Ramos, F.M., L.A.W. Bambace, I.B.T. Lima, R.R. Rosa, E.A. Mazzi and P.M. Fearnside, nd. Methane stocks in tropical hydropower reservoirs as a potential energy source: An editorial essay. *Climatic Change* (in press)

ISSN: 0165-0009

Methane stocks in tropical hydropower reservoirs as a potential energy source

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Abstract

Several studies over the last decade have shown that tropical reservoirs constitute an appreciable source of methane (CH_4) to the atmosphere. In countries like Brazil, construction of a substantial number of new dams could be averted by the promotion of energy efficiency and elimination of subsidies for energy-intensive export industries like aluminum smelting. But for the expansion of generating capacity, locally produced hydropower is seen as strategically preferable to generation from fossil fuels, imported from increasingly unreliable external sources. Within this context, we propose a promising approach to deal with the existing methane stocks and corresponding emissions: regard them as a potential clean and renewable energy source, i.e., a valuable commodity. Our estimates indicate that this proposal is economically viable and may increase considerably the energy supply in countries that possess large tropical reservoirs.

1. Introduction

Presently, hydropower represents an important fraction of the total energy supply in many countries. In Brazil, for example, this figure reaches 14%, and hydropower alone accounts for more than 95% of the national electricity production (Brazil, ANEEL, 2005). While fossil fuel contributions to global warming are well known, the impact of hydroelectric dams, in terms of greenhouse gas (GHG) emissions, is only now beginning to be unveiled. Hydroelectric reservoirs are classified as land-use changes according to the International Panel on Climate Change (IPCC), and countries with large areas covered by reservoirs should work to reduce uncertainties regarding the role of hydropower in climate change. Emissions are especially high in large tropical reservoirs built over densely forested areas, where there is a large input of organic matter, the average temperature is high and there are large areas with anoxic conditions at the bottom of the water column.

Several studies over the last decade have shown that tropical reservoirs constitute an appreciable source of methane (CH_4) to the atmosphere (Novo and Tundisi, 1994; Duchemin et al., 1995; Fearnside, 1995, 1997; Abril et al., 2005; Kemenes et al., 2007; Pacca, 2007; Lima et al., 2008). Moreover, recent data indicate that CH_4 degassing from water passing through the turbines and spillways may represent an important share of the total GHG budget of tropical reservoirs (Fearnside, 2002; Delmas et al., 2004; Abril et al., 2005; Guerin et al., 2006). Turbines degas up to 70% of the total reservoir emissions (e.g., Tucuruí Dam in Brazilian Amazonia) (Fearnside, 2004). Annual flooding of the herbaceous vegetation that regrows when drawdown areas are exposed at low water levels can provide a renewable source of methane that make the tropical reservoirs virtual methane factories (Fearnside, 2005a, 2008). In some cases, reservoir emissions surpass the GHG that would have been emitted by generating the same amount of electricity from oil (Rosa and dos Santos, 2000, Fearnside, 2005b).

The environmental and social impacts of new hydroelectric projects are very great, and in countries like Brazil a substantial amount of new dam construction could be averted by the promotion of energy efficiency and the elimination of subsidies for energy-intensive export industries like aluminum smelting (Fearnside, 2006). But for the expansion of generating capacity, locally produced hydropower is seen as strategically preferable to generation from fossil fuels, imported from increasingly unreliable external sources. A move towards nuclear energy is prevented, at least in the near future, by both cost and safety concerns. Within this context, we propose a novel and promising approach to deal with two important questions: how to mitigate the climatic impact of existing hydropower infrastructure, and how to ease the pressure for the construction of new reservoirs in tropical forest areas. Our approach turns the problem upside down. Instead of considering the existing methane stocks (and corresponding emissions) as a nuisance, we regard them as a potential renewable energy source (i.e., a valuable commodity), cleaner than burning the corresponding quantity of oil or natural gas.

