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RESEARCH ARTICLE

A global boom in hydropower dam construction

Christiane Zarfl · Alexander E. Lumsdon · Jürgen Berlekamp · Laura Tydecks · Klement Tockner

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Abstract Human population growth, economic development, climate change, and the need to close the electricity access gap have stimulated the search for new sources of renewable energy. In response to this need, major new initiatives in hydropower development are now under way. At least 3,700 major dams, each with a capacity of more than 1 MW, are either planned or under construction, primarily in countries with emerging economies. These dams are predicted to increase the present global hydroelectricity capacity by 73 % to about 1,700 GW. Even such a dramatic expansion in hydropower capacity will be insufficient to compensate for the increasing electricity demand. Furthermore, it will only partially close the electricity gap, may not substantially reduce greenhouse gas emission (carbon dioxide and methane), and may not erase interdependencies and social conflicts. At the same time, it is certain to reduce the number of our planet's remaining free-flowing large rivers by about 21 %. Clearly, there is an urgent need to evaluate and to mitigate the social, economic, and ecological ramifications of the current boom in global dam construction.

Keywords Biodiversity · Energy · River management · Sustainability · Climate change

C. Zarfl and A.E. Lumsdon contributed equally to the preparation of the manuscript.

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C. Zarfl (✉) · A. E. Lumsdon · L. Tydecks · K. Tockner
Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany
e-mail: zarfl@igb-berlin.de

A. E. Lumsdon · K. Tockner
Department of Biology, Chemistry and Pharmacy, Freie Universität Berlin, Altensteinstraße 6, 14195 Berlin, Germany

J. Berlekamp
Institute of Environmental Systems Research, University of Osnabrück, Barbarastraße 12, 49076 Osnabrück, Germany

Present Address:
C. Zarfl
Center for Applied Geosciences, Eberhard Karls Universität Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany

Introduction

Rapid growth of the human population and economic development are tightly coupled with an increase in global energy demand (UN 2012). Electricity production increased by 72 % between 1993 and 2010 and is expected to rise by an additional 56 % by 2040 (The World Bank 2014a; US Energy Information Administration 2014). At the same time, more than 1.4 billion people remain disconnected from electricity supply, especially in rural Sub-Saharan Africa and South Asia (UNEP 2012b). Securing the future energy demand and closing the electricity access gap are therefore paramount objectives set for the energy sector (Crousillat et al. 2010; UN-Energy 2010).

Energy production and conversion account for 29 % of global greenhouse gas emissions (UNEP 2012a). In addition, depletion of fossil energy resources as well as the exploitation of uranium provide reasons for concern. Their unequal global distribution leads to interdependencies between countries and in the worst case to political conflicts, which are likely to increase as these resources become further depleted (Asif and Muneer 2007). Accordingly, renewable energy sources—geothermal,

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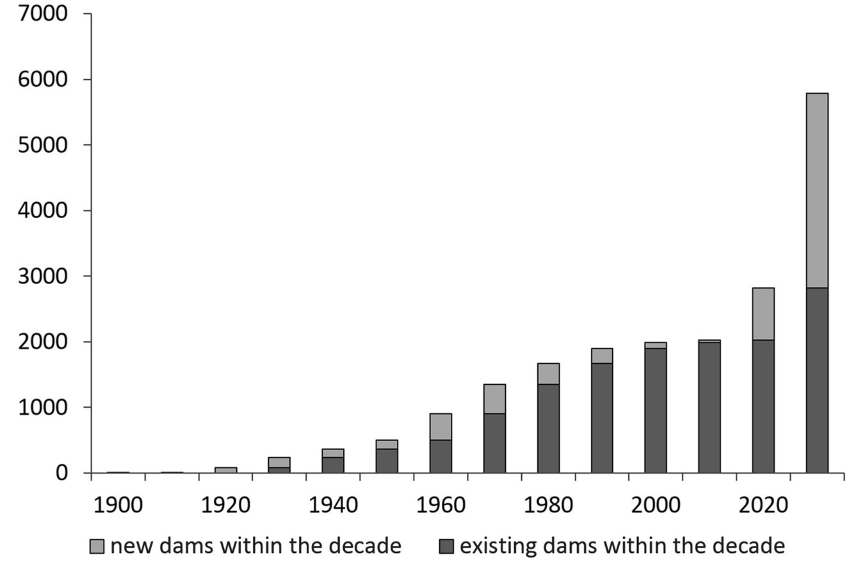

