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Cradle-to-grave greenhouse gas emissions from dams in the United States of America

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ABSTRACT

Hydropower is traditionally considered to be one type of "clean" energy, and has been heavily developed in many regions of the world. Nevertheless, this assumption is increasingly being challenged by recent findings that a large amount of methane and other greenhouse gases (GHGs) are emitted during reservoir creation, turbine operation, and dam decommissioning. Via a critical review of existing hydropower life cycle assessments and reservoir emission studies, we compared the GHG emissions of various types of dams based on their structural type, size, primary function, and geographical location during their construction, operation, and decommissioning phases. Means to improve dam performance and reduce related GHG emissions were identified. It was found that dams with reservoirs usually have much higher GHG emission rates than diversion dams. GHG emissions are mainly generated at the construction and maintenance stages for small-scale run-of-river dams, whereas decomposition of flooded biomass and organic matter in the sediment has the highest GHG emission contribution to large-scale reservoir-based dams. Generally, reservoir-based dams located in boreal and temperate regions have much lower reservoir emissions (3–70 g CO_2 eq./kW h) compared with dams located in tropical regions (8–6647 g CO_2 eq./kW h). Our analysis shows that although most hydroelectric dams have comparable GHG emissions to other types of renewable energy (e.g., solar, wind energy), electricity produced from tropical reservoir-based dams could potentially have a higher emission rate than fossil-based electricity.

1. Introduction

The United States of America (USA) has one of the most heavily dammed river systems in the world [1–3]. More than 90,000 existing "large" dams are documented in the latest National Inventory of Dams (NID) maintained by the Army Corps of Engineers [4]. This does not include an estimated 2,000,000 or more smaller dams that do not meet the NID criteria for inclusion in the inventory (high or significant hazard classification; 7.6 m in height and exceed 18,500 m^3 in storage; or, 61,700 m^3 storage and exceed 1.8 m in height). The USA also has a long history of building dams. Some of the oldest dams listed in the NID were built in the mid-1600s. The construction of dams continued to grow exponentially thereafter and did not slow down until it peaked in the 1960s (Fig. 1). In fact, more than one-third of all dams in the NID were built between 1961 and 1980. Dams are constructed for a myriad of primary functions. The primary functions of NID-listed dams are recreation (28.0% of the total number of dams), flood control (17.9%), fishing and fire protection (17.3%), water supply and irrigation (14.7%), power generation (2.3%), erosion control (1.6%), and mine tailings storage (1.3%) [4]. These primary functions have changed substantially over the years. Most of the dams constructed before the 1900s primarily serve recreational functions currently, although most likely served alternate purposes at the time of their construction. The need for dams for water supply and irrigation became prominent in the late 1800s and the first half of the 1900s, while most dams constructed in the past 50 years are primarily for flood control, fishing, and fire protection. Most of the existing hydroelectric dams (dams capable of generating hydropower) were built between 1800 and 1960; however, hydropower has consistently comprised a small percentage of primary dam functions.

Although the USA has benefited from the multiple functions provided by dams, their adverse environmental and social impacts and safety risks are increasingly being recognized and debated. For instance, dams have been criticized for altering natural flow regimes, blocking fish passage, affecting sediment transport, and changing watershed characteristics, which collectively contribute to the degradation

Abbreviations: EIO, economic input-output; GHG(s), greenhouse gas(es); GWP, global warming potential; HPs, hydropower projects; LCA, life cycle assessment; NID, National Inventory of Dams; O&M, operation and maintenance; PV, photovoltaic

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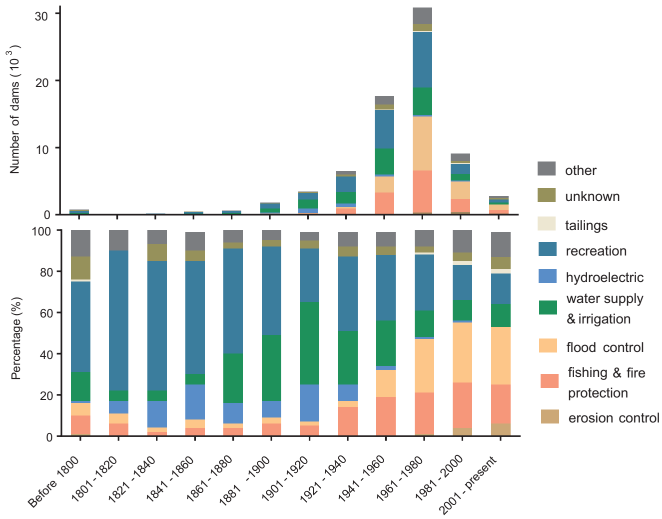

Fig. 1. The current primary functions of dams constructed in the USA history based on the data obtained from the National Inventory of Dams [4].

of water quality, fish population, and biodiversity as well as cascading social and economic problems (e.g., revenue loss in the fishing industry) [5–9]. Furthermore, some of the older and/or larger dams are often perceived as a public-safety risk under the increasing possibility of natural and man-made threats [10,11]. These changes in knowledge have led to a subtle shift in scientific and public attitudes towards dams, and the classification of hydropower as “clean” energy has also been challenged. New dam construction is often accompanied by social opposition, and most importantly, dam removal and upgrades can be contentious, often driven by grassroots movements initiated by local communities [12,13]. Table 1 summarizes existing literature on major environmental, social, and economic impacts associated with dams as well as their potential rehabilitation methods.

In the last decade, the method of life cycle assessment (LCA) has increasingly been adopted in assessing the sustainability of products and systems [14–16]. LCA, guided by the ISO 14040 and ISO 14044 standards, is an approach for characterizing the cradle-to-grave or cradle-to-cradle impacts of a product or system, i.e. from raw material acquisition, equipment manufacturing, and use to disposal or reuse [17,18]. Hydroelectric dams, although representing only 2.3% of the total number of dams in the NID, have been the core of most dam-related LCAs [17,19]. This can be partly explained by the significance of hydropower as a type of renewable energy in the USA; hydropower accounts for 6% of the annual USA net electricity generation and 46% of the total renewable energy generation (compared with 35% wind, 2% wood and waste, 1% solar, and 0.4% geothermal) [20–22]. Hydropower continues to be developed around the world and holds a critical position in meeting future energy demand, especially in countries where the hydropower potential has not yet been fully exploited [23]. Although new construction of hydroelectric dams has been sluggish since the 1960s in the USA, new programs have been implemented to increase hydropower generation, including (1) development of hydrokinetic energy technologies to extract and convert energy obtained from oceans, rivers, and man-made canals; (2) upgrades of existing

Table 1
Potential environmental and socioeconomic impacts of dams and prospective amelioration approaches.