2. Methane Production

Carbon emissions from reservoirs and wetlands in general depend on a wide range of geographical, geophysical, biochemical and other factors (Duchemin et al., 2000; St. Louis et al., 2000; Melack et al., 2004; Whalen, 2005). Carbon dioxide and methane are produced from the decomposition of organic matter. In tropical reservoirs, the main sources of organic matter are the original vegetation that is flooded, dissolved and particulate organic carbon swept from neighboring shores and drainage basins, and biomass that grows within the reservoir itself. Methane is produced under anaerobic conditions at the bottom of a reservoir, acetate and CO_2 reduction being the main methanogenic pathways (Cicerone and Oremland, 1988). Per ton of gas, CH_4 has 21 times more impact on global warming than CO_2, considering the 100-year global warming potential (GWP) adopted by the Kyoto Protocol (Schimel et al., 1996), and 25 times more impact if the most recent estimate of the Intergovernmental Panel on Climate Change is used (Forster et al., 2007, p. 212).

Methane fluxes at the reservoir surface, particularly through bubbling, are smaller in deeper water because they have a higher probability of being oxidized before reaching the water-air interface (Keller and Stallard, 1994, Joyce and Jewell, 2003). Large, deep tropical reservoirs are often thermally stratified, with a thermocline usually at roughly 10 m below the surface, which prevents water mixing and diffusion between deep and shallow waters (Fearnside, 2004). This situation favors a CH_4 concentration profile that increases rapidly with depth until the local saturation level is reached, following a pattern that may differ from reservoir to reservoir, or even within the same reservoir. This variability depends on the amount of flooded organic matter, allochthonous inputs and water redox condition. For example, reservoir secondary branches, which usually have slower water flow and greater carbon inputs than the main channel, tend to have a higher concentration of CH_4 (Lima et al., 1998). Methane concentrations also fluctuate over time in a way that correlates with the variations in climate and weather variables such as temperature and precipitation (Lima, 2005; Nozhevnikova et al., 1997).

The fact that deep waters are almost saturated with methane explains why turbine degassing is so important in many large tropical reservoirs. The cause of this scenario is quite simple but has frequently been overlooked in estimates of reservoir emissions. Since water intakes are generally located well below the surface and CH_4 concentration strongly increases with depth, much of the dissolved methane is quickly degassed when the pressure drops as the water passes through the turbines. This is more or less what happens when one opens a bottle of a soft drink (Fearnside, 2002, 2004). The solubility of the gas is higher under pressure in the closed bottle than it is when the pressure is released by opening the bottle. This is the result of Henry's law, which states that, at a constant temperature, the concentration of a solute gas in a solution is directly proportional to the partial pressure of that gas above the solution.

3. Mitigation and Methane Recovery Measures

As a basic premise, we assume that engineering solutions to CH_4 emissions should not imply any major modification of the already existing energy-producing infrastructure. From this starting point, it is clear that any simple and cost-effective mitigation strategy must be based on ensuring that only shallow, methane-depleted waters reach the intakes of the turbines and spillways. This could be achieved by using light metal structures or even membranes as barriers, associated with buoys and anchors, to control their position relative to the water surface (for details, see Bambace et al., 2007). Proper barrier dimensioning can ensure a negligible impact on the overall energy production efficiency of the dam. Other designs for CH_4 capture have been proposed (Kemenes and Fosberg, 2008).

The adoption of mitigation strategies implies that the amount of CH_4 that would be degassed downstream from water passing through the turbines and spillways remains in the reservoir and will be either oxidized by methanotrophic bacteria or transformed into new reservoir surface emissions. As a result, methane concentration in the main channel of the reservoir tends to increase, approaching the levels characteristic of secondary branches. In tropical reservoirs like Tucuruí, where the amount of methane produced is on the order of megatons per year (Fearnside, 2004), mitigation and CH_4 recovery strategies must be implemented jointly to be fully effective.

Considering the high concentration of methane in deep reservoir waters, systems similar to today's swimming-pool aspirators could do the job. The working principle is very simple: methane-rich, pressurized, deep waters are transported to surface ambient conditions, where the dissolved gas can be extracted by bubbling or by spraying into a sealed vessel (for details, see Annex). A similar approach has already been successfully implemented for degassing CO_2 from lakes Nyos and Monoun (the so-called "killer lakes") in Cameroon (Kling et al., 2005). Light and scalable, the extraction system could be moved from one site to another whenever an exploitation zone becomes poor in CH_4. If the water is collected at depths greater than 50 m within the methane saturation zone, the gas recovered will have a partial CH_4 pressure in the range of 36 to 80% (the rest being mainly N_2 and CO_2), suitable for stationary applications. Later, the methane may be pumped to large consuming centers, stocked locally and burned in gas turbines to generate electricity during high demand periods, or even purified for transport applications. The stoichiometric air/fuel mass ratio of CH_4 is 10, so the mass of impurities is low compared to the mass of air, and the impact of impurities from the burning process is small. For transport applications, the CH_4 must be purified from CO_2 with soda lime or quicklime systems in order to avoid a large increase in the size of the storage tanks needed in vehicles. The impact of N_2 on storage-tank volume is estimated to be below 10%.