Fig. 1 Global pace of hydropower dam construction of existing hydropower dams (Lehner et al. 2011) and outlook for hydropower dams which are under construction or planned

solar, wind, waves, tides, biomass, biofuels, and hydropower—are rapidly gaining importance; their production almost doubled between 1991 and 2011. Renewables currently account for 20 % of the global electricity production, with hydropower contributing 80 % to the total share (The World Bank 2014b, c). Worldwide, out of 37,600 dams higher than 15 m, more than 8,600 dams primarily designed for hydropower generation are in operation (International Commission on Large Dams 2011). Notably, 32 countries including Brazil, Mozambique, Nepal, and Norway use hydropower to produce more than 80 % of their electricity requirements (The World Bank 2014b).

The Rio+20 targets require countries to meet their growing energy demand through the use of Kyoto-compliant energy resources (UNEP 2012b). This is an additional major driver of investments in hydropower. At present, 22 % of the world's technically feasible hydropower potential [>15.6 million GWh (=10^6 kWh) per year] is exploited (International Commission on Large Dams 2011). Following a period of relative stagnation during the past 20 years, the current boom in hydropower dam construction is unprecedented in both scale and extent (Poff and Hart 2002; Fig. 1). The economic, ecological, and social ramifications are likely to be major. However, the spatial pattern of hydropower construction at the global scale is unclear, as are the cumulated fragmentation impact of the affected river systems, greenhouse gas emissions, and social impacts (such as the relocation of people).

Here, we provide a comprehensive global inventory of future hydropower dams with a capacity exceeding 1 MW. We include dams that are both currently planned or under construction. Information for each dam includes the project name, geographical coordinates, river basin, hydroelectric capacity, and construction timeline. The inventory is based on information derived from more than 350 scientific references, governmental and non-governmental sources, as well as from other public databases, reports and newspaper articles. When available, we used multiple independent references and sources for cross-validation to reduce the heterogeneity in data quality (Online Resource Table S1). This compilation provides a conservative estimate because it focuses on dams designed for hydropower production; dams designed primarily for water supply, flood prevention, navigation, and recreation are excluded. The compilation also excludes very small hydropower dams (<1 MW) that are currently under construction or planned; their number is most likely very high but not documented comprehensively over the world.

The data compilation enabled us to (1) identify future hotspots in hydropower development in comparison to contemporary patterns (Online Resource Fig. S1), (2) calculate the number of future hydropower dams related to river discharge within major river basins, and (3) estimate the cumulative future impact on the current state of river fragmentation (Poff and Hart 2002; Lehner et al. 2011, G. Grill et al. unpublished information). This information provides a solid basis for future studies to identify regional conflicts and the inevitable tradeoffs between the benefits of hydropower generation and ecological, social and economic impacts.

Methods

Data collection on hydropower investments

A data search was conducted on the scope of investments into the hydroelectricity sector to obtain an idea on its economic order-of-magnitude. Therefore, details on almost 500 investors since 1978 were collected including: name of the investor, country and year of investment, name of project, and amount spent (US$). The collection was not restricted to investments in construction activities, but also considered repair and maintenance activities as well as expansion and improvement of hydropower infrastructure in general. For the identified projects, more general overviews on investors were provided by the World Bank and International Rivers (The World Bank 2014f; International Rivers, Banks and Financial Institutions 2010). However, most of the data were derived from reports and web sources of single investors.

Data collection and processing on hydropower dams

Geo-referenced data were collected for future hydropower schemes that have a maximum design capacity of 1 MW or greater. Information on future hydropower dams below this capacity is only available sporadically, and often lacks detail because of less onerous licensing requirements. For this reason they were excluded from the study. Data for dams that are under construction or at a late planning stage were collected between August 2012 and February 2014 using different types of sources:

1. Peer reviewed literature
2. Government documents
3. NGO reports and publications
4. Newspaper articles
5. Commercial databases
6. Reports of energy producers
7. Reports of energy infrastructure engineers or consultants
8. Other web sources

Dams were annotated in the database as planned if they were described as such in the original data source, or if they were reported as being at a feasibility stage where social, cost-benefit and environmental aspects were under evaluation. Dams at a pre-feasibility stage were not included. About 80 % of the data contained spatial information in various formats; these were converted for use with the World Geodetic System 1984 (WGS 84). For the remaining data, it was possible to geo-reference the dams manually within a geographical information system (ArcGIS 10.1™), using references reported in the original data source literature and Google Maps™ or Google Earth™.

