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# The urgency of assessing the greenhouse gas budgets of hydroelectric reservoirs in China

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**Already the largest generator of hydroelectricity, China is accelerating dam construction to increase the share of hydroelectricity in its primary energy mix to reduce greenhouse gas emissions. Here, we review the evidence on emissions of GHGs, particularly methane, from the Three Gorges Reservoir, and argue that although the hydroelectric reservoirs may release large amounts of methane, they contribute significantly to greenhouse gas reduction by substitution of thermal power generation in China. Nonetheless, more systematic monitoring and modelling studies on greenhouse gas emissions from representative reservoirs are necessary to better understand the climate impact of hydropower development in China.**

China overtook the United States and became the world's largest electricity producer and consumer in 2011. The total electricity generation reached 4,722 TW h in 2011, with thermal power and hydropower contributing to 82.5% and 14.0% of the generated electricity, respectively[1]. Meanwhile, over 90% of the thermal electricity is generated by highly polluting coal-fired generation, which had a high grid emission factor of 804 g $CO_2$ equivalent ($CO_2$ e) per kW h in 2010[2]. Coal-fired plants are not only the largest stationary source emitters of greenhouse gases (GHGs) in China, but they also bring serious air pollution problems with releases of $SO_2$, $NO_x$ and fine particles. Hydropower, with more than 200 GW of total installed capacity, accounts for approximately 6% of the total energy supply and over 80% of all electricity generated from renewable sources in China. Joining the global efforts to combat climate change, China is committed to increase the share of non-fossil fuels in its total energy mix to 15% by 2020. Accordingly, the production capacity of hydropower should increase by, on average, 10 to 15 GW $yr^{-1}$ to help achieve this goal. Cascades of dams are currently being built, planned or proposed on the major river valleys in southwest China, where over two-thirds of the country's hydroelectric resources are located (Fig. 1). With physical water scarcity, and spatially and temporarily uneven distribution of water resources[3], reservoir development is also a key component of China's recent heavy investment in water infrastructures to adapt to climate change, droughts and floods, and to improve food security[4].

Although hydropower is widely claimed to be a 'clean' energy source, critics have long warned of the environmental impact of large hydroelectric projects. In particular, research over the past two decades has revealed that the decay of organic matter (OM) in reservoirs could release significant amounts of $CO_2$ and $CH_4$, and the emissions from tropical reservoirs characterized by high levels of OM and shallow depths are much higher compared with those in boreal and temperate regions[5–13]. Methane is 25 times more effective at trapping heat in the atmosphere than $CO_2$ over a 100-year period, and is responsible for over 20% of the change in the radiative forcing of the climate system[14]. It has been estimated that large dams release approximately 104 Tg $CH_4$ annually, or 20% of the total emissions from natural and anthropogenic sources[15], although current estimations on GHG emissions from global hydroelectric reservoirs bear large uncertainties[13,16].

Carbon dioxide, methane and nitrous oxide are the major GHGs that can be produced in reservoirs, but nitrous oxide emissions are typically low unless significant sources of nitrogen are present[7]. When dissolved oxygen is available in the water, $CO_2$ is produced from microbial and photochemical oxidation of OM derived from fallen plant material, sediments and soils, aquatic primary production and from upstream river inputs (Fig. 2). In thermally stratified deep reservoirs, the epilimnion (the layer of warm water at the surface) is generally well aerated. In contrast, anoxic conditions can develop in the hypolimnion (the bottom layer of colder water), where anaerobic decomposition of OM and reduction of $CO_2$ by

