DFID Research on Dams/Hydropower and Low Carbon Growth

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1.1 Definitions for hydropower plants

Definition large hydropower: > 10 MW (> 25 MW in China, > 15 MW India)
Definition small hydropower: > 500 kW < 10 MW

There is no internationally agreed definition for 'small hydropower', though the most common definition for small hydropower is a hydropower plant with a size of < 10 MW installed capacity. In China small hydropower refers to < 25 MW installed capacity and in India it refers to < 15 MW.
Sometimes small hydropower is further divided into mini hydropower < 2MW, micro hydropower < 500 kW and pico hydropower < 10kW (Paish, 2002a; Paish, 2002b; ESHA, 2009; Yuksek et al., 2006). Small hydropower does not involve the construction of large dams and reservoirs and is mainly based on river run-off (Yuksek et al., 2006).

1.2 Potential

The World Energy Council estimates that there is a global potential of more than 41,202 TWh/year (4,703 GW) of hydropower with a technically exploitable potential of more than 16,494 TWh/year (1,883 GW) (WEC, 2007). At the end of 2005, globally 778 GW were installed and another 124 GW were under construction (WEC, 2007).
In 2005, only about 5% of the global hydropower potential had been exploited through small hydro power (IEA, 2007), although this has increased in recent years with the rapid rise in small hydro power development in China, which was more than 50 GW installed small hydropower capacity in 2006 (UNEP, 2007). The main barriers to small hydropower are limited access to transmission facilities and social and environmental concerns (IEA, 2007).
The technically feasible potential for small hydropower is estimated at about 200 GW (1,752 TWh/year) (Naidu, 1998; IEA, 2007), so at about a tenth of the global technically feasible hydropower potential, whereas the estimated potential for large hydropower is about 1,663 GW. See table 1 for details.
The potential for micro, mini and pico hydropower among the small hydro power potential seems to be yet unknown. It also seems to be unclear how high the global potential is including pumped storage.

Size	Global potential*	References
Large and small hydro power	1,883 GW (16,494 TWh/year)	WEC, 2007
Large hydropower	1,663 GW (ca. 14,600 TWh/year)	Naidu, 1998; IEA, 2007
Small hydropower	200 GW (ca. 1,800 TWh/year)	IEA, 2007

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Table 1: Global potential for different sizes of hydropower plants. *Note that this is the technically exploitable potential.

1.4 Costs

The IEA reports that large hydropower is one of the lowest cost options in the electricity market today (IEA, 2007). The investment costs for new large hydropower plants in the OECD are about 2,400 US$/MW and the operation costs are between 0.03 US$/kWh and 0.04 US$/kWh (IEA, 2007). The investment costs for new small hydropower plants in Europe are about 1,200-3,500 Euros/kW (1,500-4,500 US$/kW) (ESHA, 2009) and the operating costs for small hydropower are between 0.02 US$/kWh and 0.06 US$/kWh with the lowest costs occurring in areas with good hydroelectric resources (IEA, 2007). Micro hydropower usually has investment costs of about 2,500-3,000 US$/kW (Paish, 2002a; Paish, 2002b). Costs for micro hydro can vary depending on the site and the country and have been reported to sometimes even exceed 10,000 US$/kW (Paish, 2002a; Paish, 2002b). On the other hand, costs can also be minimized to 1,000 US$/kW for micro hydro when local resources and indigenous expertise and technology is used (Paish, 2002a; Paish, 2002b). Costs in developing countries are often cheaper than in industrialised countries, especially for large hydropower (Paish 2002a; Paish, 2002b). Particularly operating costs tend to be lower. See table 2 for details.
The lifetime of a hydro power plant can be up to 50 years and once investments costs are paid off, plants can operate at even lower cost levels (IEA, 2007).

Size	Investment costs	Operating costs	References
Large hydropower	2,400 US$/MW	0.03 US$/kWh – 0.04 US$/kWh	IEA, 2007
Small hydropower	1,500 – 4,500 US$/kW	0.02 US$/kWh – 0.06 US$/kWh	ESHA, 2009; IEA, 2007
Mini hydropower	1,500 – 4,500 US$/kW	0.02 US$/kWh – 0.06 US$/kWh	ESHA, 2009; IEA, 2007
Micro hydropower	2,500-3,000 US$/kW*	Unknown	Paish, 2002a; Paish, 2002b
Pico hydropower	2,500-3,000 US$/kW*	Unknown	Paish, 2002a; Paish, 2002b

Table 2: Costs for different sizes of hydropower plants. *Investment costs for micro and pico hydropower can vary from between 1,000 US$/kW to 10,000 US$/kW depending on site and local resources.

