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Climate impact of tropical hydropower: a perspective on G-res model calculations

Frank van der Valk, *[a] Christopher Bonzi[b] and Pyi Soe Aung[c]

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Despite environmental and social issues, hydropower has been promoted as a climate-friendly form of electricity generation. This perspectives paper shows that such a claim needs to be considered with great care, especially in tropical, low-latitude areas. First, because complete climate impacts are rarely considered. For instance, the frequently cited IPCC (2014) emission intensities omit biogenic CO_2 emissions from reservoirs. The openly available G-res tool provides an opportunity to partly fill this gap. Second, individual cases show huge variability in climate impacts. In this paper, we discuss the results of G-res calculations for three projects in Myanmar, which confirm this large variability. Several international guidelines suggest to use G-res to estimate a hydropower project's climate impact. However, an analysis of the methodology shows that the G-res calculations can substantially underestimate the GHG emissions of hydropower projects due to its limitations and assumptions. Furthermore, the Earth's albedo change by the reservoirs needs to be considered. We show that the impact thereof is of comparable magnitude and variability. As a result, in many cases in the tropics hydropower will have considerably larger climate impacts than solar and wind and can even exceed those of fossil fuel installations.

Environmental significance

Net-zero greenhouse gas (GHG) emission is an important policy target to reduce human impact on climate. Globally, approximately 40% of GHG emissions are due to electricity generation; hence, reducing these forms a significant part of the needed change. To this end, low-emitting technologies such as solar, wind and hydropower are being implemented. In this context, it is important to know the emission intensity of these technologies accurately. In this article, we demonstrate that the emission intensity of hydropower can be relatively high compared to solar and wind energy.

Introduction

Despite potentially large environmental and social impacts, hydropower is often presented as an attractive form of electricity production because of its low climate impact.[1,2] However, it is also known that reservoirs can produce greenhouse gas (GHG) emissions and that, primarily due to variability in reservoir emissions, hydropower dams have a broad range of GHG emissions per unit of energy produced (0.2–20 000 g CO_2eq. per kWh), *i.e.* ranging from amongst the lowest of generally applied technologies to larger than those of coal combustion plants.[1,3–6] Fig. 1 illustrates the extreme variation in emission intensities observed for various hydropower dams. This is also reflected in Fig. 2, where the IPCC's minimum, median and maximum GHG emission intensities[3] for various forms of electricity are shown. However, the IPCC figure for hydropower does not include biogenic CO_2 from the reservoirs. Even with the limited set of emissions included, the range stretches well beyond that of coal-burning plants (in particular because of CH_4 emissions). Based on their life cycle assessment, Pehl *et al.* more recently found that median life-cycle emissions from hydropower are substantial (~100 g CO_2eq. per kWh), highly uncertain, and much larger than those of wind and solar electricity generation.[5]

In addition to GHG emissions, the change in the Earth's albedo caused by (hydropower) reservoirs can impact climate.[7] Both GHG emissions and albedo effects tend to be stronger in tropical zones.[4,7]

To fully assess the climate impacts of a hydropower project, the diverse impacts over its entire lifecycle need to be taken into account.[1,5,8] This includes impacts from construction, during operation and decommissioning, considering the relevant site-specific environments, and assessing how the mode of operation, *e.g.* which changes in water levels are applied and how sedimentation is handled, will affect the project's climate impact. Apart from other environmental and social impacts, the climate impact per unit of energy produced is a key aspect of an environmental assessment of hydropower use. Given the huge differences in the climate impact of individual cases, assessing

[a]Foinix Advice, NL-6953CK 10C Dieren, the Netherlands. E-mail: foinix1111@gmail.com
[b]WWF Switzerland, CH-8010 Zurich, Switzerland
[c]WWF Myanmar, Yangon 11201, Myanmar