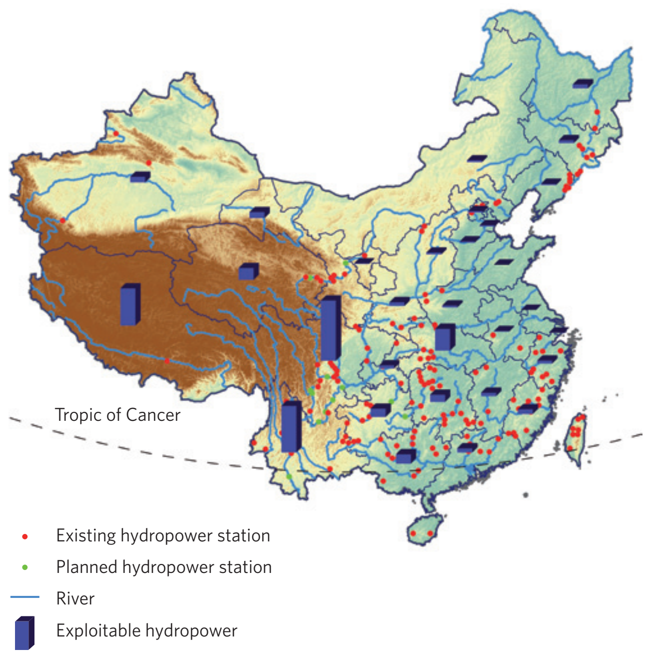


**Figure 1 | Distribution of hydropower resources and the major hydroelectric dams in China's mainland.** Blue blocks indicate the expolitable hydropower in the corresponding province. The hydropower resources are concentrated in the southwest, with Tibet, Sichuan and Yunnan hosting over two-thirds of the total hydroelectric resources. China plans to develop an additional 140 GW of hydropower capacity in the next five years, focusing primarily on the upstream section (Jinsha River) of the Yangtze River, the Lancang River and the Nu River.

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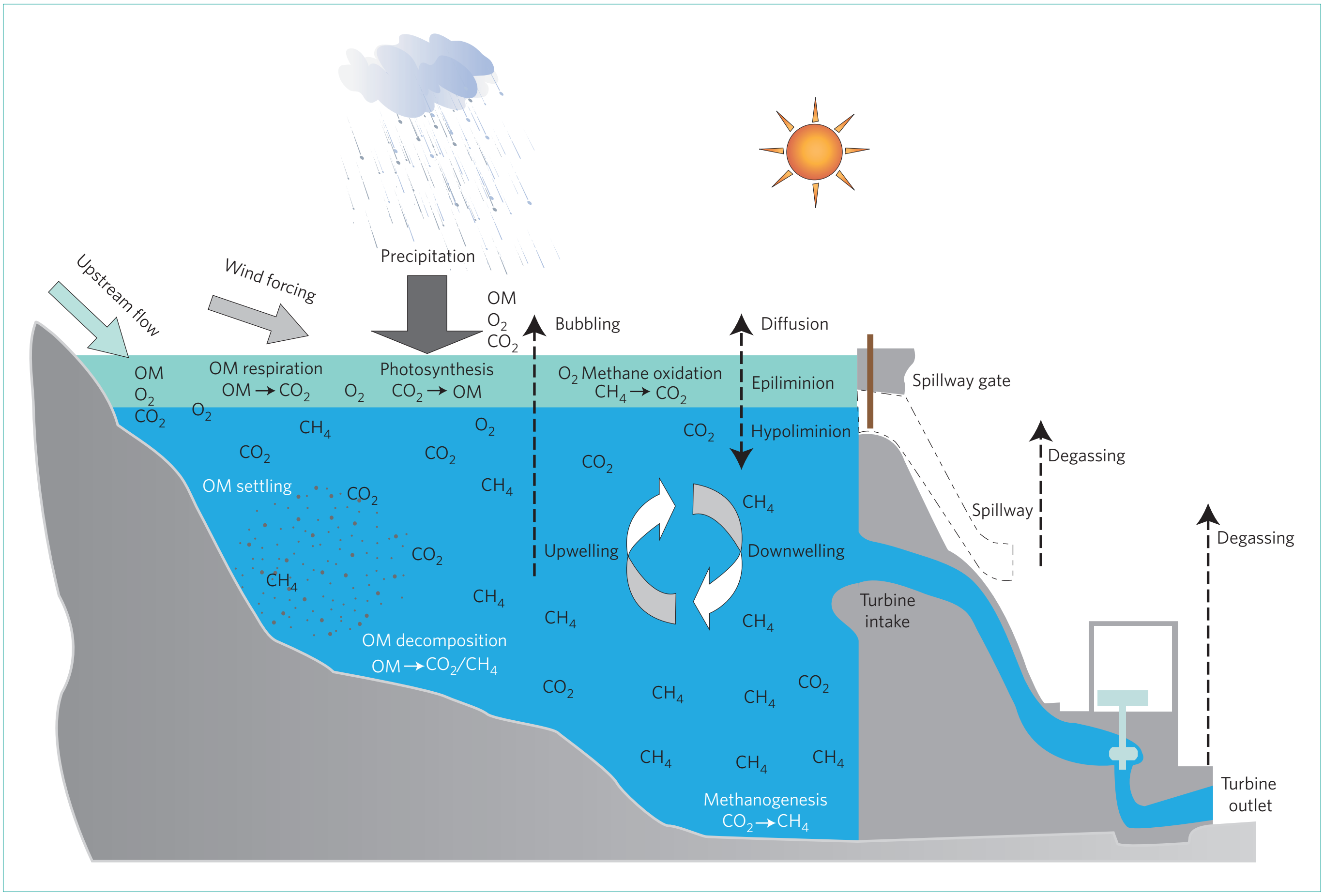