Potential impacts	Response	Potential rehabilitation tools	Impact assessment methods
Environmental impacts			
Alteration of natural flow regime	Dampening of large or seasonal floods, resulting in a negative impact on both habitat and organisms [38,39]	Allow spring floods; reduce daily fluctuations; create periodic high flows; widen river	Field observation and measurements [40]; ecological model [41]
Barriers to longitudinal fish migration	Fishes killed when they pass through turbine or fish ladder; reduction of fish population and biodiversity; economic losses from fishery	Remove dam; add or improve fish ladders; upgrade to low-impact hydropower generation technology	Field observation and measurements [42]; Bayesian state-space model [9,43,44]
Barriers for the drift of organisms	Degradation of water quality; reduction of biodiversity; reduction of property or recreation values	Remove dam	
Blockage of sediment transportation	Accelerated siltation processes; reduction of the vertical connection between the river and groundwater; effects on the benthic community and spawning conditions for fish; reduction of biodiversity [45,46]; greenhouse gas (GHG) emissions [47,48]	Remove dam; widen rivers; manually move sediment from reservoir to downstream	Ecological model for fish biodiversity [42,45]; LCA of sediment contribution to GHG emissions [48]; life-cycle cost analysis of sediment removal and processing system [49]
Temperature changes	Temperature stratification in the reservoir [50]; change of downstream temperature when warm or cool water is released	Remove dam; modify dam structure (e.g., change penstocks to allow withdrawal at different reservoir levels; add weirs downstream	Field observation and measurements [51]
Inundation of terrestrial habitat	GHG emissions from the degradation of inundated biomass; change of local land use patterns; loss of habitat of original inhabitants	Remove dam	Field measurements and empirical models; life-cycle assessment [27]
Socioeconomic impacts			
Involuntary resettlement for some local communities	Economic and cultural shocks and losses of resettling community; poverty and inequity problems	Avoid or minimize involuntary resettlement; improve livelihood of resettling community; encourage public participation and consensus; provide group support [52]	
Waterborne disease from water impoundment schemes	Fatality; economic losses; common in tropical and subtropical regions	Implement prevention strategies and appropriate disease diagnosis; finance medical care [53]	
Reduction of fish population and biodiversity	Reduction of a protein source in the diet; economic losses from fishery; reduction of property or recreation values	Remove dam; add or improve fish ladders; upgrade to low-impact hydropower generation technology	Bayesian state-space model [9,43,44]
High upfront capital cost	High cost for dam construction, engineering, and design causes public or private economic burdens [54]		Life-cycle cost assessment [55,56]
Risk of dam failure	Economic losses; life loss	Remove/upgrade dam; inspection and maintenance	Risk assessment [57,58]

hydroelectric dams; and, (3) conversion of existing non-powered dams (dams without hydropower generation capabilities) to hydroelectric dams [24–26].

Hydropower is traditionally regarded as a low-carbon energy source. Case studies in the USA [27], Canada [28], Japan [29], Turkey [30,31], and New Zealand [32] compared hydropower with renewable and fossil fuel sources, and found that greenhouse gas (GHG) emissions from the life cycle of hydropower can be as much as 79%, 62%, 88%, and 99% lower than solar photovoltaic (PV), wind, geothermal, and coal, respectively. On the other hand, some studies have suggested that hydropower production could potentially release more GHG emissions than fossil fuel energy from a life cycle perspective, especially considering the large amount of methane emitted from flooded biomass [33–35]. Steinhurst et al. [36] estimated that tropical reservoir-based dams could emit 1300–3000 g CO_2 eq./kW h, compared to 400–500, 790–900, and 900–1200 g CO_2 eq./kW h for thermoelectric plants using natural gas, oil, and coal, respectively. Similarly, Fearnside (2015) [37] compared the hydropower generated from the Petit Saut Dam (French Guiana) with electricity generated from combined-cycle natural gas, and found that the GHG emissions from the dam are 19 times higher than the natural-gas-based electricity. The contradictory conclusions of dam GHG emissions reflect our limited understanding of the overall sustainability of hydroelectric dams and the associated implications on the optimal design and operation of these dams. Furthermore, non-powered dams have been largely neglected in previous LCAs despite the large number of such dams.

In this study, a critical review was conducted based on 31 LCA case studies (16 peer-reviewed journal papers) about GHG emissions from hydroelectric dams, 4 additional river in-stream hydropower LCA case studies (2 peer-reviewed journal papers), and more than 20 peer-reviewed journal papers (non-LCA studies) about reservoir GHG emissions. The goal of this study is to understand the significance of life cycle GHG emissions associated with different types of dams, analyze the 'hot-spots' of dam GHG emissions, and identify potential approaches to reduce dam GHG emissions at construction (Section 4), operation and maintenance (Section 5), and demolition (Section 6) stages. In addition, the importance of GHG emissions from reservoirs was analyzed (Section 7). Finally, the life cycle GHG emissions from dams were synthesized and a comparison of hydropower with fossil fuel and other types of renewable energy was performed (Section 8).

2. Goal and scope of published dam LCAs

All of the 31 LCA case studies reviewed in this study are attributional LCAs, which characterize environmentally relevant flows during a dam's life cycle instead of the change of impacts resulting from possible decisions. Furthermore, the 100-year global warming potential (GWP) was adopted by all of these studies to characterize GHG emissions. Therefore, this same time frame for characterizing GWP was also adopted in the current review. A large variation of life cycle GHG emissions ranging from 0.2 to more than 185 g CO_2 eq./kW h has been reported by previous LCAs [48,59]. Potential reasons for such a wide range of GHG emissions may include discordance in the system boundary adopted and the LCA methodology applied, among others.

Various system boundaries have been adopted by the studies reported in this review (Fig. 2). All of the dam LCAs reviewed in this paper included raw material extraction, equipment manufacturing, and dam construction stages. Most of the LCA papers also included impacts associated with the operation and maintenance of hydroelectric systems, except for Gallagher et al. [60]. Three papers further considered the GHG emissions associated with reservoir flooding and the flooded biomass decomposition [27,61,62]. Four papers included dam removal and/or decommission [63–66]. Only two papers investigated the GHG emissions associated with the entire life cycle of raw material extraction, equipment manufacturing, construction, operation and maintenance, reservoir flooding, and dam demolition [48,67]. No study included GHG emissions from turbine and downstream degassing of supersaturated methane in deep water due to the pressure drop when passing through turbines and flowing at the downstream of dams. Neglecting these GHG emission sources could potentially lead to underestimation of dams' environmental impacts and misguide decision-making about dams [68,69].