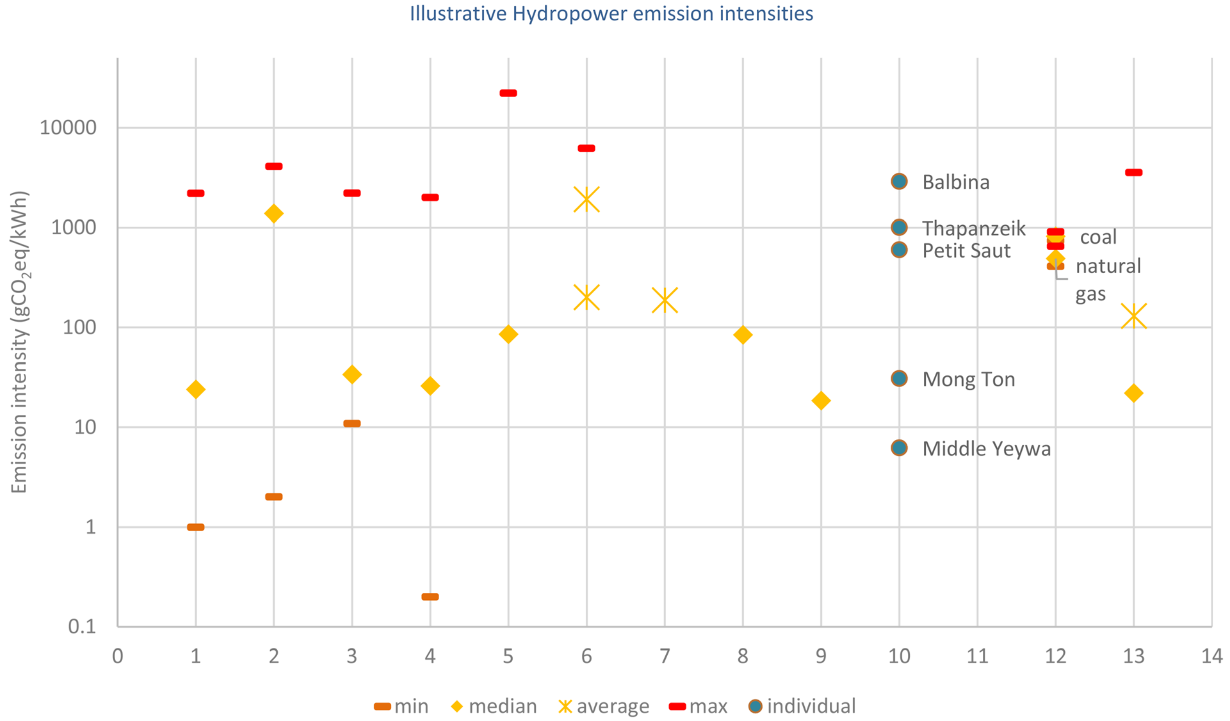

Fig. 1 Illustrative hydropower emission intensities, and coal and natural gas for comparison. Note the logarithmic scale. Figures are not fully comparable due to differences in methodologies/pathways in- or excluded. *E.g.* the IPCC values for hydropower (dataset 1) do not include biogenic CO_2 emissions from reservoirs 1: global data set IPCC 2014,[3] 2: global data set Demarty and Bastien (2011),[58] 3: global data set Pehl *et al.* 2017 (ref. 5) 4: Mekong River basin Räsänen *et al.*[59] 5: Mekong River basin Räsänen *et al.*, incl. multi-purpose dams,[59] 6: global data set Song *et al.* 2018 (ref. 30). The upper two values are for tropical areas, the lower one for temperate areas. 7: global data set Hertwich 2013 (ref. 8) 8: global data set Scherer & Pfister 2016 (ref. 60) 9: global data set IHA 2018 (ref. 61) 10: individual dams: Balbina (Brazil),[21] Petit Saut (French Guiana),[22] Thapanzeik, Mong Ton, Middle Yeywa (Myanmar) (this article) 12: IPCC values for Coal (Pulverised Coal) and Natural Gas (Combined Cycle) for comparison[3] 13: converted albedo change impacts (this article) from Wohlfahrt *et al.*[7].

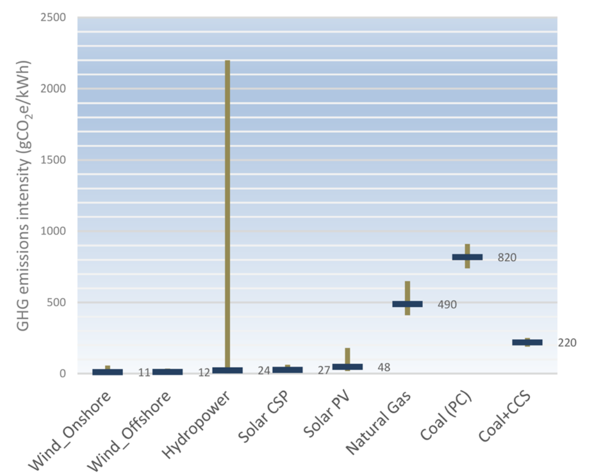

Fig. 2 GHG emissions intensity for various forms of electricity generation. Horizontal lines represent median values, vertical bars extend from minimum to maximum values. CSP: concentrated solar power, PV: photovoltaic, PC: pulverized coal, CCS: carbon capture and storage. Data from IPCC 2014 (ref. 3).

this is highly relevant for policy decisions on hydropower.[9] This article considers both key mechanisms of this impact: GHG emissions and the impact on the Earth's albedo.

Measuring and modelling the GHG emissions of hydropower is difficult because the processes determining the emissions are manifold and complex. Based on the approach of a lifecycle assessment (LCA), UNESCO and the IHA have developed the G-res tool to estimate the GHG emissions of a hydropower project.[10,11] Its applicability is greatly facilitated by the use of input data that do not require onsite measurements to be undertaken for either the pre- or post-impoundment conditions.[11] Given that this is the only commonly available and promoted (*e.g.* by the World Bank[9,12] and OpenHydro[13]) tool to calculate the GHG emissions and emission intensities of a hydropower installation it is important to evaluate its methodology. We present G-res calculations for three – very different – tropical hydropower reservoirs. We then analyse the modelling approach and its limitations for assessing the GHG emissions of hydropower in the tropics. Finally, we put these emissions in the broader perspective of the overall climate impact, taking into account the relevance of albedo changes.