The dynamics of gas-liquid separation is modeled in Bambace et al. (2007). From this model, for a given methane concentration in the water, optimal operating conditions (maximum methane output, for example) may be derived. Figure 1 presents the global efficiency of the CH_4-extraction system, defined as the ratio between the net methane output mass (i.e. the extracted gas minus the methane used to run the extraction system, considering a 23% engine efficiency) and the total CH_4 mass available in the water, as a function of the CH_4 concentration. A methane concentration above 6 g/m^3 yields a global efficiency higher than 40%. On the other hand, for concentrations levels below 3 g/m^3, the net energy output is negative and, thus, the operation is unfeasible. Tropical reservoirs present a wide range of methane concentrations. At Petit Sau in French Guiana, for example, Abril et al. (2005) measured a concentration of 12 g/m^3 in the main channel (low water, Roche Genipa station, 27 m depth), which assures an extraction efficiency of approximately 66%. In Tucuruí, a concentration of 6 g/m^3 of CH_4 was measured at the turbine entrance (high water, 30 m) (Fearnside, 2002). However, methane levels are higher at greater depths, and in reservoir secondary branches, which usually have slower water flow (Lima et al., 1998). More importantly, with the adoption of mitigation strategies, the methane concentration in the main channel will increase, approaching the levels characteristic of secondary branches.

4. Economic and Political Aspects

In order to evaluate the economic impact of methane mitigation and recovery systems, we considered five illustrative cases in our simulations: Tucuruí, Curuá-Una, Samuel and Balbina, in Brazil, and Petit Saut, in French Guiana. All five are representative tropical reservoirs, built more than a decade ago over densely forested areas in the Amazon region, and where the rapid decay of soft plant parts from the original watershed vegetation cover is probably complete. For the Petit Saut reservoir, we considered data from Abril et al. (2005), who recently published the longest and most complete study on GHG emissions from a tropical reservoir. In this study, the emissions of CO_2 and CH_4 from the Petit Saut hydroelectric reservoir (Sinnamary River, French Guiana) to the atmosphere were quantified for 10 years since impounding in 1994. After 10 years of impoundment, the total flux of CH_4 to the atmosphere amounted to 0.021 ± 0.008 Mt/y. Methane has a combustion heat of 55.7 MJ/kg. Thus, 1 Mt/y of CH_4 corresponds to an equivalent power production of 1760 MW. Even considering only the degassing at the outlet of the dam, the CH_4 emissions downstream of the turbines and spillways in Petit Saut correspond, in terms of equivalent electric power, to a considerable fraction of the hydroelectric installed capacity, ranging from 14% to 31% (see Table 1). We made similar estimates for the Brazilian reservoirs of Tucuruí, Curuá-Una, Samuel and Balbina, using data published in Fearnside (2004), Fearnside (2005b), Fearnside (2005c) and Kemenes et al. (2007), respectively. The CH_4 equivalent electric power for these four cases ranges from 22 MW, in Curuá-Una, to more than 2000 MW, in Tucuruí. The ratio between the CH_4 equivalent electric power and the hydroelectric installed capacity averages 37%, with a minimum of 14% (Petit Saut) and a maximum of 55% (Curuá-Una). Note that these are very conservative estimates since we only considered the CH_4 emitted downstream of the outlet of the dam, and not the amount of gas that is actually *produced* within the reservoir, which is much larger. In fact, most CH_4 produced in large deep tropical reservoirs like Tucuruí is consumed by oxidizing bacteria (Abril et al., 2005; Lima, 2005). In Balbina, 40% of the CH_4 that passes through the turbines is oxidized within the river before reaching the atmosphere (Kemenes et al., 2007). In Petit Saut, downstream in the Sinnamary river, the emission/oxidation ratio is not much different and ranges from 0.35 to 0.62 (Abril et al., 2005). Consequently, the potential energy production by our CH_4 recovery strategy is probably much higher, provided the gas is collected from deep, anoxic waters, in different extraction zones of the reservoirs.