Three different types of LCA methodologies have been applied in previous dam LCAs, including process-based LCAs [60,64,65], economic input-output (EIO)-LCAs [62,70–72], and process-based hybrid LCAs [73,74]. These methods differ in terms of the amount of upstream processes relevant to a target system that can be included in the analysis. Process-based LCA requires all itemized inputs (e.g., materials, energy) and outputs (emissions) relevant to a dam's life cycle for a complete analysis. As this is difficult to achieve even for the simplest types of products, one often defines a certain boundary of analysis to reduce the amount of data that need to be collected [75,76]. EIO-LCA uses EIO tables to characterize the economic interactions among all industries, and hence, no specific boundary decision is required [75,76]. EIO-LCA often has a broader and more inclusive system boundary than the process-based LCA, but its results are less site-specific due to data aggregation presented in the EIO tables. Process-based hybrid LCA utilizes EIO analysis to supplement process-based LCA for expanding the system boundary. Its system boundary comprehensiveness is often in between the process-based LCA and the EIO-LCA.

3. Classification of hydroelectric dams and projects

Hydropower projects (HPs) can be classified many different ways: by the quantity of water available (with or without reservoir), available water head (low, medium, or high head), initial installed-electricity-generation capacity (small, large, etc.), or electricity-generation facility type, for instance [77,78]. Installed capacity and electricity-generation facility type are the two most common methods used for classification. Most countries set an installed capacity of 10 MW as the demarcation between large and small HPs [79].

Based on electricity-generation facility type, HPs can be divided into four main groups: diversion (run-of-river and canal-based), reservoir-based, pumped storage, and river in-stream HPs [80]. The four types of HPs have different extent and scale of impacts on climate change, different GHG emission "hot-spots" at each of their life cycle stages, as well as different environmental and socioeconomic tradeoffs. For instance, reservoir-based HPs are capable of maximizing energy output through water release control and management and often provide additional services beyond energy generation (e.g. recreation) [81,82]. However, reservoir creation and management is also a significant source of GHG emissions [83–85]. Unlike reservoir-based HPs, diversion HPs generally have limited impacts on river flows and do not require creation of large reservoirs. Their life cycle GHG emissions are highly dependent on their structure types, material compositions, and installed capacity [60,86]. Pumped-storage HPs transfer energy from off-peak to peak hours. They are usually considered energy storage facilities rather than energy generation facilities. In the USA, the total installed capacity of pumped-storage HPs is approaching 21.9 GW, which represents around 97% of the utility-scale electricity storage in the entire nation [87]. Even though pumped-storage HPs play an important role in electricity storage, limited studies have assessed their environmental impacts, especially considering their unique requirement of two reservoirs for operation. The structure of river in-stream HPs is relatively simple and primarily comprises turbines, power cable, and onshore facilities. There is no need to build dams or weirs, pipelines, or reservoirs for river in-stream HPs. In the USA, river in-stream HPs are mainly installed along the Mississippi River system [88]. Among the reviewed LCA studies, eight studied diversion HPs [29,60,63–65,70–72], six included reservoir-based HPs [27,48,62,73,74,89], two investigated pumped-storage HPs [67,90], and two studied river in-stream HPs [66,86]. Table 2 provides the

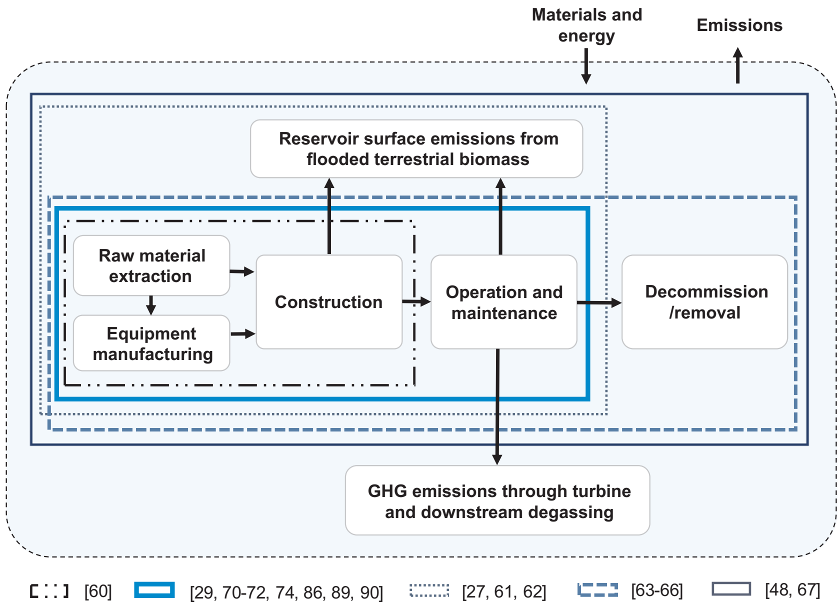

Fig. 2. System boundaries adopted by previous LCA studies.

definition, components, functions, pros and cons, as well as the related LCA studies for the four types of HPs.

4. The construction stage of dams

The construction stage is defined as the raw material extraction, equipment manufacturing, transportation, and actual building processes of dams (each will be discussed further in Sections 4.1–4.3). It has been estimated that around 2.3–37.9 g CO_2 eq./kW h are emitted from the construction stage based on GHG emissions from 27 dams worldwide [48,62,70]. Table S1 in the Supporting information (SI) provides the GHG emissions associated with each individual contributor to the construction stage. Generally, the construction stage contributes more than 70% and around 50% of dams' total construction and operation emissions (reservoir-related and demolition emissions excluded) based on results from process-based LCAs [60,64,65,92] and EIO-LCAs, respectively. The assumptions of dam life span also influence the emission results from this stage. For instance, Hondo [29] found an 83% decrease in life cycle GHG emissions (from 30 to 5 g CO_2 eq./kW h) when the lifetime of a 10 MW run-of-river dam is changed from 10 to 100 years. The life span reported by the previous dam LCAs ranges from 20 to 150 years (Table S1 in the SI). Given that the life span of dams could vary based upon factors such as dam functions, structures, and geographical locations, we adopted the originally reported life-span values in this review. The significant consumption of materials, equipment, energy, and labor makes the construction stage an important GHG emission source for dams.