2. Greenhouse gas emissions

Sources of greenhouse gas emissions from hydroelectric dams and reservoirs:

- Greenhouse gas (GHG) emissions due to the industrial production of the dams, mainly from the production of concrete, steel and power lines for connection with the nearest grid (Rashad and Ismail, 2000). However all power plants have GHG emissions from their production, transport and waste phase. These GHG emissions can be assessed using life cycle analysis. Life cycle analysis shows that the GHG emissions from both large and small hydropower are similar to those of other renewable energy and are significantly below those of fossil fuel plants (Gagnon et al., 2001; Ewan et al., 2008).

- Emissions from bacterial decomposition of organic material underwater after flooding of the vegetation (Rosa et al., 2004). Gases emitted are mainly nitrogen, carbon dioxide and methane. There is uncertainty about whether methane emissions depend on the age of the dams, some studies indicate that methane emissions are higher in the first years after the reservoir filling (Fearnside, 2002; Rashad and Ismail, 2000), while other studies indicate an independence from age (Ruiz-Suarez et al., 2003; Rosa et al., 2004). The carbon content in tropic ecosystems is higher than that of boreal and grass land ecosystems, so that more GHG emissions are emitted from tropical dams (Rashad and Ismail, 2000).
- Emissions from above-water decay: aerobically decay of biomass which has not been completely flooded and parts are above the water surface (Fearnside, 2002). This is however only assessed in studies by Fearnside (2002) with average emissions about 0.678 kg CH_4/ha/year.
- Emissions from turbines and the spillway: Fearnside (2002) mentions that methane emissions might vary depending on the turbine inflow and outflow and the quantities of water transported on the spillway. He distinguishes between high-flow and low-flow and talks about 'methane export' through the turbines/spillway. This phenomenon is however not mentioned in other studies. Rosa et al. (2004) suggest that Fearnside is counting similar effects double, so that GHG emissions are counted double. Other studies only take into account the emissions from the bacterial decomposition of organic material underwater after flooding.
- Fearnside (2002) also calculates the net GHG emissions from loss of forest resources and carbon sinks which are in the range of 0.1 Mt CO_2 equivalents/ha/year for the Tucurui hydropower dam in Brazil. Other studies do not take this phenomenon into account.

The International Hydropower Association reports that GHG emissions occur naturally from many wetland ecosystems, such as bogs, marshes, swamps, floodplains and lakes (IHA, 2005). The GHG emissions from reservoirs are similar to those from other wetland ecosystems. The IHA further reports that measuring the emissions from the surface of the reservoirs is misleading. Instead, net emissions should be calculated which should consider the emissions from ecosystems before the creation of the reservoir. "To define 'net' emissions, it is essential to look at the different ecosystems that are replaced by freshwater reservoirs" (IHA, 2005). Also, methane is mentioned often in relation to emissions from hydropower. The IHA (2005) however reports that methane emissions account only for 1% of the total GHG emissions from reservoirs while CO_2 accounts for 99%.

Small hydropower plants, and particularly micro and pico hydropower plants, usually have fewer impacts on GHG emissions, because they are mainly from river run-off and often do not have any reservoirs.

The environmental impacts of reservoirs are not only important for large hydropower plants, but also for other reservoirs such as freshwater reservoirs used for drinking water.

The comparison of GHG emissions from hydropower plants can be difficult, because different units are used in different studies (e.g. mg/m2/day, kg/km2/day, Mtons/year, g/kWh, kt/TWh etc). The most important GHG emission ranges and findings are summarised in table 3.

Size	Location / climate	Emissions	Findings and possible mitigation measures	References
Large	Brazil (7 sites, in tropical climate (vegetation: rain forests, savannah) and in coastal Atlantic climate (vegetation: Atlantic forest)).	Tucurui: 8,000 kg CO_2/km2/ day (2.92 Mtons CO_2/km2/year) Samuel: 7,000 kg CO_2/km2/ day Xingo: 6,000 kg CO_2/ km2/day Tres Marias: 1,000 kg CO_2/km2/ day Miranda: 4,000 kg CO_2/km2 /day Barra Bonita: 3,800 kg CO_2/ km2/day Segredo: 2,100 kg CO_2/km2/ day Tucurui: 100 kg CH_4/km2/ day Samuel: 100 kg CH_4/ km2/day Xingo: 40 kg CH_4/ km2/day Tres Marias: 190 kg CH_4/km2/ day Miranda: 150 kg CH_4/km2 /day Barra Bonita: 10 kg CH_4/km2/ day Segredo: 5 kg CH_4/km2/day	The highest CO_2 emissions were measured in the dams located in rain forest, the lowest CO_2 emissions were measured in dams located in the Atlantic forest. The highest CH_4 emissions were measured in the dams located in the savannah, the lowest CH_4 emissions were measured in dams located in the Atlantic forest. Mitigation measures: Prioritising the building of dams in cooler (coastal) areas in the tropics instead of in rain forests/savannahs might mitigate emissions. Variations due to temperature, measurement depth, wind, sunlight, water parameters, biosphere composition and dam operating systems (power density) were noticed. It seems to be very difficult to separate anthropogenic emissions from those occurring from the dam (e.g. carbon from biomass in soil, sewage, waste water and fertilisers swept down from upstream drainage basins into thereservoirs). It also seems to be difficult to separate the organic matter produced by the lake itself (e.g. phytoplankton) from that occurring from the dam. Uncertainty remains high.	Rosa et al., 2004
Large	Brazil (Tucurui), tropical	Open water (mean): 37 mg CH_4/m2/day	Mitigation measures: The emissions seem to be highest when dead trees	Fearnside, 2002