**Figure 2 | Schematic of the major biological, chemical and physical processes involved in the production, consumption and atmospheric release of $CO_2$ and $CH_4$ in a typical deep reservoir.** Precipitation and upsteam flow introduce $CO_2$, $O_2$ and OM into the reservoir. These processes are strongly influenced by the watershed hydrological processes and reservoir operation. In particular, mixing within the reservoir is caused by upwelling (movement of cold, deep water to the surface mixed layer) and downwelling (movement of surface water to deeper layers) forced by variable wind fields.

methanogens result in $CH_4$ production. Carbon dioxide can be fixed to organic carbon through photosynthesis, whereas methane can be oxidized by methanotrophs as they migrate towards the surface and the rest can escape into the atmosphere by diffusion and bubbling (slow natural degassing through formation of bubbles) in reservoirs and downstream rivers[6,12]. In particular, significant $CH_4$ emissions occur when the methane-rich water from a depth below the thermocline (the thin transition zone that separates the warmer, mixed layer at the surface from the colder deep water) rushes through the hydropower turbines with the drastic changes in pressure and temperature[12]. Dissolved $CO_2$ and $CH_4$ can also be released into the atmosphere as the water from the top layer of the reservoir passes through the spillways, owing to intense turbulence. In addition, $CH_4$ emissions can occur in the drawdown areas that are seasonally exposed due to periodic flooding and draining of reservoirs[17,18].

With more than 220 large- and medium-scale (>50 MW) and over 40,000 smaller-scale hydropower plants, China is already the world's largest producer of hydroelectricity. Given the rate of dam construction in the foreseeable future, the GHG emissions from hydroelectric reservoirs may have significant global impact. Although hydroelectricity is a substitute for high-emitting coal-fired generation, emissions of GHGs — particularly $CH_4$ — from the reservoirs may negate the climate benefits. Here we use the Three Gorges Reservoir (TGR) as an example to illustrate that the hydropower dams in China, although they release large amounts of $CH_4$, contribute significantly to GHG reduction by substituting for thermal electricity generation. The climatic and geographical conditions that contribute to the relatively low $CH_4$ emissions from Chinese hydroelectric reservoirs (compared to the tropical ones) are also discussed. We call for more systematic monitoring and modelling studies on the GHG emissions from the hydroelectric reservoirs over their life cycles (including construction, operation and decommissioning) to understand and quantify the short- and long-term climate impact of hydropower development in China.