All data were aligned to the HydroSHEDS (Lehner et al. 2008) 15 s ($\sim$500 m) global river network, except for 12 records that were beyond the extent of the HydroSHEDS. Dams were snapped to the nearest river line within HydroSHEDS. This approach relies on the accuracy of the original coordinates and could introduce bias through snapping to the incorrect river line. Therefore, all dam locations were manually cross-validated wherever possible by using additional data sources to ensure that they had snapped to the correct river line.

The availability and accuracy of attribute data (including spatial information) for each individual dam record was determined by the stage of the project. Consequently, projects that were under construction invariably had more detailed supplementary information. Furthermore, this information was cross-referenced with the original objective noted in the data source. Where possible, records were cross-validated with multiple data sources to confirm the status of the project, or to provide attributes that were missing in the original data source. Additional attributes were collected on the dam name, continent, country, main river system, major basin (Food and Agriculture Organisation 2011), sub basin (Food and Agriculture Organisation 2009), stage of construction, maximum designed capacity (MW), dam height (m), start of construction, and planned date of completion. Discharge ($m^3\ s^{-1}$) calculations were processed at a later stage.

To analyze the spatial distribution of future hydropower dams, additional data were collected for those countries where new hydropower dams are under construction or planned. This included numbers for each country on the size of the population without electricity access, which was complete for all required countries in 2002 (Dorling 2007), as well as GNI (gross national income; The World Bank 2014e) and GDP (gross domestic product; The World Bank 2014d) per capita (US$) in 2012. Both indices were related to the expected future hydropower capacity per capita. In addition, data on the technically feasible hydropower potential (E_{pot} in GWh year^{-1}), the installed hydropower capacity (K_{inst} in MW) and the electricity production in 2011 (E_{prod} in GWh year^{-1}) were compiled (International Journal on Hydropower and Dams 2012). Based on these data, the potential electricity production E_{future} (in GWh year^{-1}) by hydropower plants under construction or planned with their planned capacities (K_{future} in MW) could be conservatively estimated as (assuming the same average efficiency as in existing large hydropower plants):

$$E_{\mathrm{future}} = \frac{E_{\mathrm{prod}}}{K_{\mathrm{inst}}} \cdot K_{\mathrm{future}}$$

Combining information on the technically feasible hydropower potential, the currently produced electricity, and the potentially produced electricity, allowed us to calculate the future exploitation of the remaining technically feasible potential in each country.

Discharge data estimation

River discharge was calculated for 3,688 dam locations within the available extent of HydroSHEDS. Therefore, a global runoff raster grid was constructed to summarize mean annual net cell runoff from 1980 to 2009. These values were derived from the WaterGAP Global Hydrology Model, and include runoff from land, lakes and wetlands, but also consider evapotranspiration from open water surfaces (Döll and Fiedler 2008). Standard Arc Hydro Tools (Maidment 2002) within the ArcGIS software using unprojected data were used to delineate upstream drainage basins for all dam locations. Discharge values could then be calculated using an adapted zonal statistics tool (Clark 2012).

Terrain preprocessing

The HydroSHEDS 15-arc second GRID provided the input for stream definition by applying the following implemented procedures:

- Terrain Preprocessing | Stream Definition
- Terrain Preprocessing | Stream Segmentation
- Terrain Preprocessing | Catchment Grid Delineation
- Terrain Preprocessing | Catchment Polygon Processing
- Terrain Preprocessing | Drainage Line Processing
- Terrain Preprocessing | Adjoint Catchment Processing

River basin processing

For the river basin processing, the following procedure within the ArcHydro Tool software was applied:

- Watershed Processing | Batch Watershed Delineation

The global precipitation raster map from the WaterGAP Global Hydrology Model (Döll and Fiedler 2008) was converted to a new raster with the same cell size and extent as the HydroSHED GRID inputs for each continent. To calculate discharge values for each dam location, the delineated dam basins were projected to continental Lambert Conformal Conic projections, with the exception of New Zealand, where the New Zealand map grid (NZMG) was used.