Results

G-res calculations for three reservoirs in Myanmar

G-res model calculations were performed for the GHG emissions of three reservoirs in Myanmar, one existing and two in different stages of planning. These reservoirs were chosen to

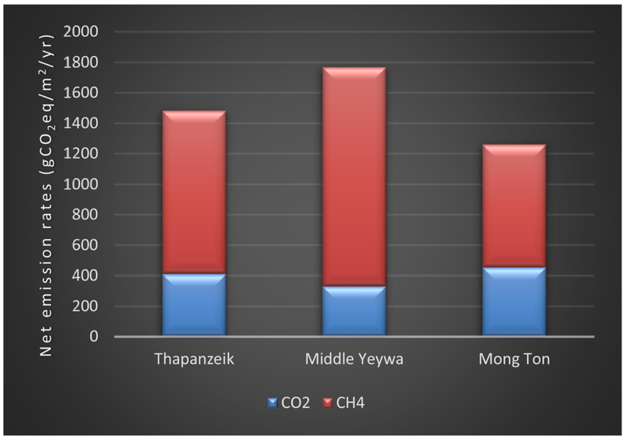

Fig. 3 G-res calculated net emission rates for 3 (potential) dams in Myanmar.

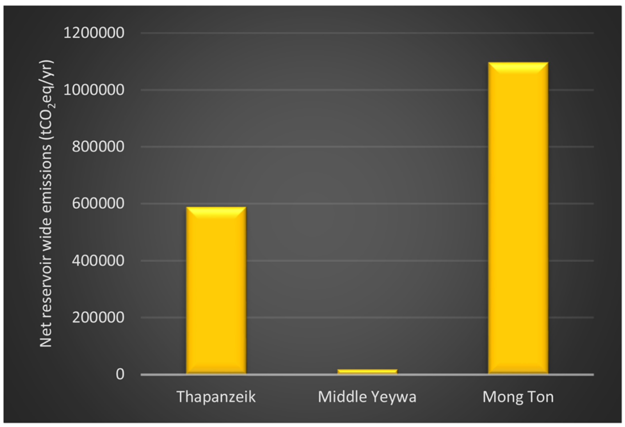

Fig. 4 G-res calculated net reservoir emissions for 3 (potential) dams in Myanmar.

represent very different types of reservoirs, not considering the likelihood of the implementation of the planned dams or their other potential (environmental or social) impacts. The reservoirs are;

• Thapanzeik, an existing multipurpose dam in the Mu River, a tributary of the Ayeyarwady (Irrawaddy), as a (large) example of the circa 15 existing multi-purpose dams in Myanmar;

• Middle Yeywa, a planned hydropower dam within a cascade in the Myitnge River, a tributary of the Ayeyarwady;

• Mong Ton, a large planned dam on the main stem of the Thanlwin (Salween).

Net (*i.e.* post-impoundment minus pre-impoundment) emissionrates per m^2 per year are shown in Fig. 3. The figure shows that these are comparable for the three dams, and that, according to the G-res tool, for all three dams the largest part of the calculated emissions stems from methane (CH_4).

The averaged total net annual emissions for each reservoir are shown in Fig. 4. These results reflect the large differences in the size of the reservoirs.

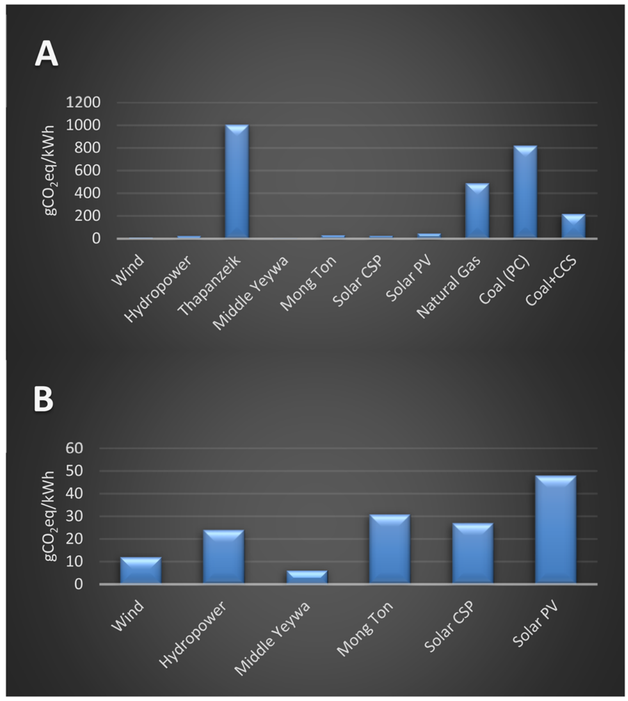

Fig. 5 G-res calculated GHG emission intensities for 3 (potential) dams in Myanmar, compared to other forms of electricity generation (median values from IPCC, 2014 (ref. 3)): A: full spectrum, B: low emission cases from A only note: as mentioned in the text, only Middle Yeywa figures include emissions related to the construction of the dam.

In Fig. 5 the 100 years average GHG emission intensities of the three systems are compared with other forms of electricity generation (median values from IPCC, 2014 (ref. 3)). Note that Thapanzeik is a multipurpose dam with irrigation as its main function. For any multipurpose dam, when calculating the emission intensity of the electricity production, the issue arises as to which part of the emissions should be attributed to the electricity production.[11] As this attribution is always somewhat arbitrary and our calculations are mainly illustrative to demonstrate model outputs, we just attributed 20% of the emissions to electricity production, in line with the G-res methodology on the operating regime.[11] The calculated values for Middle Yeywa and Mong Ton, 6.2 and 30.9 g CO_2eq. per kWh, respectively, are similar to those of other renewables, but those of Thapanzeik are two orders of magnitude higher, illustrating the extreme variability described earlier (*cf.* Fig. 5).† This relates to the very low power intensity of Thapanzeik, 0.1 W m^{-2}, and the extraordinarily high (planned) value for Middle Yeywa, 66.8 W m^{-2}.