	climate, tropical vegetation (rainforest)	Macrophyte beds (mean): 70 mg CH_4/m2/day Standing dead trees (mean): 210 mg CH_4/m2/day Weighted emissions: 117 mg CH_4/m2/day The total emissions from above-water decay, the reservoir surface, the turbines, the spillway and the loss of carbon sinks adds up to emissions of 7.03 – 10.11 Mtons CO_2 equivalents/year. Fearnside also mentions other studies which calculated the emissions for Tucurui which range between 0.07 – 3.1 Mtons CO_2 equivalents/year (Fearnside 1995 (3.1 Mtons); Rosa and Schaffer, 1995 (3 Mtons); Novo and Tundisi, 1994 (0.49 Mtons); Rosa et al., 1996/1997 (0.07 Mtons); Matvienko et al., 2000 (0.57 Mtons) and Matvienko and Tundisi, 1997 (0.08 Mtons)).	are standing in the reservoir. Vegetation removal might possibly reduce a share of these emissions.	Other literature suggests that Fearnside's emission results might be too high (Rosa et al., 2004).
Large	Mexico (Aguamilpa), tropical climate, tropical vegetation	Near the hydropower dam wall: - 455 µg CO_2/m2/h (-10.9 mg/day), 417 µg N_2O/m2/h (10 mg/day), -2.6 µg CH_4/ m2/h (0.06 mg/day) Near the side with less flooded vegetation underwater: 202 µg CO_2/m2/h (4.8 mg/day), -72.7 µg N_2O/m2/h (1.7 mg/day), 20 µg CH_4/ m2/h (0.5 mg/day) Near the side with possibly more flooded vegetation underwater: 417 µg CO_2/m2/h (10 mg/day), 88.1 µg N_2O/m2/h (2.1	CO_2 and CH_4 emissions seem the highest where more vegetation is underwater, N_2O emissions are the highest near the dam wall. Mitigation measure: Vegetation removal might possibly reduce a share of these emissions. Variations due to seasonality and weather were noticed.	Ruiz-Suarez et al., 2003 This study is the only one which uses the unit µg/m2/h while other studies use mg/m2/h. It seems to be that µg is incorrect and should be mg, so that the emissions are comparable to those of other studies.

		mg/day), 66.6 µg CH_4/ m2/h (1.6 mg/day)		
Large	Global (northern temperate climates and tropical climates)	Average CH4 emissions from reservoirs: 90 mg CH4/m2/day. Average CH4 emissions from other wetland ecosystems: marshes: 253 CH4/m2/day, floodplains: 100 mg CH4/m2/day, swamps: 84 CH4/m2/day, lakes: 43 CH4/m2/day, bogs: 15 CH4/m2/day. Gross emission factors for reservoirs in northern temperate regions: < 40 kt CO2 equivalents/TWh. Net emissions considering pre-impoundment emissions: 10 kt CO2 equivalents/ TWh. Emission factors for reservoirs in tropical regions: there seems to be much controversy about it. Coal-fired power plants emit about 100 times more GHG emissions and natural gas combined cycle turbines emit about 40 times more GHG emissions than hydropower reservoirs.	The IHA assumes that natural wetlands produce about similar emissions like reservoirs. They also report that the loss of carbon sinks by flooding of forests is not considered significant and that reservoirs can even be larger carbon sinks than the ecosystem which they replace.	International Hydropower Association, 2005.
Large	Global	Gross emissions: 1-28% of global warming potential of GHG emissions might be from hydropower. Hydropower may emit about 10 times fewer emissions than thermal options in some cases and may emit more than thermal options in other cases. Emissions from reservoirs seem to be higher in tropical regions than in temperate regions. Average GHG emissions from reservoirs: Brazil: 50-4,000g CO2/m2/year, Canada: 600-1400g CO2/m2/year,	Mitigation measure: Environmental offsetting: e.g. in India it is a legal requirement that the forests flooded by reservoirs must be replanted elsewhere. In reality, only half of the required forest area is typically been planted. Other mitigation options might be to set up an additional compensatory trust fund to manage parts of the revenues and use if for environmental purposes like for National Parks, e.g. proposed for Laos. Emissions vary from year to year and large uncertainties	World Commission on Dams, 2001.