Discharge of dam catchments

To calculate the sum of runoff for each delineated dam catchment, a modified zonal statistics tool (Clark 2012) was used to deal with overlapping areas of the derived catchment polygons. The annual runoff raster grid (Döll and Fiedler 2008) provided input values used in calculating the output statistics for each dam catchment polygon. The tool calculates the sum of runoff (mm year^{-1}) as the sum of zonal statistics based on delineated dam catchments, which are based upon the values of the underlying annual runoff raster. Taking the cell size (m^2) into account, discharge was calculated as follows:

$$\text{Discharge } [\text{m}^3\text{s}^{-1}] = \frac{\text{sum of runoff } [\text{mm year}^{-1}] \times \text{cell size } [\text{m}^2]}{(365 \times 24 \times 60 \times 60)\ [\text{s year}^{-1}] \times 1000\ [\text{mm m}^{-1}]}$$

To determine whether regional projections provided sufficient resolution to process the discharge data accurately, a sensitivity analysis was undertaken based on a local projection (TUREF TM42) for the Coruh river catchment in Eastern Turkey, which lies at the Eastern extension of the European Lambert Conformal Conic projection and thus experiences the largest distortions of all grid cells when using a regional instead of a local projection. Discharge values were calculated as described above, except that the TUREF TM42 projection was used. A comparison of the discharge data calculated based on the two projections showed a mean relative difference of less than 2 %, indicating that the regional projection could be used invariably.

Based on the discharge information for each hydropower dam, the number of dams in five different discharge categories (<10, 10–100, 100–1,000, 1,000–10,000, $\geq$10,000 m^3 s^{-1}) was calculated for each major basin. This provides distribution patterns of dam locations within a river network and informs about the stream size classes likely to be most influenced by hydropower dams.

Discharge of major basins

The total water resources (km^3 year^{-1}) available within each major basin were calculated to assess the extent to which water resources are potentially exploited in major basins. This was done by following the same procedure as described above for the dam catchments using the major basin catchment area instead of the dam catchment polygon as the vector input. A density value, i.e. number of dams per water resources availability (km^3 per year), was then calculated for each major basin for both existing dams and a scenario combining existing and future dams.

Fragmentation of large river systems

Locations of future hydropower schemes were assigned to catchments of 292 large river systems (LRS) classified by Nilsson et al. (Nilsson et al. 2005) as "not affected", "moderately affected" or "strongly affected" according to their classification of river channel fragmentation and water flow regulation by dams. In total, 2611 hydropower dams out of our database are located within 108 of the LRS. Numbers of future dams were then summarized for each of the LRS to investigate which LRS might undergo initial or further fragmentation by future hydropower dams.

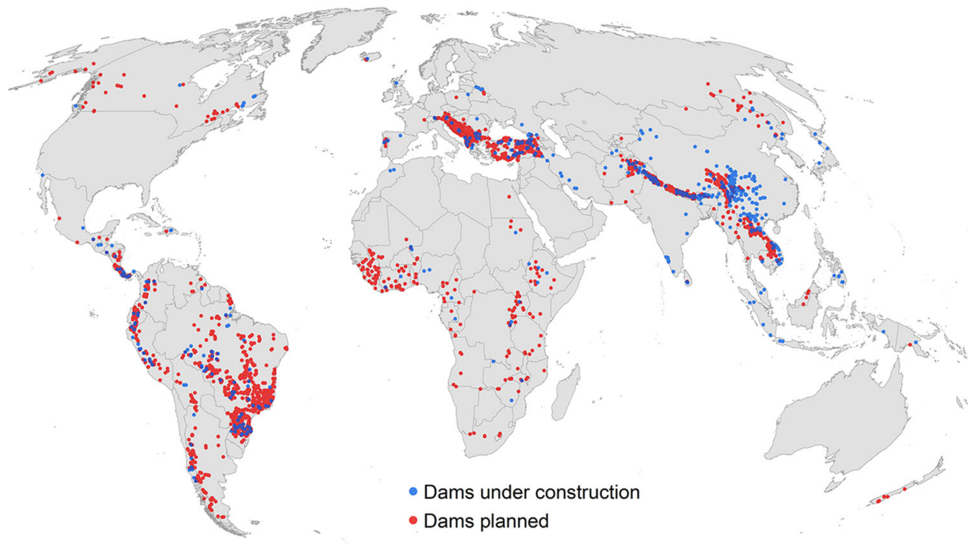

Fig. 2 Global spatial distribution of future hydropower dams, either under construction (*blue dots* 17 %) or planned (*red dots* 83 %)

Maps

All maps were drawn using the Mollweide projection, which provides a global representation of the major river basins that is accurate in area and true to scale along the equator and the central meridian.