4.1. Raw material extraction and equipment manufacturing

A typical dam structure includes the dam core, pipelines, powerhouse, turbine, and generator. Based on structure design, dams can be divided into four groups: embankment, arch, gravity, and buttress dams. The simplified sectional view of the four types of dams is shown in Fig. 3. Embankment dams come in two types: earth dams and rock-filled dams, constructed mainly by earth and rock, respectively. The cross section of an embankment dam has a hill-like shape [93,94]. Gravity dams are mainly fabricated from concrete and stone masonry, with a triangular cross section [95]. The weight of the dam is used to hold back large volumes of water. Buttress dams are made from concrete and masonry. They have a watertight upstream side supported by a series of triangular-shaped walls (buttresses) on the downstream side [96]. Arch dams are curved in the shape of an arch, with its convexity towards the upstream side. The cross section of an arch dam is comparatively thinner than a similar-scale gravity dam [97]. In the USA, embankment dams are predominant and account for about 86% of all dams in the NID database, followed by gravity dams (3.4%).

Dam structures influence both the quantities and the types of materials needed to build the dam and the associated emissions. For example, buttress dams generally require smaller amounts of construction materials compared to similar-scale gravity dams because of the clear spaces between buttresses [99]. Embankment dams usually require more construction materials than similar-scale arch, gravity, and buttress dams because of their larger structural volumes [99]. However, they may have lower GHG emissions because sand and rock used for embankment dams have significantly lower GHG emission factors than those of cement and concrete used for constructing gravity and buttress dams [74]. Zhang et al. estimated the life cycle GHG emissions of an earth-rockfill embankment dam and a similar-scale concrete gravity dam, and found that the embankment dam has around 46% fewer raw-material GHG emissions compared to the gravity dam [73]. Table 3 provides the typical quantities of common materials used to build HPs, their associated GHG emission factors, and the average typical GHG emissions of each material.

The aforementioned studies have mainly been focused on hydroelectric dams, while the raw-material GHG emissions associated with the large number of non-powered dams remain unknown. As a preliminary attempt to address this knowledge gap, a comparison of the total hydroelectric versus non-powered dams was carried out using dams located in the USA as a case study. In Fig. 4, the product of dam height and length (perpendicular to river flow direction) was used as a surrogate of dam size and construction material quantities. We calculated the product of dam height and length for each dam in the NID, and summed the products for each of the four dam structure types (Fig. 4). Within each structure type, we further divided the results into two groups: hydroelectric and non-powered dams. This comparison relies on two critical assumptions. First, the material composition and design variations within each dam structure type are neglected. Second, the influence of dam width variations (parallel to river flow direction) on the quantities of construction materials needed is assumed to be the same for all dams. The results show that there are relatively few arch and buttress dams in the USA, and they have relatively low height

Table 2
Comparison of the four types of hydropower projects based on electricity-generation facility type.

Type of hydropower projects (HPs)	Definition	Components	Primary functions	Pros	Cons	Life cycle studies
Diversion HPs (run-of-river and canal-based HPs)	A facility that channels flowing water from a river through a tunnel or pipeline to power turbines [91]	Dam/weir, feeder channel, forebay, penstock, powerhouse, electro-mechanical equipment[a]	Power generation	Limited social and environmental impacts; river flow pattern remains unchanged	Electricity output varies with the river's natural flow	[29,60,63–65,70–72]
Reservoir-based HPs	A large system that uses a dam to store water in a reservoir [91]	Dam, penstock, powerhouse, electro-mechanical equipment[a]	Recreation; water supply; fire protection; flood control; power generation	Steady power output; deliver multiple services	Social and environmental impacts for local community and the whole watershed; alteration of the ecosystem and natural habitats; displacement of local communities, etc.	[27,48,62,73,74,89]
Pumped-storage HPs	Projects harness water that is cycled between a lower and upper reservoir by pump [91]	One or more dams, penstock, electro-mechanical equipment[a], pump, powerhouse	Water supply; fire protection; flood control; power generation	Load following, peaking power, and standby reserve [67]	Energy consumption; low efficiency	[67,90]
River in-stream HPs	Projects that generate electricity from the flow of inland waterways [91]	Turbines, power cables, onshore facility	Power generation	Limited social and environmental impacts	Electricity output varies with the river's natural flow	[66,86]

[a] Electro-mechanical equipment includes turbine, generator, switchgear, control and protection equipment, electrical and mechanical auxiliaries, transformer and switch-yard equipment.

× length values for non-powered and hydroelectric dams, indicating their limited overall raw material usages and associated emissions. The total height × length value of the embankment dams is up to 240 times greater than the other three structure types combined, indicating a popularity of embankment dams in the country. Furthermore, the non-powered embankment dams have a significantly higher total dam height × length value than that of the hydroelectric dams (13 times larger), indicating the importance of non-powered dams in material consumption and contributions to raw-material GHG emissions. The results also indicate that hydroelectric dams generally have a larger size than the non-powered dams.

Linking dam structures to hydropower-generation facility types, reservoir-based HPs are usually large embankment and gravity dams. Construction of these dams requires a large amount of materials, which dominates their total construction GHG emissions (including raw material extraction, equipment manufacturing, transportation, and actual construction) [62,73]. On the other hand, unlike the large reservoir-based HPs, diversion HPs are usually small and mainly function as a river-diversion channel to penstocks for electricity generation. Hence, pipeline manufacturing is another major contributor to the total construction GHG emissions of diversion dams given that they are usually made of carbon-intensive steel or polyvinyl chloride (PVC) materials [29,60,63–65]. Gallagher et al. calculated the environmental impacts of three small-scale run-of-river HPs in the UK, and found that polyethylene pipework accounted for around 53–60% of the total construction GHG emissions, followed by turbine and generator (19–23%), and powerhouse (13–17%) [60]. Other construction materials, such as earth and concrete, only present a very small portion of the total construction GHG emissions. Similarly, a case study of a 10 MW run-of-river HP in Japan found that around 39.8% of the construction and operation GHGs come from the penstock [29].

The importance of material type and quantity in dam construction suggests that reduction of material consumption, design optimization, and utilization of recycled or green materials could be potentially viable ways to improve dams' sustainability [60,65]. Gallagher et al. examined a number of eco-design measures for the installation of small hydropower plants ranging from 50 to 650 kW, including replacement of concrete-block cavity walls with wooden-frame super-structures for the powerhouse, replacing a fraction of the aggregate or cement with increased recycled content, and using biofuels for onsite machinery and transportation. The results showed that these eco-design measures led to a cumulative reduction of 2.1–10.4% of the total construction GHG emissions [103].