Discussion

The example of Thapanzeik shows that in some situations the adverse climate impacts of hydropower generation may be

† Even if a much smaller % of emissions (*e.g.* 5%) is allocated to electricity production, emission intensity of Thapanzeik would still be very high.

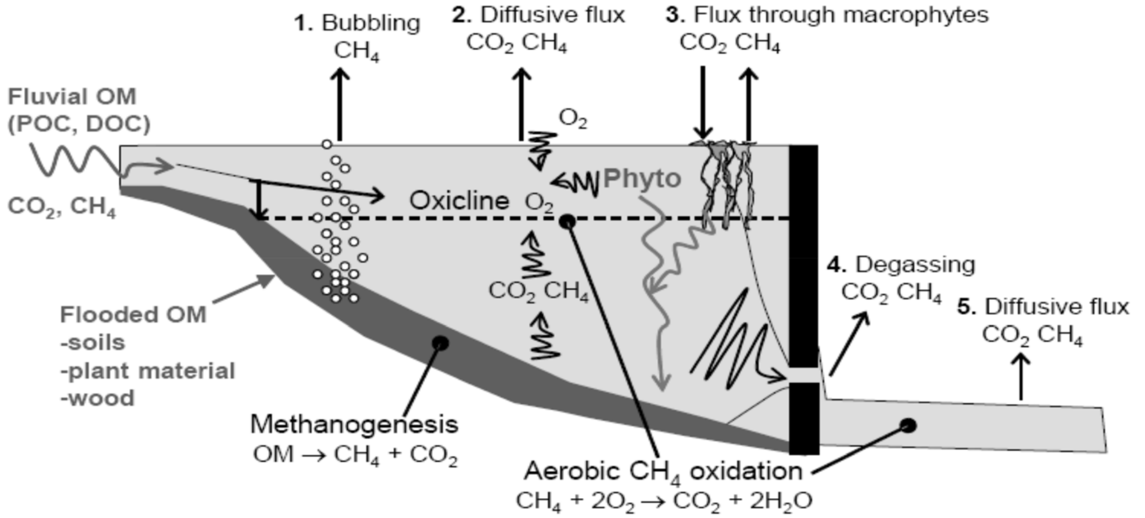

Fig. 6 Carbon dioxide and methane pathways in a freshwater reservoir. Source: UNESCO/IHA (2009)[18]

obvious. However, for better-performing installations (concerning climate impacts), it is important to have an accurate assessment of their climate impact, *e.g.* to enable a meaningful comparison with other forms of low-carbon electricity generation such as solar and wind. As G-res is promoted as tool to assess the "climate profile"[14] (and even "environmental impact"[15]) of hydropower (reservoirs), we review the limitations of using the G-res model for assessing the climate impacts of hydropower projects. As mentioned above, these impacts mainly consist of changes in the emissions of GHG gases and of the earth's albedo.

Changes in GHG emissions

Through the use of G-res, it has become relatively easy to calculate an estimate of the change in GHG emissions caused by a reservoir hydropower installation. However, such calculation comes with several limitations.

Limitations due to the exclusion of aspects in the tool

GHG emissions from hydropower involve emissions of CO_2, CH_4, and N_2O from the post-construction (eco)system, particularly the reservoir, its drawdown zones and the dam outlet, through various pathways. These emissions mainly stem from the aerobic and anaerobic decay of organic material and the bacterial formation of nitrous oxide, N_2O. In new reservoirs, OM mainly comes from submerged biomass and soil organic carbon with different absolute and relative contents of OM. Later, OM may also come from primary production or other biological processes within the reservoir.[1] Reservoir GHG emissions can also be positively correlated with temperature.[16,17] Consequently, the negative correlation between latitude and hydroelectric GHG emissions reported in previous work could reflect higher average water temperatures at low latitudes. In addition, lower latitude regions typically experience higher rates of terrestrial net primary production (NPP), a factor that has been positively correlated with GHG emissions from hydroelectric reservoirs.[8] High rates of NPP may promote enhanced leaching of dissolved organic matter (DOM), fuelling additional decomposition of terrestrial organic matter within tropical reservoirs.[4]

Fig. 6 depicts common pathways for carbon-related emissions from a reservoir.[18] The importance of the various routes in terms of climate impacts varies widely.[4,19] CH_4 can have a particularly strong impact as its Global Warming Potential is 86 and 34 times that of CO_2 on a 20 and 100 years' timescale, respectively.[20] In tropical regions, high temperatures coupled with an important demand for oxygen (due to the degradation of substantial amounts of organic matter, OM) favour the production of CO_2, and the establishment of anoxic conditions and thus the production of CH_4.[1,8] Hence, in tropical reservoirs, very high emission intensities have been observed such as for the Balbina dam (Brazil)[21] and Petit Saut (French Guiana):[22] 2900 and 600 g CO_2eq. per kWh, respectively (*cf.* Fig. 1).