Results

As of March 2014, a total of 3,700 hydropower dams with a capacity of more than 1 MW each were either planned (83 %) or under construction (17 %). These dams are predicted to increase global hydropower electricity capacity from 980 GW in 2011 (International Journal on Hydropower and Dams 2012) to about 1,700 GW within the next 10–20 years. Although small and medium-sized dams (1–100 MW) will dominate in number (>75 %), 93 % of the future hydropower capacity will be provided by 847 large dams with a capacity of more than 100 MW each.

Future hydropower development is primarily concentrated in developing countries and emerging economies of Southeast Asia, South America, and Africa. The Balkans, Anatolia, and the Caucasus are additional centers of future dam construction (Fig. 2, Online Resources Fig. S2, Table S2). More than 40 % of the hydropower capacity under construction or planned will be installed in low and low-middle income countries (GNI < $4,085 per capita; The World Bank 2014e), which excludes China ($5,720 GNI) and Brazil ($11,630 GNI) but covers hotspots such as the Democratic Republic of Congo ($230 GNI), Pakistan ($1260 GNI), and India ($1580 GNI).

The Amazon and La Plata basins in Brazil will have the largest total number of new dams in South America, whereas the Ganges–Brahmaputra basin (mainly India and Nepal) and the Yangtze basin (China) will face the highest dam construction activity in Asia (Fig. 3; Online Resource Tables S2, S3). Very large dams, each with a capacity of more than 1 GW, will primarily be located in Asia, especially in the Yangtze basin, and in South America, mainly in the Amazon basin (Online Resource Fig. S3). The Xi Luo Du dam in the Yangtze basin (14.4 GW) and the Belo Monte dam on the Xingú River in the Amazon basin (11.2 GW) are examples of very large dams already under construction.

Assuming the current efficiency of electricity production (GWh per year) per installed dam capacity (GW) and that all dams will be realized, China will remain the global leader in hydropower dam construction because it still has a remaining technically feasible potential of more than 1.8 million GWh per year. Nevertheless, China's share of total future global hydropower production will decline from currently 31 to 25 % because of a disproportionate increase in new hydropower dam construction in other parts of the world. In Africa, for example, out of the technically feasible hydropower potential (1.5 million GWh per year) less than 8 % are currently exploited (International Commission on Large Dams 2011). There, the focus is on the construction of large dams, each with a capacity of more than 100 MW (Online Resource Table S4).

Construction of the 3,700 dams worldwide may increase global hydropower production by 73 %, corresponding to an increase in the exploitation of the technically feasible hydropower potential from a total of 22 % today (International Commission on Large Dams 2011) to 39 %.

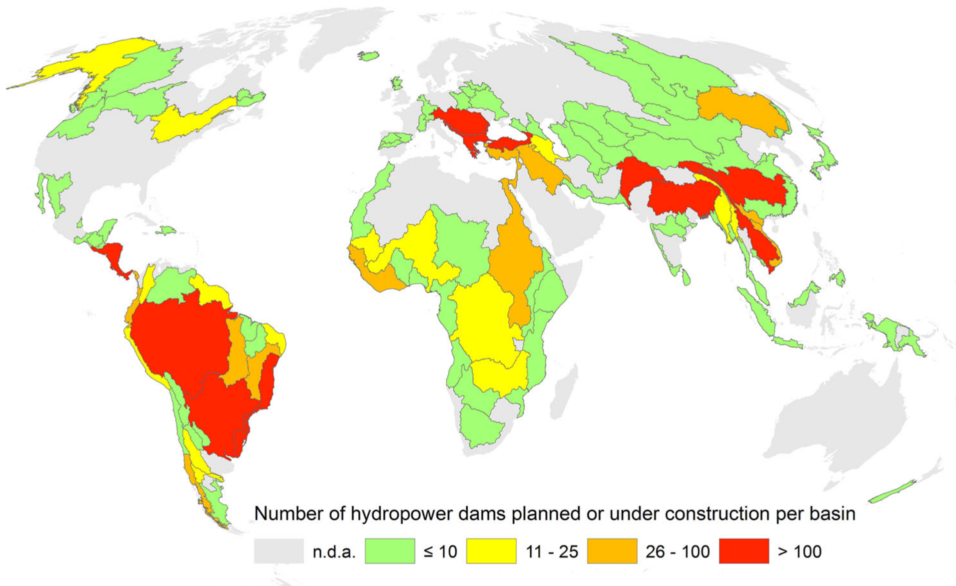

Fig. 3 Number of future hydropower dams per major river basin. *Red* >100, *Orange* 26–100, *Yellow* 11–25, *Green* ≤10, *Gray* no data available