4.2. Transportation

GHG emissions at the transportation stage are mainly from the consumption of fuel by truck, train, ship, or plane [73,104]. The total weight of transported goods, travel distances, and the types of transportation mode used are the major factors influencing GHG emissions at the transportation stage [73]. A wide variation from 0.06 to 5.6 g CO_2 eq./kW h was estimated by previous LCA case studies. Of all LCA's reviewed in this study, only four papers reported the transportation GHG emissions separately in their analysis [60,64,65,73], while other studies combined the impacts of transportation with raw material extraction or actual construction. Of these studies that reported transportation GHG emissions separately, six case studies suggested that transportation only has a marginal impact of less than 3% of the construction GHG emissions [60,61,65]. However, a study of five run-of-river HPs located in Thailand found that around 32% of life cycle GHG emissions are from transportation [64]. This is mainly because the pressure pipelines and electro-mechanical equipment have to be imported from overseas through a long distance to the construction site. Collectively, these varied estimates indicate that localization of material and equipment production is essential to reduce transportation-related environmental impacts [65]. In addition, utilization of alternative and renewable

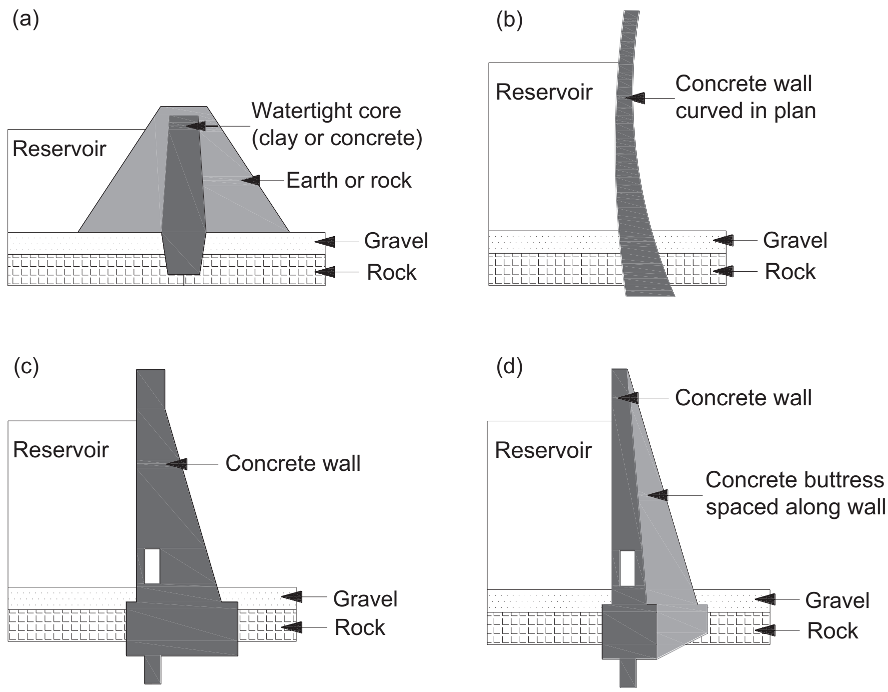

Fig. 3. The sectional view of four types of dams: (a) embankment dam, (b) arch dam, (c) gravity dam, (d) buttress dam (adapted from the British Dam Society [98]).

energy sources for transportation could also potentially reduce GHG emissions.

4.3. Actual building and construction processes

GHG emissions during the actual dam-building process are usually combined with the impacts of raw material extraction and equipment manufacturing. Among the 31 dam LCA case studies reviewed, only 9 case studies provided the GHG emissions of the actual building process separately, with results ranging from 0.06 to 11 g CO_2 eq./kW h. The construction of HPs is a complicated process, which includes procedures like excavating, dam filling, concrete mixing, drilling, and blasting [73,74]. The process of reservoir flooding for reservoir-based dams is not included in this section and will be discussed separately in Section 7. GHG emissions during the building and construction process are mainly from diesel fuel and electricity consumption by on-site equipment installation and usage [73]. A previous LCA found that GHGs generated by a conventional concrete dam during actual construction are around 50% higher than a similar-scale rockfill dam mainly because the building of conventional concrete dams requires larger amounts of electricity and oil by cable cranes, air compressors, and dump trucks [74]. Other factors, such as hydrologic conditions, hydraulics, soil and sediment characteristics, HP designs, and construction techniques, will influence the workload and hence the GHG emissions of the building process [64,65,105].

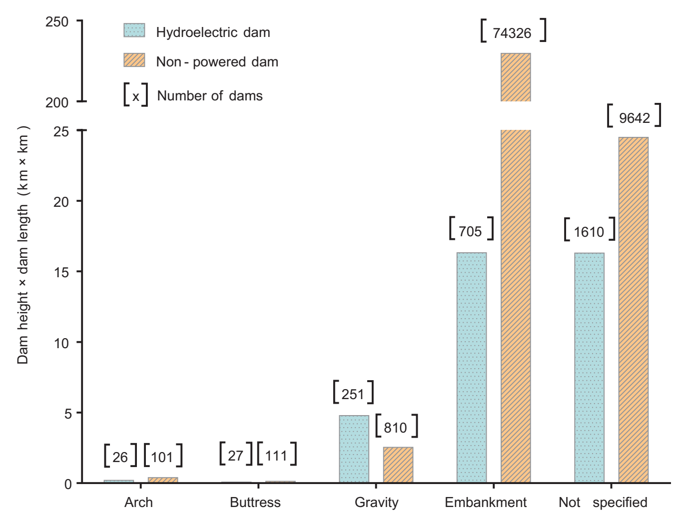

Fig. 4. The summed value of dam height times dam length (a surrogate value of the total construction-material requirement) for each type of dam in the USA based on NID database.

Table 3
GHG emission factors and typical quantities for different materials.

Materials	Application	Typical quantity (kg/MW h)	Emission factor (kg CO_2 eq./kg of material)	Average GHG emissions (kg CO_2 eq./MW h)
Steel	Dam framework; Penstock	0.5 [64,65,89]	2.2 [73]	1.1
Cement	Dam body (arch, gravity, buttress) or dam core (embankment); Penstock	8.3 [64,65,89]	0.9 [100]	7.1
Polyvinyl chloride	Penstock	2.9 [63]	1.8 [101]	5.1
Sand	Dam body (embankment)	11.0 [64,89]	0.002 [102]	0.02
Gravel & rock	Dam foundation	16.6 [64,89]	0.002 [102]	0.03

Note: Average GHG emissions (kg CO_2 eq./MW h) = Typical quantity (kg/MW h) × Emission factor (kg CO_2 eq./kg of material).