The impact of hydropower development can be calculated as the difference between the post- and pre-construction conditions. The G-res model includes four emission pathways for GHGs from reservoirs: diffusive CO_2 and CH_4 emissions, bubbling CH_4 emissions from the reservoir surface, and CH_4 emissions due to degassing downstream of the reservoir. However, various other pathways are not included, as described below.

Change in land use before construction

Considerable infrastructural works occur before the actual construction of a hydropower installation. This includes the construction of roads and clearing of the impoundment area, often forests. These activities cause GHG emissions from both the production of the materials used, their transport, and the transport of cleared material (*e.g.* timber). Similar impacts are caused by constructing transmission lines. However, quantification of this impact is not generally available. Therefore, although the changes in net emissions due to forest clearing for roads and transmission lines (often long for hydropower) are not included in G-res, the significance cannot be assessed.

Drawdown effects

In recent years, research has been published drawing attention to increased emissions of both CO_2 (ref. 23) and CH_4 (ref. 24) when a reservoir's water is drawn down. This is caused by the larger emissions from the aquatic sediments which fall dry compared to the water body (mainly CO_2)[23] and strongly increased methane ebullition in shallower waters.[24] Neither effect is included in G-res. For CO_2, it was estimated that therefore global emissions may be approximately 50% higher than previously estimated (and that drawdown areas are on average larger in the tropics).[23] For CH_4, it was observed that the magnitude of ebullition events associated with drawdowns can constitute a large fraction (more than 90%) of the total annual CH_4 flux from reservoirs.[24] Because of the strong effect observed across all six reservoirs in that study and the ubiquity of reservoir drawdown events, the authors infer that CH_4 emissions from reservoirs can be substantially underestimated in studies that omit drawdown-associated CH_4 flux estimates. As Prairie *et al.*[10] recognize, G-res neither specifically includes drawdown areas,‡ nor does its database of observed emissions include these emissions. Based on the observations of Keller *et al.*[23] and Harrison *et al.*,[24] its calculated emissions may be significantly underestimated, by a factor of 2 for CO_2 and 10 for CH_4.

Nitrous oxide, N_2O

Because nitrous oxide, N_2O, is 264 or 298 times as powerful a GHG compared to CO_2 for a 20 and 100 year time scale, respectively,[20] even small emissions may form a significant GHG contribution. As N_2O emissions are larger in stratified reservoirs,[25] they will be more important in tropical areas, where stratification occurs more commonly. In four reservoirs in tropical forest areas, N_2O formed 29–31% of the total GHG emissions from the reservoir surface considering CO_2, CH_4 and N_2O.[26] N_2O emissions are larger in eutrophic waters with increased nitrogen loads[4] and may also occur in drawdown zones.[1] Deemer *et al.*[4] estimated that N_2O contributes 4% of the global GHG emissions from hydropower reservoir surfaces over a 100 year time span. However, their data also show that N_2O emissions are highly variable and that the average emission in low latitude reservoirs (<40°, $n = 16$) is twenty times higher than that at higher latitudes (>40°, $n = 42$). More recent studies[27,28] have shown that degassing at the dam outlet and downstream emissions may be similar or even larger (up to five times[28]) than those at the reservoir surface, thereby significantly increasing total emissions. These significant N_2O emissions are not included in the G-res tool.[11]

Removal of sediments

The accumulation of sediments within a reservoir leads to a reduced reservoir volume over time. Therefore, reservoirs must be dredged, flushed, and/or eventually abandoned. These activities can lead to significant emissions through the decomposition of organic matter from released sediments[8,29] that Pacca estimates to be 2.3–8.3 kg CO_2eq. per tonne sediment.[29] In addition, a reduction in the reservoir volume can lead to reduced electricity production and hence increased emission intensity.

Emissions from decommissioning

These emissions are generally neglected in hydropower LCAs, including in G-res. However, LCA studies that include this pathway have indicated that the associated GHG emissions could be large, up to ten times those during the lifetime, in particular, because of the decomposition of organic matter from released sediments after decommissioning.[1,29,30]

Table 1 summarizes which emission effects are included in the G-res model calculation and which are not.

Uncertainties in the calculations

Like most modelling approaches G-res calculations come with various types of uncertainties. Several of these are addressed in the G-res documentation.[11] Sources of uncertainty include the complex mechanisms of GHG emissions resulting in large variations, limited data availability, and the use of many proxy data. Another uncertainty comes from the question of how representative the underlying database of reservoirs/dams and their emissions is given the large variety of methods (in- and excluding different pathways) comprised. This is illustrated by the quite poor correlation factors in the modelled GHG emissions (*e.g.* $R^2 = 0.36$ for CO_2 emissions).[10] As a result "the G-res model predictions carry large numerical uncertainty",[10] which appears to be only partly reflected in the stated 95% confidence intervals of approximately 15–20%.

