should be in the agenda of further studies on this topic. We also recognize that hydropower reservoirs are not the only reservoirs that emit GHGs. For example, Wang *et al* (2017) report from China that largest GHG fluxes were found in urban reservoirs.

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 $\mathrm{kg\,CO_2e\,MWh^{-1}}$ over a 100 year lifetime with a median of 26 (1–114) $\mathrm{kg\,CO_2e\,MWh^{-1}}$. Altogether, 82% of hydropower reservoirs (119) and 45% of reservoirs facilitating also irrigation (22) have emissions comparable to other renewable energy sources ($<190\,\mathrm{kg\,CO_2e\,MWh^{-1}}$), while the rest have higher emissions equalling even the emissions from fossil fuel power plants ($>380\,\mathrm{kg\,CO_2e\,MWh^{-1}}$). Several of these high -emission reservoirs are still in the planning phase. The results further show that the total basin-wide emissions (t CO_2e) 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 fuels 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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