5. Operation and maintenance of dams

GHG emissions during the operation and maintenance (O&M) stage are mainly associated with the O&M of civil structure and electro-mechanical equipment, consumption of thermal back-up power due to variable electricity generation, and reservoir GHG emissions (further discussed in Section 7). Maintenance of civil structure includes activities such as repairing cracks in the dam body, powerhouse and other civil works, as well as replacing pipework and screen filters. Maintenance of electro-mechanical equipment mainly includes replacement of generators and turbines, changing lubricant oils, and replacing seal plates. A wide range from 0.9 to 77 g CO_2 eq./kW h has been reported by previous LCAs. Some of the important causes of such a wide range include adoption of different LCA methodologies and the wide variance of GHG emissions from reservoirs. For instance, an EIO-LCA of a run-of-river dam with an installed capacity of 3000 kW in India reported a GHG emission of 18.7 g CO_2 eq./kW h at O&M stage [70]. In comparison, a process-based LCA of a run-of-river dam with an installed capacity of 3200 kW in China reported a much smaller O&M GHG emission of 0.9 g CO_2 eq./kW h [65]. Among the LCAs reviewed, EIO-LCA is a commonly used method to assess GHG emissions of the O&M stage due to the unavailability or difficulty in obtaining detailed historical O &M data of the dams.

Additionally, the match between dams' installed capacity and the available hydraulic capacity will also influence the GHG emissions at the O&M stage. The optimal installed capacity was commonly determined by comprehensive evaluations of historical hydrology data and predictions of the future change of water resource before construction. However, uncertainties of future climate and inaccuracies in these predictions may lead to under-installed capacity and longtime over-loaded operations, accelerating equipment exhaustion and failures. On the contrary, if the available water resource is overestimated, more installed capacity than necessary will be constructed, leading to waste of installed capacity or idling [65].

6. End-of-life of dams

The end-of-life of dams usually includes the decommissioning of construction components, and recycling valuable metals and equipment. There have been three different ways to deal with the end-of-life stage by previous LCAs. Most previous LCAs simply exclude the demolition stage due to a lack of data. Some argued that most dams remain for preserving the adapted ecosystems and environments, even though they no longer produce hydropower [60,62]. Neglecting the end-of-life stage could potentially lead to underestimation of dams' GHG emissions, given that dam removal has a large impact on the release of GHGs from accumulated sediments [48]. A few other studies estimated the GHG emissions associated with the removal of major dam components, such as concrete structures, powerhouse structures, pipelines, and electricity machines, and with the recycling of high-value materials, such as steel, stainless steel, and iron [64,65]. GHG emissions were calculated based on the energy consumption of the demolition machines and material transportation to the landfill or recycling sites. End-of-life GHG emissions in this case were estimated to be low enough to be neglected. Only one LCA paper considered the decomposition of organic matter in the sediment after dam removal [48]. This study pointed out that the decomposition of sediments could generate around 35–380 g CO_2 eq./kW h based on data collected from six LHPs located in the USA with an installed capacity ranging from 185 to 2000 MW, which is around 18–65 times larger than its construction GHG emissions and 3–26 times larger than the O&M GHG emissions (including the reservoir emissions) [48]. Yet, the ripple effects of ecosystem interruptions after the dam removals, such as downstream fish kills, destabilization of stream banks, and fill-in of riffle-pool habitat, were still not included [48]. Furthermore, there remains a lack of data and studies on the GHG emissions associated with large dam removals, as most of the dams that have been removed in the USA are small dams with a height lower than 4 m [106].

7. Reservoir GHG emissions

Decomposition of flooded biomass and organic materials generates carbon dioxide and methane in both aerobic and anaerobic conditions after impoundment. Some of these GHGs emit to the atmosphere through diffusion (CO_2 and methane) or ebullition (methane) at the reservoir surface. These diffusive GHG emissions have been included in LCAs such as Pacca and Horvath [27], Zhang et al. [62,73]. However, reservoir GHG emissions happen not only at the reservoir surface, but also when water passes through turbines or spillways, and downstream of dams [34]. Water passing the turbine is drawn from certain depths of the reservoir. The deeper the water is, the higher the pressure and the lower the temperature becomes. In stratified systems where density boundaries limit the mixing of GHGs, the solubility and concentration of GHGs become higher at greater depth in the reservoirs. When the supersaturated water passes through the turbine, the sudden pressure drop could result in direct release of GHGs into the air. Another part of GHGs are gradually released through diffusion or bubbling downstream of the dam after passing through the turbine. Kemenes et al. measured that around 39 Gg CO_2 eq. were emitted annually through turbine degassing and downstream emissions at the Balbina dam (Brazil), whereas 34 Gg CO_2 eq. were generated annually at the reservoir surface [107]. De Faria et al. [108] estimated that GHG emissions through turbine and downstream degassing are around three times the GHG emissions from reservoir surface. Reservoir GHG emissions have been widely studied outside of the LCA field [108,109]. Table S2 of the SI provides the estimated GHG emissions from the previous studies' aforementioned pathways.

Under the IPCC guidelines, it is an option rather than a requirement to include reservoir GHG emissions for dam LCAs because of three main difficulties with measuring and estimating such emissions [37,83]. First, methane is usually produced through anaerobic digestion in sediments and rises up as bubbles. It is hard to accurately measure methane ebullition since bubbles happen in bursts rather than a steady flow [84,107,110,111]. Second, factors such as the amount and carbon content of flooded biomass and reservoir productivity often influence reservoir GHG emission rates [35]. HPs in humid tropical regions typically have higher GHG emission rates because of larger unit biomass quantities, higher average biomass carbon contents, and warmer temperatures accelerating the decomposition process [17]. Flooded biomass per unit of reservoir area has been shown to vary from 10 kg/m^2 in boreal regions to 50 kg/m^2 in tropical forests, and carbon content varies from 0.3 kg CO_2 eq./m^2 for desert shrubland to 18.8 kg CO_2 eq./m^2 for tropical forests [112]. GHG emissions from tropical reservoirs have been reported to be around 2–13 times higher than temperate reservoirs [113], and around 3–26 times higher than boreal reservoirs [79]. In addition, older reservoirs tend to have a lower GHG emission than newly created ones because of the depletion of the labile flooded biomass and soil organic carbon over time [113–115]. Hence, site measurements of specific dams are often difficult to generalize or to apply directly to other dams. Third, different emission pathways dominate depending on reservoir depth [116]. In stratified deep waters ($>$ 7 m) where anaerobic conditions prevail, decomposition of organic matter might result in a higher ratio of methane production. Thus, the deeper the electricity generation turbines are located in the water, the more methane will be emitted when water passes through the turbine and flows downstream.

Additionally, reservoir emissions associated with the non-powered dams have been largely neglected. Given the large number of reservoir-based, non-powered dams, understanding the relative scale and importance of their GHG emissions is imperative. Accordingly, we provide a comparison of the total reservoir GHG emissions from hydroelectric dams and non-powered dams in the USA and the results are presented

Table 4
GHG emissions from total reservoir-based hydroelectric and non-powered dams in the USA based on NID data.