## GHG emissions from the TGR

Located on the Yangtze River in Hubei province, the TGR is the most high-profile hydropower project in China. The 185-m-high dam was completed in 2008, forming a 630-km-long reservoir with an average width of 1.3 km. TGR is the world's largest hydroelectric power station by total capacity (22.5 GW), with a total of 34 generators. GHG emissions from the TGR received widespread attention following the controversial results reported by Chen and co-workers[17]. They estimated that the total $CH_4$ emission from the surface of the TGR was 3.6 Mg $h^{-1}$ by assuming an emission rate (3.3 mg $m^{-2}$ $h^{-1}$) comparable to those of tropical reservoirs, which are known to emit more GHGs than those in other climatic zones[8,9,11,12]. They also reported that $CH_4$ was emitted at an average rate of 6.7±13.3 mg $m^{-2}$ $h^{-1}$ from the newly created marshes in the drawdown zone from July to September 2008, with the marsh area accounting for 19% of the total $CH_4$ emissions from the reservoir surface[17]. These findings led to widespread concerns on the potential $CH_4$ emissions from hydropower projects in China, with the Chinese dams being dubbed a 'methane menace'[19]. The same team measured much lower $CH_4$ emission fluxes from the drawdown zone (0.29±0.37 mg $m^{-2}$ $h^{-1}$), the permanently flooded sites (0.23±0.38 mg $m^{-2}$ $h^{-1}$) and the downstream surface water (0.24±0.37 mg $m^{-2}$ $h^{-1}$) one year later[18]. Meanwhile, monthly monitoring from November 2009 to January 2011 by another team showed that the average $CH_4$ emission fluxes were 0.454±0.306, 0.260±0.310, 0.115±0.127 and 0.280±0.164 mg $m^{-2}$ $h^{-1}$ at 240, 120 and 3 km upstream from the Three Gorges Dam, and 5 km downstream, respectively[20]. The drawdown areas (excluding rice paddies) were found to be $CH_4$ sources (0.22±0.26 mg $m^{-2}$ $h^{-1}$) in the inundated season but sinks (−0.008±0.035 mg $m^{-2}$ $h^{-1}$) in the drained season, and together they contributed to 42–54% of the total $CH_4$ emissions (2.46 Gg $yr^{-1}$) from the TGR surface[21]. Part of the discrepancy in the reported $CH_4$ emission fluxes might be contributed by the different sampling times as GHG emissions from reservoirs typically decline after dam construction, as discussed later. Nonetheless, these results consistently indicate that the rate of $CH_4$ emission from the TGR surface was comparable to the average (0.48±0.18 mg $m^{-2}$ $h^{-1}$) of large dams in the temperate zone[15], and was approximately an order of magnitude lower than those of the Amazonian reservoirs[8,9,15].

Wu *et al.* estimated that a total of 1.40 Tg $CO_2$ e was emitted by the TGR from October 2009 to September 2010 on the basis of monthly monitoring of $CO_2$, $CH_4$ and $N_2O$ emission fluxes at four sites located on the Yangtze River and a major tributary[22]. Over the same period a total of 81.9 TWh of electricity was generated[22], which corresponds to a reduction of 74.5 Tg $CO_2$ e by substitution of coal-fired power generation, or 53 times the estimated GHG emissions. The TGR has a power density of 20.8 W $m^{-2}$. According to the rules of the Clean Development Mechanism[11], this means that its GHG emissions can be neglected. This is because emissions from hydroelectric reservoirs with power densities exceeding 10 W $m^{-2}$ are considered to be overwhelmingly offset by power generation. Besides hydropower generation, the TGR has significantly improved the navigation conditions and drastically increased the shipping capacity of the Yangtze River. With the water levels raised by over 100 m, the annual cargo transportation through the 192-km-long Three Gorges stretch increased from 18 Tg before reservoir filling to over 74 Tg in 2009, and the transportation cost was reduced by about half with higher capacity shipping vessels[22]. This has significantly reduced the demand on the more energy-intensive land transport to reach inland cities, such as Chongqing. In combination, the improved navigation and substitution of land transport resulted in an estimated net reduction of over 4.7 Tg $CO_2$ e in 2009[22].