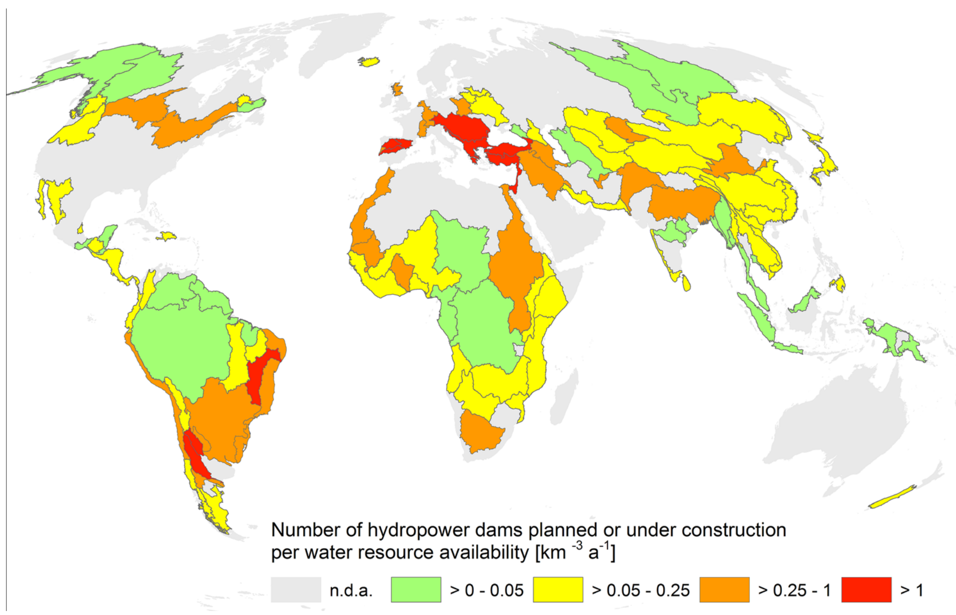

Fig. 4 Number of future hydropower dams in relation to major river basin discharge (dams per km^3 year^{-1}). *Red* >1, *Orange* >0.25–1, *Yellow* >0.05–0.25, *Green* >0–0.05, *Gray* no data available. For comparison with existing hydropower dams please see Online Resource Fig. S10

However, the share of hydropower in total global electricity production will rise only slightly from 16 % in 2011 to 18 % until 2040 because of the concurrent increase in global energy demand.

In regard to environmental impacts, our analyses show that the re-accelerating construction of hydropower dams will globally lead to the fragmentation of 25 of the 120 large river systems currently classified as free-flowing (Nilsson et al. 2005), primarily in South America (Online Resource Table S5). Worldwide, the number of remaining free-flowing large river systems will thus decrease by about 21 %.

We also gave a special focus to the evaluation of environmental consequences of dam building in basins that will experience high levels of water resource exploitation in relation to the discharge volume available (Fig. 4). In only a few cases, future dam building activities will concentrate on the high-discharge river segments (>100 m^3 s^{-1}), i.e. on large lowland river segments and main tributaries (Online Resource Table S7). The majority of basins will experience the exploitation of river segments with low discharge and high gradient, which goes along with the future high global share of small and medium-sized dams (<100 MW).

Earlier studies show that average CO_2 and methane emission rates amount to 85 g and 3 g per kWh (with an uncertainty factor of 2) of produced hydropower electricity (Barros et al. 2011; Hertwich 2013). This means, that future hydropower plants may add 280–1,100 Tg (1 Tg = 10^{12} g) CO_2 and 10–40 Tg methane to the atmosphere, which corresponds to 4–16 % of the global carbon emissions by inland waters (Raymond et al. 2013).