Climate zone	Reservoir GHG emission rate[a] (g CO_2 eq./m^2/yr)	Reservoir surface area (km^2)		GHG emission (Tg CO_2 eq./yr)	
		Hydroelectric dam	Non-powered dam	Hydroelectric dam	Non-powered dam
Boreal	873 [34,113–116]	54	30	0.05	0.03
Temperate	557 [34,113–116]	48374	51291	26.94	28.57
Tropical	2733 [34,113–116]	16	22	0.04	0.06
Total		48444	51343	27.03	28.66

[a] Reservoir GHG emission rates adopted are gross reservoir surface GHG emission rates averaged for the three climate zones based upon previously reported values.

in Table 4. Reservoir GHG emission rates in different climate zones were directly obtained from previous reservoir studies [34,113–116]. Total reservoir surface area in each climate zone was calculated based on NID data (natural lakes excluded). Around 5% of the total dams did not report their functions, and hence they are excluded from this analysis. Table 4 indicates that the total reservoir GHG emissions of non-powered dams are as important as those of hydroelectric dams.

Net reservoir emission is another way to quantify reservoir GHG emissions. It is defined as the gross reservoir GHG emissions minus baseline GHG emissions before reservoir creation [117]. Baseline GHG emissions before flooding can either be positive (source) or negative (sink) depending on prior land use. For instance, boreal and temperate forests on average absorb 2100 mg/m^2/d of CO_2 and 1.0 mg/m^2/d of methane [118,119] and hence have negative baseline GHG emissions. Lakes have a positive baseline GHG emission of 1180 mg/m^2/d of CO_2 [120,121] and 46 mg/m^2/d of methane [121,122]. When the forests are flooded to form lakes, the resulting net reservoir emissions will be 3280 mg/m^2/d of CO_2 and 47 mg/m^2/d of methane. Pacca and Horvath (2002) reported that the loss of baseline GHG absorption capacity alone could contribute 7–13% to a dam's life cycle GHG emissions [27]. Besides, the creation of dams also alters the carbon cycle in the original river flow by trapping suspended materials behind the dams [34,47]. Mendonca et al. estimated that carbon burial could potentially outweigh the carbon emissions from the reservoir surface [123,124], yet dam removal will release those trapped sediments which may result in GHG emissions [48]. Nevertheless, this net effect of burial and releasing of GHGs from the trapped sediments has not been included in current dam LCAs. Overall, our understanding of dams' impact on the global carbon cycle is still limited and more research is needed in this area for more accurate quantifications.

8. Life cycle GHG emissions of dams

The synthesized values of life cycle GHG emissions from different types of dams are shown in Fig. 5. Additionally, numerical values of GHG emissions from each life cycle stage provided by previous LCAs and reservoir emission studies are presented in Table S3 of the SI. According to Fig. 5, pumped storage dams have significantly higher O&M emissions than other types of dams. This is mainly due to the large amount of energy needed by pump operation. Demolition GHG emissions could contribute significantly to the boreal and temperate reservoir-based and pumped storage dams. Reservoir GHG emissions have the largest contribution to the tropical reservoir-based and pumped storage dams. However, boreal and temperate reservoir GHG emissions could be underestimated due to a lack of studies linking these emissions to hydropower productions [35]. Reservoir-based HPs are generally much more carbon intensive than diversion HPs. Upstream impoundment emissions, turbine degassing, and downstream emissions from diversion dams have rarely been studied and hence are excluded from Fig. 5. Fearnside provided the only impoundment GHG emission estimation of 63 g CO_2 eq./kW h for a tropical run-of-river dam [125,126]. Given the importance and large variability of reservoir GHG emissions, more attention needs to be paid to reservoir GHG emissions when decisions have to be made for the development of dams, especially in tropical regions, as most of the future expansion of hydropower is likely to happen in these areas.

In order to put the GHG emissions of HPs in perspective, they have been compared with conventional and other renewable electricity-generation technologies and the results are shown in Fig. 6. River instream, run-of-river, and reservoir-based HPs located in boreal and temperate regions generally have a lower GHG emission rate compared with fossil fuel, solar PV, and biomass energy. However, reservoir-based HPs located in tropical regions could have a higher GHG emission rate than fossil fuel energy. Given the importance of reservoir GHG

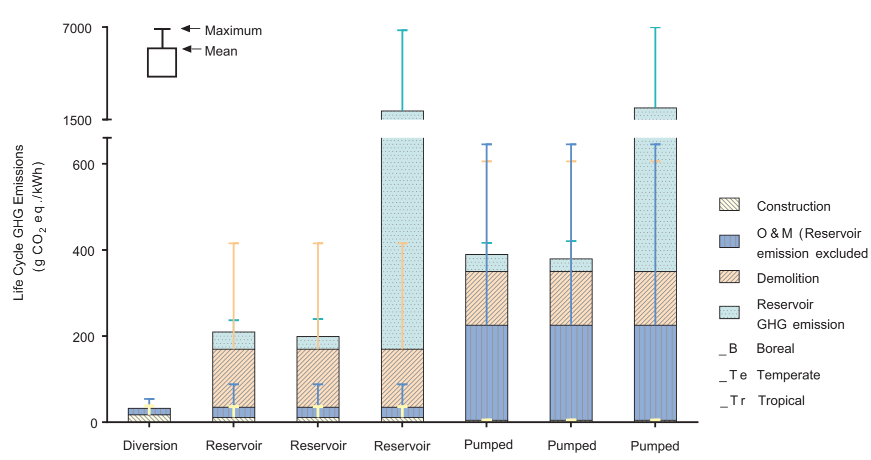

Fig. 5. Life cycle GHG emissions from dams (The reservoir GHG emissions shown are the global mean values of diffusion, ebullition, and/or degassing emissions from reservoir surface and downstream of dams.).