It is well documented that GHG emissions from most reservoirs in temperate and boreal regions increase dramatically immediately following construction, then decrease over a few years and eventually stabilize[6–8,23]. As most of the flooded plant material decomposes in the first 3 years after being inundated with water, the emissions of $CH_4$ and $CO_2$ decrease rapidly to levels typical of natural aquatic ecosystems 5 and 10 years later, respectively[6,7,23]. Filling of the TGR began in June 2003, and the water level was raised to the normal storage level (175 m) for the first time in October 2010. Model calculations showed that the $CO_2$ and $CH_4$ emissions from the 25 $km^2$ core reservoir area above the dam in 2008 reached 0.04 and 0.02 Tg, respectively, which were 40 and 20 times above those before impoundment[24]. Nonetheless, the emissions of $CO_2$ and $CH_4$ would decrease by 76% and 40%, and by 89.5% and 58.3% after 5 and 10 years, respectively[24]. Fig. 3 compares the GHG emissions from the TGR estimated over a 100-year period with those from equivalent thermal power plants. Despite the very large uncertainties in the estimates, the results indicate that the cumulative GHG emissions from the TGR could be three orders of magnitude lower than those from equivalent thermal alternatives over a century of operation.

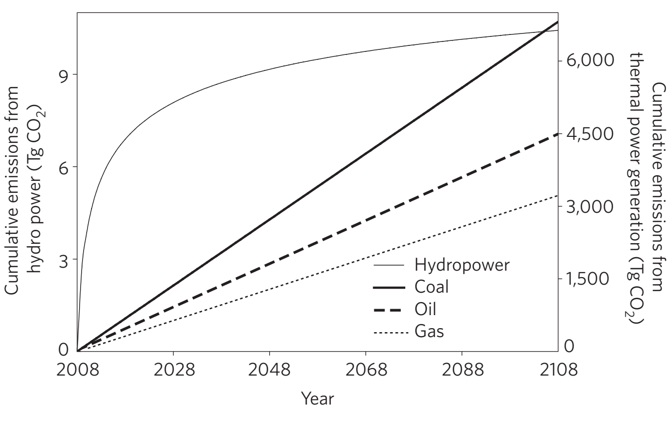


**Figure 3 | Cumulative GHG emissions from the TGR and from equivalent thermal alternatives for electricity production over 100 years.** The GHG emissions from the TGR (designed with an operating life of 300 years, which can be doubled) were estimated based on the emissions for the 2009–2010 period as reported by Wu *et al.*[22] and on extrapolation of the simulation results by Lo[24]. The GHG emissions from thermal power generation were calculated with the latest emission factors of coal-, oil- and gas-fired power generation in China[2]. It should be noted that the emission estimates for the TGR are subject to large uncertainties.

## Climatic and geographical settings of reservoirs

The limited measurement data indicate that $CH_4$ emissions from large hydroelectric reservoirs in China are much lower than those of tropical reservoirs. For example, the $CH_4$ emission flux was as low as 0.117 mg $m^{-2}$ $h^{-1}$ from the Ertan Reservoir, which is located in the subtropical plateau climate zone of the southwest[25]. Several factors could contribute to the relatively low $CH_4$ production in Chinese reservoirs:

The hydropower resources are concentrated in southwest China, and the large hydroelectric reservoirs — including those to be developed — are predominantly located in the plateau and temperate climate zones (Fig. 1). GHG emissions from the reservoirs in boreal and temperate regions are generally lower than those from equivalent thermal power plants[8,11].

The hydroelectric dams along the large rivers were built in deep gorges with natural vertical drops to harness greater potential energy from the dammed water, and much fewer trees and plants would be flooded compared with shallow reservoirs. Despite the occurrence of thermal stratification, such deep reservoirs have high power densities (>10 W $m^{-2}$) and thus negligible GHG emission factors[11].

The practice of biomass clearing (that is, removal of vegetation cover and fertile top-soils) in the reservoir area before impounding in China helps to further reduce the sources of OM[18]. Trees and plants are cut down to no more than 30 cm above the ground, and the timber is collected and used for various purposes (for example, house building and firewood) outside the flooded area[26]. The branches and other plant material with little economic value are piled up and burnt on-site, such that the residual biomass is less than 0.1% after clearance, which helps safeguard the water quality in the reservoirs[26].