As the developers recognize, reservoirs in cascades (such as Middle Yeywa) cause various issues for input variables, particularly for attribution, and concerning the applicability/validity of the model calculations, thus increasing the uncertainty of the results.[10]

Setup and assumptions of the tool

A key determining factor of the emission intensity of energy production in the G-res tool is the arbitrary allocation of emissions to a 100 year period as default. As the IPCC notes, "the assumed operating lifetime of a dam can significantly influence the estimate of lifecycle GHG emissions as it amortizes the construction- and dismantling-related emissions over a shorter or longer period".[1] IEA[31] and IPCC[1] have used 80 years as the lifetime for hydropower projects. Normally the life of hydroelectric power plants is 40 to 80 years.[32] Although turbines can be replaced, lifetime is often limited because of sedimentation behind the dam impoundment and aging construction materials leading to increased failure risk, with prohibitive repair costs.[33] Using 80 years would increase the emission intensity by approximately 25% compared with the G-res calculation. In a tropical country like Brazil, dams are planned for a 30 year lifespan (which could be extended with technical retrofits and newer turbines).[34]

‡ The emissions from drawdown areas are not explicitly included in G-res, although they are assumed implicitly to be of the same magnitude as the surface flux because G-res uses the maximum surface of the reservoir in the footprint calculations.[10]

Table 1 Summary of topics covered or not by the G-res tool

Topic	Included in G-res v. 3.0?
GHG emission changes:	
•Carbon	Partly – no provision for drawdown areas
•Nitrous oxide N_2O	No
Land use change pre-construction and outside reservoir area (roads, transmission lines)	No
GHG emissions from construction	Optional
Sediment removal (during operational phase)	No
Decommissioning	No

As most GHG emissions occur early in the lifecycle (*e.g.* because of construction and decay of organic material), the G-res figures largely (∼2–3×) underestimate the emissions during the first 20 or 30 years of operation.§ Further, the globally agreed-upon target to reach net zero emissions by 2050, and the realistic assumption that by then, low-carbon solutions have reached full market penetration, emphasises the need for a tool that focuses on emissions for a 30 year timeframe.

Unrealistic or incomplete inputs

An important input to determine the GHG emission intensity of electricity production is the annual electricity production. Often, the values presented are unrealistically high, certainly for a 100 year period, during which production is likely to decrease, in particular, because of the reduction of the usable reservoir volume due to sedimentation.[29,35–38] This effect could become even stronger in the future as climate change makes water supply more erratic and droughts may further decrease production.[38–40]

The manufacture, transportation and installation of reservoir infrastructure (dam, powerhouse, *etc.*) can lead to significant GHG emissions. In their life cycle assessment, Pehl *et al.* estimated these to be 30% of the total lifetime emissions for hydropower.[5] In the case of Middle Yeywa, the calculations with G-res show that, even taking emissions over a 100 year lifetime, construction-related emissions still account for more than 10% of the total emissions (Table 2).

In the G-res tool, it is optional to include emissions related to the materials use (incl. transport) during dam construction. If this option is not used, a significant part of the emissions can be missed.

G-res overall

In its suggested usage of the G-res tool, the World Bank includes a step to make a thorough qualitative judgement about the reliability of the reservoir emissions estimated with the G-res tool. It requires that any presentation of the G-res tool estimate should be accompanied by transparently acknowledging the uncertainty associated with the results.[9] This article may help prepare such a judgement.

As for any model calculation, the results from G-res come with uncertainties such as those associated with limited data, limited statistical correlations, and limited knowledge of underlying mechanisms, *etc.* However, in the case of G-res, the limitations described point to a substantial underestimation of the climate impact of hydropower installations, particularly (but probably not only) in tropical situations. This stems from the fact that several important emission mechanisms are omitted and an arbitrary, unusually long lifetime is assumed, particularly if constant power production is assumed.¶

By presenting averaged emissions over 100 years, the tool is less relevant for policy decisions because it does not present the much larger climate impact hydropower installations have in the short and medium term (0–20 years) when impact reductions are urgent. Presenting the calculated emission development over time, and figures for the medium (20 or 30 years) term would enhance the transparency and relevance of the tool.‖

Albedo

While the G-res tool focuses on GHG emissions, the climate impact of hydropower is not limited to this mechanism. The establishment of hydropower reservoirs typically involves a land-use change, where former terrestrial ecosystems are inundated or damming enlarges an existing water body at the expense of terrestrial surface cover. The consequence of this land-use change can be a decrease in surface albedo, as water bodies reflect less sunlight than most terrestrial ecosystems.[7] Hence, depending on the albedo of the pre-impoundment landscape, a lower albedo of a hydropower reservoir contributes to global warming.

Although often neglected, some authors have documented the impact of hydropower reservoirs through changes in surface albedo.[7,41–43] However, it is difficult to compare the impact of the two different mechanisms.[7,44–46] Wohlfahrt *et al.*[7] elegantly compared the impact of albedo change with GHG emissions by calculating break-even times (BETs) for fossil fuel displacement: how long it would take before the increased global warming due to the albedo effect of a reservoir would be compensated by avoided fossil fuel CO_2 emissions (because it is replaced by the reservoir's hydropower production).[7] To facilitate comparison with GHG impacts, we represent their data in a different form in

§ *E.g.* if 75% of the total 100 year emissions occur in the first 30 years, the average yearly emissions in these 30 years would be 2.5 times the average yearly emissions that the G-res tool calculates. Conversely, they would on average be 36% of the G-res value during the last 70 years.

¶ An indication of the magnitude of the underestimation is as follows. If construction is omitted, up to 30% of emissions may be omitted;[5] the CH_4 emissions due to drawdown maybe 10 times those of the rest of the reservoir;[24] N_2O emissions may add up to 30%;[26] decommissioning emissions may be similar to the total 100 year reservoir emissions (hence leading to a factor 2 underestimation);[29] and the magnitude of the impact of pre-construction land-use change and sediment removal/flushing is unknown.