Tables A1 and A2 in the Annex present a detailed description of equipment, operational and maintenance costs, for the spraying extraction system, assuming a water flow rate of 10 m^3/s. Since all technologies are off-the-shelf, unit prices have been obtained directly from appropriate Brazilian suppliers. Based on these figures, we estimated the in situ extraction cost (in US$ per million BTUs) as a function of the CH_4 concentration in the water, considering differing scenarios for the Brazilian market interest rate and the depreciation period. Results are presented in Fig. 2. For 10 g/m^3, extraction costs range between a minimum of 4.4 US$/MMBtu (6% interest rate and 20-year depreciation period) and a maximum of 5.5 US$/MMBtu (15% and 10 years). To the costs estimated above, a transportation cost from the extraction sites to the main distribution unit on the reservoir shore should be added. Considering an average transport distance of 90 km, a value of 0.78 US$/MMBtu was estimated, based on similar systems operated by the Brazilian gas industry in the Amazon region.

The overall extraction cost should be compared to the price of natural gas on the international market. Currently, natural gas imported from Bolivia is distributed in the Brazilian market at a price of 7.8 US$/MMBtu, transport costs included. At this price, methane extraction requires a concentration of at least 7 g/m^3 to be economically profitable, in the worst case scenario, or slightly below 8 g/m^3, in the best case scenario. Profitability may increase by reducing the extraction costs through a larger scale of operation, government subsidies and technological improvements, or by higher gas prices on local and international markets. Although the long-term trend points towards higher prices, in 2008 natural gas spot prices at Henry Hub fluctuated from a minimum of 7 US$/MMBtu to a maximum of 14 US$/MMBtu.

The economics of methane capture also depend on whether the gas will be burned locally or transported to distant consuming centers. In the Amazon region, considering the lack of pipeline systems, an interesting approach is to take advantage of the existing electricity transmission lines and install thermoelectric plants in the vicinity of the reservoir sites. Beyond 100 MW of electrical power, efficient and cost-effective gas turbines are readily available in the market. End users for this energy may be the industrial district of Manaus (located 196 km from Balbina) or the large aluminum plants installed near Tucuruí, which are already facing energy shortages. Naturally, depending on the scale of the operation, transmission lines to large end users or to the Brazilian integrated transmission network may be upgraded. The amount of investment needed is probably smaller than building new transmission lines since it does not require new environmental licenses or expensive land expropriations or acquisitions.

Disregarding the costs of electricity generation or gas transportation to distant consumer centers, we estimate US$ 1.5 million as the investment needed to collect 2000 t-CH_4/y, at a concentration of 10 g-CH_4/m^3 and a flow rate of 10 m^3/s. Annual operational and maintenance (O&M) costs are on the order of 3% of the total investment, or US$ 45,000 per year. Considering a gas price of 7 US$/MMBtu, the gross revenue reaches US$ 84,000 per year. These figures assume an internal rate of return of 6%, considering a depreciation period of 20 years. Considering a large-scale production of 1 Mt-CH_4/y, the investment needed, including the logistics of gas transport from distant collecting locations, increases to US$ 750 million. With O&M costs of US$ 22.5 million per year, this scenario implies a net revenue of US$ 42 million per year.

From a political perspective, it is important to note that, within the United Nations Framework Convention on Climate Change (UNFCCC), implemented by the Kyoto Protocol, the additionality principle of the Clean Development Mechanism (CDM) can be entirely fulfilled here. As defined by the Marrakesh Accords, a project can be included in the CDM for awarding Certified Emission Reductions (CERs) if it substitutes for a higher GHG-emitting one. In the present context, tropical reservoirs are already emitting methane, the current Brazilian legislation does not require any mitigation action, and the proposed procedures will significantly reduce methane emissions by *in situ* oxidation or by gas recovery for energy production.