An economic perspective reveals that the 3-year-average investment in hydropower has increased more than sixfold in 2010–2012 in comparison to the 3-year average a decade ago (Maeck et al. 2013; Online Resource Fig. S4). Estimated investments total about 2 trillion US$ for all future hydropower dams currently under construction or planned, assuming average construction costs of large dams at 2.8 million US$ per MW (Ansar et al. 2014). With an average construction time of 8.6 years for a dam (Ansar et al. 2014), the annual investments for future hydropower dams may thus be as high as 220 billion US$.

Concerning the involvement of investors, about 35 investors contributed, for example, to the Brazilian hydroelectricity industry between 2010 and 2012, seven of which were investors from the USA, Spain, France, and Switzerland. In Africa, the main investors have been Hydromine (USA) and Sinohydro (China) with more than 1 billion US$ of investments contributing to the hydropower sector in Cameroon and Zambia, respectively (Online Resource Table S8).

Similarly, there is no correlation between future hydropower dam construction and the economic condition (GNI) of a country (Online Resource Fig. S5). Nevertheless, the future hydropower capacity per country increases with increasing rates of GDP growth (Online Resource Fig. S6), as well as with the technically feasible hydropower potential remaining (Online Resources Figs. S7, S8). The correlation with economic growth rates corresponds to the high industrial share (90 %) of future energy demand (OECD 2012).

In contrast, we found no correlation between the per-country estimate of the planned increase in hydropower capacity and the number of people lacking access to electricity. In India, for example, almost 300 million people lacked access to electricity in 2009, but the low technically feasible potential for hydropower in most parts of the country will prevent narrowing the electricity gap substantially, even if the entire potential were exploited. On the other hand, countries like the Democratic Republic of Congo and Brazil, where large proportions of the population lack access to electricity as well, exhibit an enormous potential for hydropower development (Online Resource Fig. S9). With the expansion of their hydropower capacity, these countries might seek to close their electricity access gap, which would require developing a national electricity grid. The expansion, however, might also be driven by private economic interests in exploiting the hydropower potential to export power or develop the industrial sector. Countries with a very low electrification rate (<20 %), such as Kenya and Tanzania, could already supply the whole population with electricity by their hydropower capacity installed at present, if it were not used by industry, for example, for mining operations. Pakistan and Nigeria are other examples for which the expansion of hydropower could allow the electricity access gap to be closed in the future. This assumes that the demand caused by rapid population growth in these countries (UN Department of Economic and Social Affairs, Population Division 2013) and increasing industrial requirements will consume only part of the expected electricity surplus generated by new hydropower dams.

Discussion

Our results show that hydropower will not be able to substitute non-renewable electricity resources such as coal, oil, and uranium. Even if the entire technically feasible hydropower potential will be exploited, which would correspond to a dam construction boom almost five times that currently estimated, hydropower would contribute less than half of the global electricity demand projected until 2040. Without any additional hydropower dam construction, however, its share in electricity production would drop to 12 %.

Although being a renewable electricity source, hydropower is also accompanied by significant environmental impacts on free-flowing rivers, ranging from fragmentation, which prevents free movement of organisms, to severe modification of river flow and temperature regimes and to dramatic reductions in sediment transport (Vörösmarty et al. 2010; Liermann et al. 2012). Future hydropower dam construction may affect some of the ecologically most sensitive regions globally. For example, the Amazon, Mekong, and Congo basins, which will be heavily impacted by future hydropower dams, jointly contain 18 % of the global freshwater fish diversity (http://www.fishbase.org). Similarly, the Balkan region, a hot spot area in hydropower development, is a key freshwater biodiversity region in Europe (Griffiths et al. 2004). Notably, hydropower dams under construction or planned within the currently free-flowing large river systems will contribute less than 8 % to the planned global hydropower capacity, ranging from 3 % in Africa to 10 % in Asia, and from 0.3 % of the total planned capacity in Brazil to more than 80 % in Malaysia, Papua New Guinea, and Guyana (Online Resource Table S6). This suggests that fragmentation impacts on the remaining free-flowing rivers in the world could be reduced by evaluating (transboundary) construction options in river systems already strongly fragmented to date. In East Africa, for example, fragmentation impacts could be reduced by abandoning hydropower dams in the Rufiji River, the last remaining large free-flowing river network in this region, while implementing compensatory capacities in the Nile and Zambezi Rivers, which are already heavily fragmented today. Of course, given the clustering of new dams in specific areas of the world, this is not a generally feasible strategy but should be considered in some regions.