		Finland: 900-1450g CO_2/m2/year.	exist.	
Large	Global (northern temperate climates and tropical climates)	Methane emissions from dams and reservoirs: 75 Mtons/year, conventional energy production 95 Mtons/year. Examples hydropower emissions from dams and reservoirs: Canada: < 75-90g CO_2 equivalents/kWh, Tropics: 3,280 – 30,250g CO_2 equivalents/kWh. Emissions from other fuels: Lignite: 1,150-1,270g CO_2 equivalents/kWh, Coal: 790-1,200g CO_2 equivalents/kWh, Heavy Oil: 690-730g CO_2 equivalents/kWh, Diesel: 5550-880g CO_2 equivalents/kWh, Combined-Cycle Natural Gas: 460-760g CO_2 equivalents/kWh, Photovoltaic: 30-210g CO_2 equivalents/kWh, Biomass energy: 17-210g CO_2 equivalents/kWh, Wind: 7-40g, Nuclear: 2-60g CO_2 equivalents/kWh	Dams and reservoirs seem to have much lower GHG emissions in northern temperate regions than in tropical regions. They seem to have higher emissions in the tropics compared to many other fuels, but seem to have emissions comparable to other renewable energy technologies (e.g. PV) in moderate climates.	International Rivers Network, 2002
Large	Egypt	Emissions hydropower Egypt: 410 g CO_2/kWh Carbon content of tropic ecosystems before flooding: 20 kg C/m2, grasslands: 0.7 kg C/m2, boreal ecosystems are about 10 km C/m2	Parameters which determine the GHG emissions from hydropower dams are the geomorphology of the reservoir, the electrical capacity of the plant, the composition of the dam e.g. earth/rock vs concrete.	Rashad, S.M. and Ismail, M.A., 2000.
Large and small	Global	GHG emissions from hydropower: 1 – 250g CO_2/kWh, average value is 41 CO_2/kWh, which is comparable with GHG emissions from wind, solar PV and geothermal energy	Life cycle analysis shows that hydropower has comparable emissions to other renewable energy technologies and that these emissions are lower than the emissions from fossil fuel plants.	Evans et al., 2008
Large and small (river-run-off and reserv oir)	Global	GHG emissions from large hydropower with reservoir: 15 kt CO_2 equivalents/TWh. GHG emissions from small hydropower without reservoir (river run-off): 2 kt CO_2 equivalents/TWh.	Both large and small hydropower plants have significantly lower GHG emissions than fossil fuel plants when their whole life cycle is considered. Emissions are site-specific,	Gagnon et al., 2001

		Emission factor large hydropower (with reservoir): 60 times lower than modern coal-fired generation, even lower emissions for river run-off. Other emissions like NOx and SO2 are also very low when considering the life-cycle of hydropower plants in comparison to fossil fuel plants.	depending mainly on whether there is a reservoir or not (with the reservoir having higher emissions) and the following factors: area of reservoir, amount of flooded biomass (500t/ha for tropics vs 100t/ha for boreal climate). Uncertainty remains on the emissions from flooded biomass. Mitigation measure: building smaller hydro power plants without a reservoir / water management for decreasing reservoir size. Disadvantages: lower electric output, lower efficiencies, lower flexibility.	

Table 3: GHG emissions from hydropower plants.

To conclude, the most important GHG emission sources seem to be bacterial decomposition of organic material underwater and GHG emissions from the production phase of hydropower plants.

Many studies seem to agree that GHG emissions from hydropower plants range between 1-30,250g CO_2 equivalents/kWh with small hydro power and hydropower in cooler climate being at the lower end of the scale and large hydro power and hydropower in the tropics being at the upper end of the scale (Rashad and Ismail, 2000; Gagnon et al, 2001; International Rivers, 2002; IHA, 2005; Evans et al., 2008). The average seems to be about 40 – 45g CO_2 equivalents/kWh (Gagnon et al, 2001; IHA, 2005; Evans et al., 2008).

It seems to be a widely accepted fact that there are GHG emissions from hydropower plants. Most studies however agree that hydropower produces less GHG emissions during their lifetime than fossil fuel plants, namely between 10-10 times less and that GHG emissions from hydropower are comparable to those of other renewable energy technology (Gagnon et al., 2001; World Commission of Dams, 2001; IHA, 2005).

There seems to be a degree of uncertainty about how much carbon dioxide and methane is emitted per m2 or km2 per dam. In general, variability is large due to various factors such as climate, amount of biomass flooded, size of reservoir and measuring depth.

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