The drawdown zones and surrounding areas in the mountainous regions of the southwest range mostly from granite and limestone rocks to shallow nutrient-poor acidic soils, which cannot support fast vegetation growth. As a result, the OM input from upstream watersheds of these reservoirs is significantly lower than the tropical ones.

Hydroelectricity generation (662.6 TWh) led to a reduction of 532.7 Tg $CO_2$ e over coal-fired power generation in 2011[1]. The total GHG emissions from hydroelectricity production would be 13.3 Tg $CO_2$ e if calculated with the designated emission factor of 20 g $CO_2$ e $kWh^{-1}$ (ref. 4), although such estimation is far from accurate. On the basis of a theoretical model and bootstrap re-sampling, Lima *et al.* estimated that China's large dams emit 2.69 Tg of $CH_4$ per year[15], which is equivalent to an annual GHG emission of 67.25 Tg $CO_2$ e. Therefore, the reduction of GHG emissions by hydropower is approximately an order of magnitude higher than that could be emitted from the large dams when only $CH_4$ is considered. The net GHG reduction would be significantly lower if $CO_2$ emissions from the reservoirs were also accounted for. However, production of $CO_2$ from the decay of OM from the watersheds makes no net contribution to global warming — in contrast with the release of carbon in the form of $CH_4$ — as it would occur without reservoir creation. Overall, despite the potentially large amounts of GHGs that may be emitted by the reservoirs, hydropower contributes significantly to GHG reduction in China by substituting for thermal electricity.

## Outlook

It is widely agreed that there is a compelling need for a systemic assessment of GHG emissions from large hydropower dams. Globally, there is a paucity of emission data — particularly from China and India, which are hosts to many large hydropower plants[15,16]. Although a few studies have quantified GHG emissions from reservoirs in China[17,18,20–22,25], none of them measured the releases occurring at turbines and spillways. The GHG emissions from the drawdown zones of hydropower reservoirs, which can be significant[17,18,21,27,28], have also been largely overlooked. The lack of a comprehensive assessment of the life cycle GHG emissions of hydropower reservoirs may result in ignored or underestimated emissions, which negatively affects the ultimate objective of the Climate Change Convention[29]. Monitoring and characterization of $CH_4$ and $CO_2$ fluxes in representative reservoirs of different power densities, locations and time since construction are critically needed to better quantify the total GHG emissions from the hydroelectric reservoirs in China. Although various sampling and analysis techniques have been used, measurement of GHG emissions from reservoirs — which can cover several hundreds of square kilometres and have depths exceeding 100 m — is a complicated process[30,31]. The limited number of sampling spots may not be able to represent the overall emissions from the reservoirs with complex hydrodynamics[23,30]. Furthermore, the rate of biomass decomposition, and thus the production rates of GHGs, are influenced by geographical location, temperature, water depth, the amount and type of vegetation flooded and reservoir age[6–9,16,23]. Therefore, development of appropriate, statistically valid sampling strategies and standardization of the analysis methods are essential for consistent emission monitoring.

As reservoir development alters the regional biogeochemical carbon cycling, the current function of the ecosystems that would be transformed should be considered to avoid building reservoirs with large GHG emissions. It is important to characterize the sink/source strength for GHGs in the reservoir areas prior to impoundment, which would allow direct comparison of the GHG budgets and accurate assessment of the net climate impact of the reservoirs. Predictive models that can simulate the GHG emissions from reservoirs in different climatic and geographical settings, as well as the temporal variation of emissions caused by environmental variables (for example, wind, precipitation and current) are also necessary. Development of such models requires a full understanding of the fundamental physical, chemical and biological processes involved in the production, consumption and atmospheric emissions of GHGs in reservoirs, which is not an easy task[5,32]. The models can be calibrated with the emission data obtained from representative reservoirs. Compared with actual measurement of GHG emissions from the over 40,000 hydroelectric reservoirs in China, a modelling approach is much more practical for assessing the net GHG contribution from hydropower.