It is known that hydropower is not a climate neutral electricity source (Wehrli 2011). Depending on the environmental and technical conditions, reservoirs can be important emitters of greenhouse gases (Maeck et al. 2013). Our estimations for methane and carbon dioxide emissions by future hydropower dams are a rough estimate because emissions depend on the location and morphometry of the reservoir but also on how the stored water is released from the reservoir (e.g. deep water or surface water release). Future hydropower plants will primarily be constructed in the subtropics and tropics, where greenhouse gas emission from reservoirs is estimated to be high, particularly during the first years after completion (Barros et al. 2011). According to IPCC (2014), estimated maximum emissions may even exceed by up to a factor 10 the emissions avoided by refraining from burning fossil fuel. On average, however, lifecycle GHG emissions of hydroelectricity are more than 30 times lower than that of coal (IPCC 2014), which underlines the need for attention to be paid to how to weigh the greenhouse gas emissions against the damage to water resources, biodiversity, and ecosystem processes and services.

These also include the direct and indirect consequence of relocating or displacing humans, especially of indigenous people, the loss of access to natural resources, and a highly disproportional distribution of economic benefits and costs for (international) companies, local governments and populations. Our results also demonstrate that the expected huge expansion of hydropower capacity will most likely fail to close the global electricity access gap. In addition, the increase of transboundary hydropower projects creates potential for conflict similar to that experienced among interdependent consumers of fossil and nuclear energy resources (Stone 2010; Online Resource Table S3). Thus, dams could intensify the complexity of resource demands for energy, water, flood prevention, and food supply (Vörösmarty et al. 2010; Costanza et al. 2014), which emanate from users and stakeholders with multiple social backgrounds and interests.

Hydropower dam construction and related investments are also a "transboundary", i.e. international, business. Our analysis on involved investors underlines a shifting geopolitical situation, with an increasing number of projects financed by internationally operating companies based in foreign countries. In general, these parties only seize investment opportunities but are not involved in project development or dam operation (McDonald et al. 2009). Nevertheless, most of the global investors follow the so-called equator principles, a credit risk management framework to ensure internationally-agreed minimum standards for social and environmental risk assessments (Equator Principles Association 2013). Concerning the estimated annual investment for the future hydropower dams of 220 billion US$, it must be noted that these costs include neither the operational costs of hydropower dams nor the gains through electricity production. Potential social and environmental costs are not included either.

Based on our analyses, it is evident that hydropower will not be a general or the only solution (1) to tackle the problems of growth in energy demand and climate change, (2) to close the electricity access gap, or (3) to erase interdependencies in electricity production. Indeed, we urgently need to advance existing regulatory guidelines and standards to create synergies, rather than trade-offs, among the different water users, including ecosystems. The Hydropower Sustainability Assessment Protocol (International Hydropower Association 2010) for evaluating the impacts of hydropower dams to be built provides a first step towards encompassing the environmental and social aspects of sustainability during the planning, implementation, and operation stages of hydropower dams. However, a participatory approach that includes the affected people is still missing in the protocol. The global database of future hydropower dams we present here may form a valuable basis to evaluate where to build hydropower dams, and how to improve the dam building management to support a systematic planning approach that includes environmental and social costs as well as the consultation of stakeholders and affected people.

Conclusion

Global population growth and increasing electricity demand on the one hand, and the urgent need to decrease greenhouse gas emissions on the other hand, lead to a new boom in the construction of hydropower dams worldwide. Despite the renewable nature of hydroelectricity, this technology also comes along with severe social and ecological adverse effects, e.g. relocation of people and transboundary conflicts, fragmentation of free-flowing rivers, and habitat changes, thus further threatening freshwater biodiversity. This does not necessarily need to be the case since we can develop sustainable ways of implementing and operating hydropower dams to optimize the production of renewable electricity while minimizing negative consequences. With our comprehensive synthesis of effort to map current and planned hydropower dam construction, we provide the basis to quantify and localize future hydropower dams on a global scale. This allows for a systematic management approach that takes network effects and cumulated impacts of multiple dams within a river basin into account.

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Conflict of interest The authors declare that they have no conflict of interest.

Compliance with ethical standards This article does not contain any studies with human participants or animals performed by any of the authors.

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