5. Conclusion

Methane production in tropical reservoirs is highest in the first years, declining to a lower but stable level once initial decomposable carbon stocks dwindle (Fearnside, 2005a, 2008). The illustrative examples examined here have all passed the initial emissions peak but are probably still above their long-term equilibrium emissions levels. They are therefore conservative as indications of the amounts that could be captured during the first years of a new reservoir, but overstate the long-term production level. Finally, we note that, in addition to the CH_4 produced by decaying organic matter originally found in the reservoir area, methanogenesis also occurs due to the continuing arrival of new carbon inputs from the drainage basin. Tropical reservoirs may, therefore, be considered as potentially substantial methane sources for their complete life cycle.

In summary, we have shown here that the use of low-cost, innovative mitigation and recovery strategies would be able not only to reduce atmospheric methane emissions from tropical hydroelectric reservoirs, but also to transform existing biogenic methane stocks into a renewable energy source. Recovered gas may be pumped to large consuming centers or stored locally and burned by gas turbines to generate electricity during high-demand periods, or even purified for transport applications. Our analysis shows that the use of biogenic methane may increase considerably the energy supply in countries, like Brazil, which possess many large tropical reservoirs. As a result, it would be possible to reduce the need for building new reservoirs, protecting important pristine biomes such as the Amazon Forest, and avoiding the resettlement of villages and damage to indigenous reserves. From an economic standpoint, we have shown that, under different operational scenarios, CH_4 mitigation and recovery projects are economically viable, especially in the case of large and young tropical reservoirs. All this makes, we believe, the use of CH_4 from tropical hydropower reservoirs a promising idea. The need for more research in this area is urgent, including better estimates of the magnitude of current methane stocks and how they evolve over time, in response to aging, land-use change and climatic variables.

Acknowledgements

This work was partially supported by CNPq-Brazil. The first four authors have patents pending for methane-capture equipment.

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Table 1: Reservoir biophysical and energetic characteristics.

Reservoir	Watershed vegetation cover	Area (km^2)	Beginning of reservoir filling	CH_4 downstream degassing ($Mt\text{-}CH_4/y$)	CH_4 equivalent power (MW) [A]	Installed capacity (MW) [B]	A/B (%)
Petit Saut	Amazon Forest	300	1994	0.009-0.020 [a]	16-36	115	14-31
Curuá-Una	Amazon Forest	78	1977	0.012 [b]	22	40	55
Balbina	Amazon Forest	2360	1987	0.052 [c]	92	250	36
Samuel	Amazon Forest	540	1988	0.033 [d]	58	216	27
Tucuruí-I	Amazon Forest	2430	1984	0.7-1.2 [e]	1232-2112	3960	31-53

Sources: [a]Abril et al., 2005; [b]Fearnside, 2005b; [c]Kemenes et al., 2007; [d]Fearnside, 2005c; [e]Fearnside, 2004.

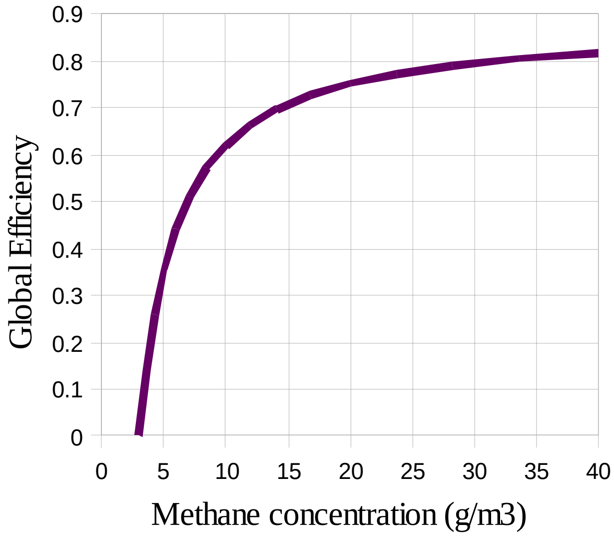

Figure 1: Global efficiency of the CH_4-extraction system as a function of the CH_4 concentration.