‖ The recent update of G-res (v. 3.2) now provides a graphical representation of the evolution of emissions over time and integration over different timescales, which signifies a major improvement.

Table 2 Key inputs and outputs of G-res calculations

	Thapanzeik	Middle Yeywa	Mong ton
Inputs			
Reservoir area (km^2)	397.1	11	870
Installed capacity (MW)	30	735	7000
Power density ($W\ m^{-2}$)	0.1	66.8	8.0
Littoral area (%)	20.85	5.97	5.21
Water residence time (days)	170	6	156
Discharge from intake ($m^3\ s^{-1}$)	188	688	3361
Outputs			
Emissions from construction (t CO_2eq.)	NA	226 567	NA
Emissions from reservoir (t CO_2eq. per year)	588 282	19 458	1 096 246
Emission rate per area (g CO_2eq. per m^2 per year)	1481	1769	1260
Total lifetime emission ($t$$CO_2$eq.)	58 828 200[a]	2 172 403	109 624 598[a]
Allocated GHG emissions intensity (g CO_2eq. per kWh)	1005.6	6.2	30.9

[a] Not including construction-related emissions.

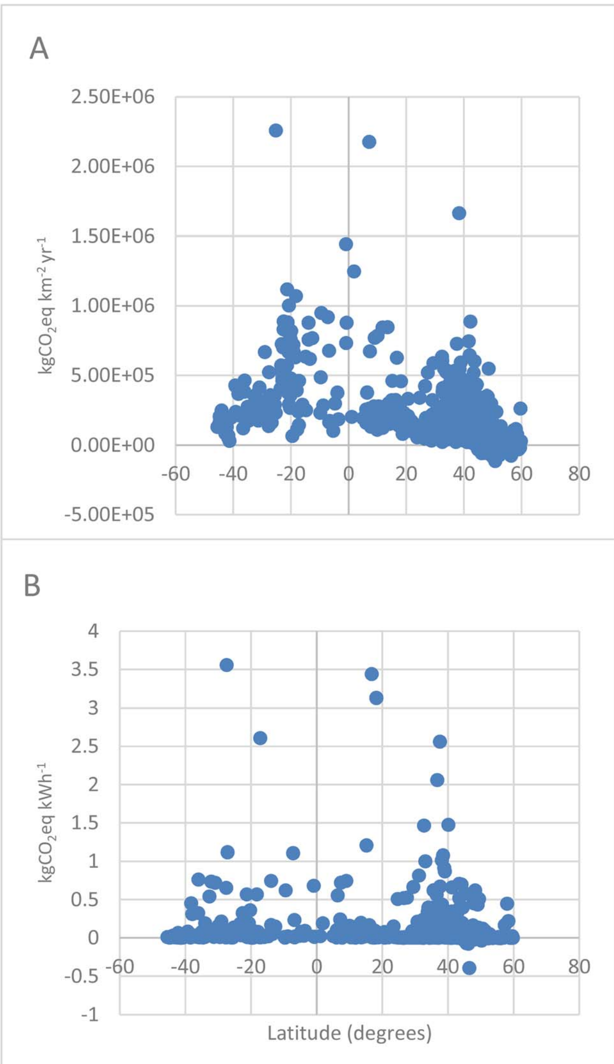

Fig. 7 Calculated (see text) CO_2 equivalents for albedo effect of reservoirs. (A): per area-year, (B): emission intensity per kWh electricity produced.

Fig. 7. As those authors noted, climate impacts tend to be stronger at lower latitudes because of solar irradiation. However, also for albedo impacts the variability among individual cases is huge. Overall, the calculated GHG emission equivalents vary from −400 to 3560 g CO_2eq. per kWh (average 130, median 22, including negative values) in their data set (n = 615). Note that negative values occur because reservoirs can also induce a (small) increase in surface albedo, particularly in boreal areas. The values show that the albedo impact of hydropower generation is of similar magnitude and variability as the GHG emissions and can also exceed that of fossil fuel combustion (7.5% of the cases > 400 g CO_2eq. per kWh (*cf.* Fig. 1).

Methodology

Calculations for the three reservoirs in Myanmar were performed using G-res version 3.11. Table 2 presents an overview of the inputs for the G-res tool and the outputs obtained for the three dams and reservoirs. Basic physical and geographical data on the three reservoirs and dams were used as inputs following the G-res v3.0 User Guide[11] using open access information, including from the Google Earth Engine platform.[47] Only for Middle Yeywa data were available and used for construction parameters, from the Environmental and Social Impact Report.[48] Calculated emissions are presented as CO_2 equivalents (CO_2eq.), using the IPCC 100 year global warming factor of 34 for methane (CH_4).[3,11]