In addition to effective biomass clearing in the reservoir areas, land use in the upstream watersheds should also be properly managed to control river inputs of OM associated with the sediment that is eroded and washed into waterways. Moreover, eutrophication — which occurs naturally on geological timescales but is significantly accelerated by anthropogenic nutrient input — is also a major problem in China. At present about 20% of the reservoirs in the country suffer from water pollution, particularly eutrophication caused by discharges from municipal and agricultural sources[33]. The enhanced biomass formation, combined with suppression of dissolved oxygen levels in reservoirs resulting from nutrient and carbon loadings from the watersheds, increases their $CH_4$ production[27,34]. Therefore, more attention should be paid to improving watershed management and curbing the pollution of upstream rivers, to weaken the role of reservoirs as $CH_4$ factories.

Despite the relatively low $CH_4$ production in the TGR and other large hydropower reservoirs in China, engineering technologies should be developed and implemented to avoid such emissions. Several low-cost, innovative technologies are available for efficient capture of $CH_4$ in deep reservoirs, both at the turbines and spillways and downstream[10,15]. Recovery of 1 Tg $yr^{-1}$ of $CH_4$ could lead to generation of 1.76 GW of thermal electricity[10]. Therefore, recovering $CH_4$ from hydropower reservoirs will not only reduce atmospheric GHG emissions, but will also provide a viable source of extra clean energy.

GHG emissions from hydroelectric reservoirs have received little attention in China until recently. International collaboration is expected to greatly advance the characterization and modelling of GHG emissions from reservoirs, and the development of $CH_4$ recovery technologies in China. It can also help to enhance the management of existing reservoirs and reduce the environmental and social impacts of hydropower development, while maximizing the benefits in an era of climate change[35].

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## References

1. *2011 National Electric Power Industry Statistics* (China Electricity Council, 2012).
2. Michaelowa, A. *Rule Consistency of Grid Emission Factors Published by CDM Host Country Authorities* (CDM Watch, 2011).
3. Cheng, H., Hu, Y. & Zhao, J. Meeting China's water shortage crisis: Current practices and challenges. *Environ. Sci. Technol.* **43,** 240–244 (2009).
4. Li, S. China's huge investment on water facilities: An effective adaptation to climate change, natural disasters, and food security. *Nat. Hazards* **61,** 1473–1475 (2012).
5. Galy-Lacaux, C., Delmas, R., Kouadio, G., Richard, S. & Gosse, P. Long-term greenhouse gas emissions from hydroelectric reservoirs in tropical forest regions. *Glob. Biogeochem. Cycles* **13,** 503–517 (1999).
6. Abril, G. *et al.* Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). *Glob. Biogeochem. Cycles* **19**, GB4007 (2005).
7. Tremblay, A., Varfalvy, L., Roehm, C. & Garneau, M. (eds) *Greenhouse Gas Emissions: Fluxes and Processes, Hydroelectric Reservoirs and Natural Environments* (Springer, 2005).
8. Barros, N. *et al*. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nature Geosci.* **4,** 593–596 (2011).
9. Fearnside, P. M. & Pueyo, S. Greenhouse-gas emissions from tropical dams. *Nature Clim. Change* **2,** 382–384 (2012).
10. Ramos, F. M. *et al.* Methane stocks in tropical hydropower reservoirs as a potential energy source. *Climatic Change* **93,** 1–13 (2009).
11. Makinen, K. & Khan, S. Policy considerations for greenhouse gas emissions from freshwater reservoirs. *Water Alternatives* **3,** 91–105 (2010).
12. Kemenes, A., Forsberg, B. R. & Melack, J. M. Methane release below a tropical hydroelectric dam. *Geophys. Res. Lett.* **34**, L12809 (2007).
13. Wehrli, B. Climate science: Renewable but not carbon-free. *Nature Geosci.* **4,** 585–586 (2011).
14. Shindell, D. T., Faluvegi, G., Bell, N. & Schmidt, G. A. An emissions-based view of climate forcing by methane and tropospheric ozone. *Geophys. Res. Lett.* **32**, L04803 (2005).