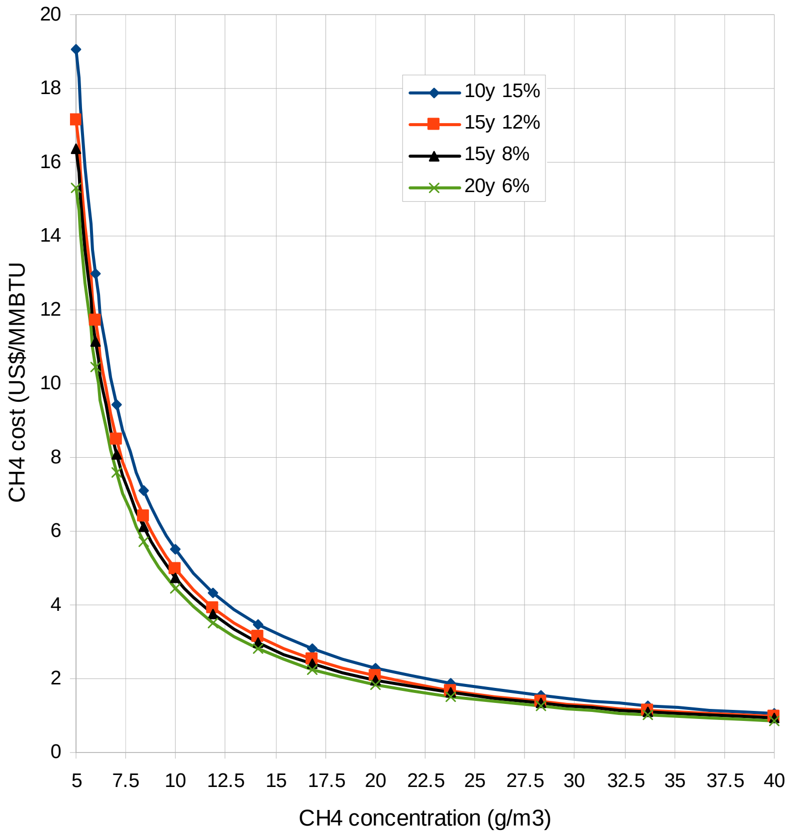

Figure 2: In situ extraction cost (in US$ per MMBtu) as a function of the CH_4 concentration, considering different interest rates and depreciation periods.

ANNEX

The proposed CH_4 recovery strategy is based on the transport of CH_4-rich, pressurized, deep waters to surface ambient conditions, where the dissolved gas can be extracted by bubbling or by spraying droplets into a sealed vessel. Gas extraction by bubbling requires high CH_4-concentration levels in the water (>100 g/m^3), like those found in deep African volcanic lakes (Kling et al., 2005), in order to keep the residence time within the bubbling chamber below a reasonable threshold (Bambace et al., 2007). In tropical reservoirs, like those considered in this paper, where maximum CH_4-concentration levels seldom reach 10 g/m^3 (Guérin et al., 2006), spraying systems are more cost-effective and, thus, will be the only approach described in detail below.

The overall functioning principle of the spraying technique is illustrated in Figs. A1 to A3, and based on well-known jet-impingement technologies. Costs are detailed in Tables A1 and A2. Light and scalable, the CH_4 extraction system is designed to be placed on-board of a catamaran-like boat, in order to be moved from one site to another whenever an exploitation zone becomes poor in methane. The gas extraction unit comprises several independent spraying units, working in parallel within a sealed membrane vessel. It also includes water pumping systems, gas recirculation blowers, column-batch gas absorbers and the associated piping. Two-stage gas compressors transfer the CH_4 from the absorbers into the storage-skids placed on an accompanying barge. The spraying subsystem includes the following items: spraying nozzles, water feeding pipes, a fan with the associated flow-directing frame, and a spinning honeycomb cutter. The nozzles throw water against the spinning honeycomb cutter, creating a cloud of droplets whose residence time within the vessel is controlled by the upward gas flow generated by the fan.

Table A1: Equipment costs for the spraying extraction system, for a water flow rate of 10 m^3/s; most data obtained from suppliers' web sites.

Equipment	# Items	Basic Specification	Cost (KUS$)
Suction hoses	36	100 m x 400 mm diameter gauge 1/16	8
Connections and valves			5
Gas engine and generator	2	190 HP (Volvo Penta D3)	44
Bilge pumps	36	Rule 4000 GPH	60
Jet pump mounting	40	900 cfm each	10
Main pumps	2	4 ft (1.22 m) diameter marine axial propeller hull thruster (Brunvoll or KameWa)	450
Sealed bag	1	20x12x6 m	20
Boat	1	78 ft (23.8 m)catamaran	200
Impingement rotors	9	Honeycomb or wire cutter	100
Carbon activated cylinders	8		140
Gas compressor	1	Sullair 750 H + 2 airlung AL7002	8
Recirculation blowers	13	Axial exhauster Ventisilva E100T8	60
Recirculation air ducts			2
Nozzles	20		1.5
Fuel tank	4	automobile gas cylinder, 14 m^3	2
Traction system	1		10
Control unit	1		15
TOTAL			1,135.5

Table A2: Operational and maintenance costs of a for the spraying extraction system, for a water flow rate of 10 m^3/s.