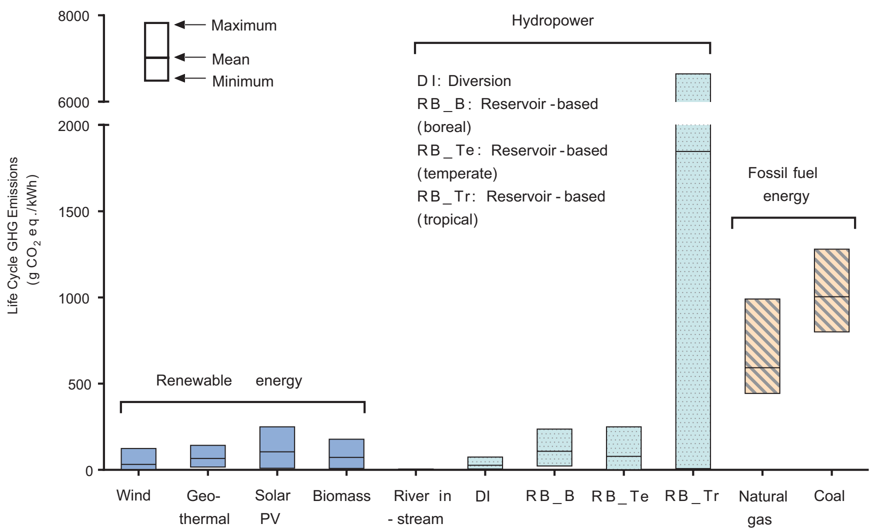

Fig. 6. Life cycle GHG emissions from different types of energy (*Source*: Coal [29,92,130,131], natural gas [92,130], wind [131–135], biomass [136–138], solar PV [29,139,140], geothermal [138], river in-stream [66,86], diversion HPs [60,65,72], reservoir-based (boreal) HPs [116], reservoir-based (temperate) HPs [48,62,73,116], reservoir-based (tropical) HPs [37,83,116]).

emissions for tropical dams and the potential influence of the GWP characterization time scale on the GHG emissions, a comparison of the 100-year and 20-year GWP was performed for the reservoir GHG emissions (Table S2 in SI). This comparison was not conducted for other life cycle phases due to a lack of data on the emitted GHG compositions. The GHG emissions per kW h from reservoirs can be up to 2.4 times greater when the 100-year GWP is converted to the 20-year GWP, which further elevates the potential impacts of tropical reservoir-based dams. The 20-year GWP of boreal and temperate dams is around 7–97 and 6–107 g CO_2 eq./kW h respectively, which is still lower compared to the coal-fired [127] (1000 g CO_2 eq./kW h) and natural gas [127] (470 g CO_2 eq./kW h) power generation.

Although reservoir-based HPs located in the tropical regions are shown to have the largest GHG emissions, caution should be exercised in drawing strong conclusions from this comparison due to the uncertainties in the assessment and the specific conditions under which individual projects are evaluated [63]. In addition, previous LCA studies only calculated and weighted GHG emissions based on the amount of hydropower generated, while other services provided by dams (e.g., water supply, irrigation, flood control, erosion control, fishing and fire protection) are largely neglected. Furthermore, dams also present environmental impacts other than GHG emissions, such as blocking fish passage, altering natural flow variation, and eliminating small floods and sediment that replenishes stream beds and floodplain soils. These disadvantages should not be neglected. For example, according to Goralczyk's study, hydropower has a light burden for GHG emissions (4.6 g CO_2 eq./kW h) compared with photovoltaic (104 g CO_2 eq./kW h) and wind turbines (6 g CO_2 eq./kW h), but its acidification potential is larger than these two technologies [128]. Thus a range of key indicators must be considered when evaluating the sustainability of energy generation technologies [129]. The comprehensive evaluation of the pros and cons of hydropower generation is imperative in decision-making about dam construction, operation, and end-of-life.

9. Conclusions

Life cycle GHG emissions from dams are highly site-specific based on different types, scales, and locations of projects. The results of this study considered data from hydropower LCA studies and non-LCA reservoir GHG emission studies. By comparison, published LCA studies estimate a range of 0.2–185 g CO_2 eq./kW h, up to 36 times less than our results. This difference reveals the importance of utilizing a consistent and comprehensive system boundary and considering different dam characteristics in understanding the sustainability of HPs. In general, river in-stream and diversion HPs have much lower GHG emissions compared with reservoir-based HPs. Flooded biomass decomposition, although not commonly considered in existing dam LCAs, is one of the greatest contributors to the GHG emissions of reservoir-based HPs, especially to those located in tropical regions. A comparison among hydro, wind, solar, geothermal, biomass-based, and fossil-fuel-based electricity shows that hydropower generally has comparable GHG emission rates to other types of renewable energy (within a range of 3–250 g CO_2 eq./kW h), but electricity produced from tropical reservoir-based dams could potentially have 27 times higher emission rates than other hydropower and renewables, and around 6 times that of fossil-fuel-based electricity. Collectively, these findings suggest that reservoir-based HPs are viable as a lower GHG emission replacement for fossil-fuel-based electricity in temperate and boreal regions, and river in-stream and diversion HPs are viable options in general. Tropical reservoir-based hydropower is likely to contribute more to climate change than natural-gas-based electricity and possibly even more than coal-based electricity. Hence, decisions regarding new development of hydropower in tropical regions should be made carefully, and should take into consideration the possibility of integrating design measures to minimize GHG production. More studies on the accurate quantification of reservoir GHG emissions are still needed given its potential significance and variability. This study also underscores the need to take a more local/regional approach to energy policy. For example, in a region with site-specific conditions that make reservoir-based hydropower on the higher end of life cycle GHG emissions but biomass or geothermal on the lower end, it may be worthwhile to consider providing greater incentive for the lower-emitting renewable options through carve-outs in a renewable portfolio standard, rather than incentivizing all renewable energy at the same level.

While existing LCAs are primarily focused on hydroelectric dams, the current analysis of NID data revealed potentially equal contribution of reservoir GHG emissions by all non-powered dams (27.03 Tg CO_2 eq./yr) in the USA compared with all hydroelectric dams (28.66 Tg CO_2 eq./yr). Non-powered dams are difficult to assess through LCAs because their primary functions (e.g., recreation, flood control) are often difficult to quantify. Nevertheless, these dams present similar types of impacts as hydroelectric dams. Many of them have approached or exceeded their design life, and shifted their primary functions as they are no longer needed or suited for their original purposes. Some of them remain only because they are costly to be removed or upgraded. As preferences for dams and watershed ecosystem services change, society will need to make thousands of decisions about the future of these dams in the coming decades. Given the diverse uses (e.g., hydropower, water supply, recreation) and consequences of dam presence (e.g., effects on climate change, nutrient flux, habitat availability, diadromous fish populations, safety and liability risks associated with aging infrastructure), alternative decisions for individual dams or networks of dams have unique and emergent economic, technological, environmental, social, and political trade-offs. Multi-scale, integrated social and biophysical analyses are required to provide a holistic view of these trade-offs and to guide future decision-making about dams. The current review is just one of the first steps in quantifying and understanding some of these tradeoffs through the lens of lifecycle GHG emissions. Consideration of future changes in water availability, climate, population, and land use also calls for an improved understanding of their effects on dam operation and management.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2018.04.014.

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