15. Lima, I. B. T., Ramos, F. M., Bambace, L. A. W. & Rosa, R. R. Methane emissions from large dams as renewable energy resources: A developing nation perspective. *Mitig. Adapt. Strat. Glob. Change* **13,** 193–206 (2008).
16. Li, S. & Lu, X. X. Uncertainties of carbon emission from hydroelectric reservoirs. *Nat. Hazards* **62,** 1343–1345 (2012).
17. Chen, H. *et al.* Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir. *J. Geophys. Res.* **114**, D18301 (2009).
18. Chen, H. *et al.* Methane emissions from the surface of the Three Gorges Reservoir. *J. Geophys. Res.* **116**, D21306 (2011).
19. Qiu, J. Chinese dam may be a methane menace. *Nature News* (29 December 2009); available via http://go.nature.com/Es4bow
20. Yang, L. *et al.* Spatial and temporal variation of methane concentrations in the atmosphere of the Three Gorges Reservoir and its relationship with methane emissions from the reservoir. *Resour. Environ. Yangtze Basin* **21,** 209–214 (2012).
21. Yang, L. *et al.* Surface methane emissions from different land use types during various water levels in three major drawdown areas of the Three Gorges Reservoir. *J. Geophys. Res.* **117**, D10109 (2012).
22. Wu, B., Chen, Y., Zeng, Y., Zhao, Y. & Yuan, C. Evaluation on effectiveness of carbon emission reduction of the power generation and shipping functions of the Three Gorges Reservoir. *Resour. Environ. Yangtze Basin* **20,** 257–261 (2011).
23. Teodoru, C., Prairie, Y. & del Giorgio, P. Spatial heterogeneity of surface $CO_2$ fluxes in a newly created Eastmain-1 reservoir in northern Quebec, Canada. *Ecosystems* **14,** 28–46 (2010).
24. Lo, W. *Modelling Greenhouse Gas Emissions from the Three Gorges Dam* (Hong Kong Polytechnic Univ., 2009).
25. Zheng, H. *et al.* Spatial-temporal variations of methane emissions from the Ertan hydroelectric reservoir in southwest China. *Hydrol. Process.* **25,** 1391–1396 (2011).
26. *Specification for Reservoir Basin Cleaning Designing of Hydroelectric Project (DL/T5381–2007)* (National Development and Reform Commission, 2007).
27. Fearnside, P. M. Do hydroelectric dams mitigate global warming? The case of Brazil's Curuá-una Dam. *Mitig. Adapt. Strat. Glob. Change* **10,** 675–691 (2005).
28. Lu, F. *et al.* Preliminary report on methane emissions from the Three Gorges Reservoir in the summer drainage period. *J. Environ. Sci.* **23,** 2029–2033 (2011).
29. Raadal, H. L., Gagnon, L., Modahl, I. S. & Hanssen, O. J. Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power. *Renew. Sustain. Energy Rev.* **15,** 3417–3422 (2011).
30. Bastviken, D. *et al.* Methane emissions from Pantanal, South America, during the low water season: Toward more comprehensive sampling. *Environ. Sci. Technol.* **44,** 5450–5455 (2010).
31. Schubert, C. J., Diem, T. & Eugster, W. Methane emissions from a small wind shielded lake determined by eddy covariance, flux chambers, anchored funnels, and boundary model calculations: A comparison. *Environ. Sci. Technol.* **46,** 4515–4522 (2012).
32. Roland, F. *et al.* Variability of carbon dioxide flux from tropical (Cerrado) hydroelectric reservoirs. *Aquat. Sci.* **72,** 283–293 (2010).
33. Cheng, H. & Hu, Y. Improving China's water resources management for better adaptation to climate change. *Climatic Change* **112,** 253–282 (2012).
34. Abe, D. S. *et al.* The effect of eutrophication on greenhouse gas emissions in three reservoirs of the Middle Tiete River, southeastern Brazil. *Verh. Internat. Verein. Limnol.* **30,** 822–825 (2009).
35. Pittock, J. Better management of hydropower in an era of climate change. *Water Alternatives* **3,** 444–452 (2010).

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## Author contributions

Both authors contributed equally to this work.

## Additional information

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## Competing financial interests

The authors declare no competing financial interests.