Item	**Cost (US$/h) IRR=15% 10-year deprec.**	**Cost (US$/h) IRR=6% 20-year deprec.**
Labor (including taxes)	11	11
Maintenance	0.41	0.41
Set-up operations	1.70	1.70
Skid boat coupling operation	2.08	2.08
Capital amortization (6% IRR) + 20-year depreciation	49.44	36.74
TOTAL	64.63	51.93

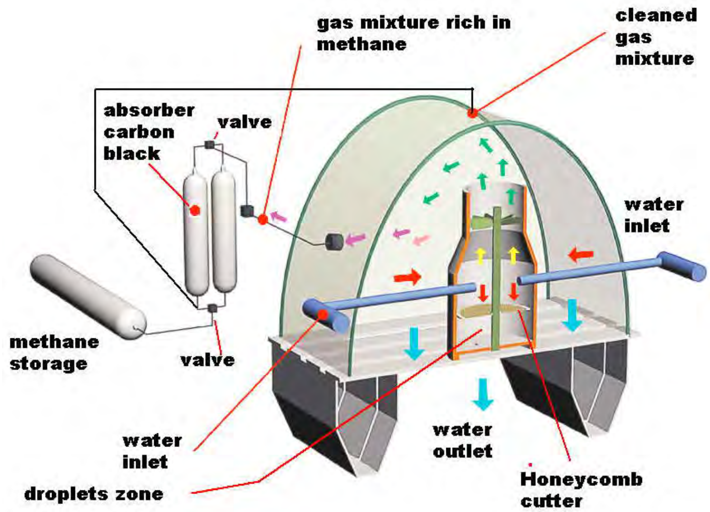

Figure A1: Schematic view of the spraying CH_4-extraction system.

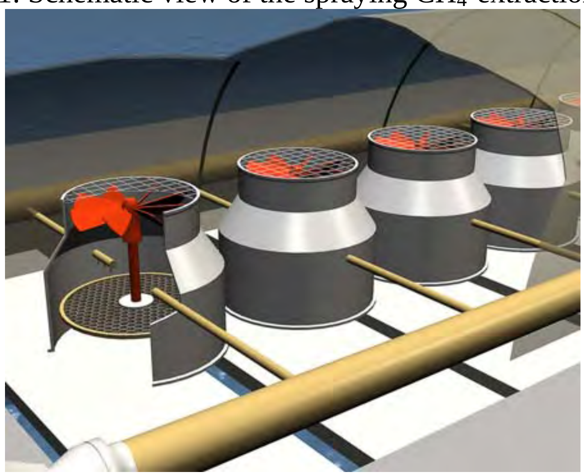

Figure A2: Detail of the spraying CH_4-extraction system.

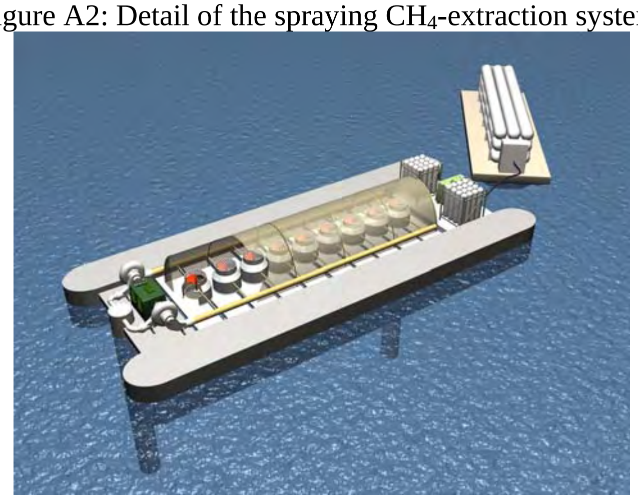

Figure A3: General view of the spraying CH_4-extraction boat with storage unit.