For the impacts of albedo change, we used the dataset of Wohlfahrt *et al.*[7,49] who compared albedo change to GHG emissions by calculating the break-even time (BET) for a lower albedo to compensate for the fossil fuel displacement from hydropower production. In other words, how long it would take before the increased global warming due to the albedo effect of a reservoir would be compensated by avoided fossil fuel CO_2 emissions (because it is replaced by the reservoir's hydropower production). To further facilitate comparison with the impacts of GHG emissions, we calculated, based on their data, for the period until BET the equivalent GHG emissions of the reservoirs per km^2 per year and emission intensity (g CO_2eq. per kWh) using the following simple formulas:

$$\text{BET-CO}_2\text{eq.} = \text{EP} \times \text{CI} \times \text{BET}\ [\text{g CO}_2\text{eq.}]$$

$$\text{GHG per km per year} = \text{BET-CO}_2\text{eq.}/(\text{RA} \times 100)\ [\text{g CO}_2\text{eq. km per year}]$$

$$\text{GHG per kW per h} = \text{BET-CO}_2\text{eq.}/(100 \times \text{EP})$$

where: BET-CO_2eq. = total amount of CO_2eqs displaced until BET EP = electricity production/year CI = carbon intensity of the EP RA = reservoir area.

Following the approach of Wohlfahrt *et al.*, these formulas imply that the impact of the albedo change is taken as equivalent to the total avoided GHG emissions from fossil fuel accumulated until the BET, when the hydropower has fully compensated the albedo change, and divided by 100 years, as the theoretical lifetime of the hydropower installation, to ensure comparability with the G-res GHG model calculations.

Conclusions

Hydropower is promoted as a low-carbon source of electricity,[1,2] despite the usually large environmental impacts, particularly of dam/reservoir-based installations.[50] This article shows that for dam plus reservoir types of installations, the validity of such "low-carbon" claims may be limited, especially in comparison to solar and wind energy, particularly in tropical areas. First, extreme differences occur between individual cases, with emission intensities occurring that can exceed those of coal-burning plants. However, even at the low side of the emission spectrum, hydropower in tropical settings will seldom be able to match wind or solar figures. Hydropower climate impact has been systematically underestimated, as calculations are generally incomplete. For instance, the widely used IPCC (2014) figures for emission intensity[3] omit biogenic CO_2 emissions. IPCC's more recent 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[51] now includes such emissions and refers to the G-res which enables to calculate these to some extent. However, its limitations point to a very substantial underestimation of the climate impact of hydropower installations, in particular in tropical situations. This stems from the fact that several important emission mechanisms are omitted, including emissions from drawdown zones, and an arbitrary, unusually long lifetime of 100 years is assumed. While this paper is limited to methodological considerations, it would be highly interesting to see how any new LCAs based on complete measurement and assessment of hydropower installations' GHG emissions would compare to G-res calculated values.

In addition, the impacts of albedo change by creating a reservoir show similarly large variations. Expressing these impacts in terms of emission intensities shows that these, too, can exceed the impacts of the use of fossil fuels. Wohlfahrt *et al.* note that "Reaching meaningful BETs between ±40° latitude, where 90% of the hydropower capacity that is globally under construction/planned is located, requires a much more favourable electricity to water surface area ratio compared to Northern latitudes".[7] It would be very useful to develop a publicly available tool to calculate albedo impacts of reservoirs based on the approach of Wohlfahrt *et al.*[7] and our calculations.

Several important guidance documents used for international financing of hydropower projects recommend to use G-res to evaluate their climate impact.[9,12,52–55] This approach holds a serious flaw in neglecting albedo effects. Furthermore, especially in the tropics, G-res may seriously underestimate GHG emissions.

Emission intensities for wind and solar (PV) energy are approximately 12 and 48 g CO_2eq. per kWh,[3] respectively, with the latter expected to further decrease due to decreasing emissions for the production of solar panels. On the other hand, these technologies require stabilizing/storage mechanisms which may increase emissions to 100–150 g CO_2eq. per kWh.[56,57] Still, when a complete assessment of the climate impact of (reservoir) hydropower in the tropics is made, in many cases these exceed (up to several magnitudes) those of wind and solar energy generation including associated storage facilities.

Our analysis corroborates the commentary of Fearnside and Pueyo[6] and the observations of Pehl *et al.*: "The specific emissions of hydropower can be strikingly high, but are also highly variable, uncertain and dependent on geography. This uncertainty indicates the need for further research and suggests that careful assessment of individual hydropower projects prior to implementation is required to ensure that such projects deliver an actual climate change mitigation benefit."[5] In this respect, it would be useful if a generally applicable assessment tool on the albedo effect, allowing for comparison to emission intensities, *e.g.* based on the approach of Wohlfahrt *et al.*,[7] as illustrated above, was developed.

Given the potentially large early emissions of hydropower dams (construction and emissions from organic matter decomposition) and given the urgency of reducing global warming, reservoir hydropower should not be considered a "climate-friendly" option for electricity generation, unless such emissions in combination with the albedo impact can be proven to be competitive with wind or solar impacts.

Data availability

Input data used in the G-res calculations are available at: DOI: **https://doi.org/10.5281/zenodo.11607725** the data set of Wohlfahrt *et al.* used in the discussion of albedo effects was made available by those authors at: DOI: **https://doi.org/10.5281/zenodo.4432576**.

Author contributions

Author contributions were as follows: Frank van der Valk: conceptualization, formal analysis, methodology, visualization, writing – original draft; Christoffer Bonzi: conceptualization, methodology, project administration, writing – review & editing;

Pyi Soe Aung: conceptualization, methodology, writing – review & editing, supervision.

Conflicts of interest

There are no conflicts to declare.

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