LIFE CYCLE ASSESSMENT OF GREENHOUSE GAS EMISSIONS FROM NAM THEUN 2 HYDROELECTRIC PROJECT IN CENTRAL LAOS

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MP Advisor's signature

Abstract

Conventional energy generation techniques such as coal and oil power plants release large amounts of greenhouse gases (GHGs) due to fossil fuel combustion while renewable energy sources, particularly, hydroelectric generation, are considered as climate-benign since they do not emit fossil carbon to produce energy. However, dams and their associated reservoirs are not entirely GHG-neutral and their emissions need further investigation. In particular, reservoirs contribute to a major source of methane emission owning to the energy and material input in the construction and the decommissioning phase as well as the anaerobic decomposition of flooded biomass in the operation phase.

This master's project evaluates the greenhouse gas (GHG) emissions associated with Nam Theun 2 hydroelectric power plant in central Laos. A life cycle perspective is coupled with two Monte Carlo Simulations and time-specific global warming potential (GWP) for methane, all to predict the statistically most likely 100-yr GWP of Nam Theun 2.

The stochastic models indicate GHG emissions of 2.5±0.5 gCO2 eq/kWh GWP in the construction phase, 75±5 gCO2 eq/kWh GWP in the operation phase and 0.60±0.05 gCO2 eq/kWh GWP in the decommissioning phase. The operation phase emission estimation is larger than previously believed (around 10 gCO2 eq/kWh for hydropower) due to the accounting for biomass decomposition. However, the hydropower plant is still significantly lower than the lifetime GWP of a typical coal plant (800-1000 gCO2 eq/kWh).

A literature review on the topic of reservoir GHG emissions is conducted, an introduction of the Nam Theun 2 project is presented and GHG mitigation recommendations are provided for various stages of a dam's life.

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1. Introduction

The filling of reservoirs behind dams causes major alteration of ecosystems. Dams alter the flow of rivers and block corridor for aquatic and wetland species and greatly affect biodiversity. The fragmentation of a river ecosystem and the impoundment of water alter river water quality, especially sedimentation loads. The construction of dams may also require relocation of human populations and disruption of indigenous lifestyles and cultures. In brief, dams may cause environmental and social effects that require close evaluation prior to construction.

This master's project, in particular, discusses the global warming potential associated with greenhouse gas emissions from reservoir surfaces as well as from turbines and spillways in Nam Theun 2 hydroelectric dam in Laos.

As we know, conventional energy generation techniques such as coal and oil power plants release large amounts of greenhouse gases (GHGs) due to fossil fuel combustion while renewable energy sources, particularly, hydroelectric generation, are considered as climate-benign since they do not emit fossil carbon to produce energy. However, recent research indicates that dams and their associated reservoirs are not entirely GHG-neutral and their emissions need further investigation. In particular, reservoirs contribute to a major source of methane emission owning to the energy and material input in the construction and decommissioning phase as well as the anaerobic decomposition of flooded biomass in the operation phase.

The impoundment of reservoirs greatly alters a terrestrial carbon sink which previously assimilated carbon dioxide by photosynthesis and creates a new anthropogenic GHG source from where the originally stored carbon is released as carbon dioxide and methane. In addition to the initial allochthonous terrestrial carbon load, in a tropical reservoir, the respiration of autochthonous plants and vegetation grown after the creation of the reservoir overwhelms their photosynthesis and therefore acting as an additional source.

Different initial ecosystems contain different amounts of soil and vegetation carbon and decompose under different climate conditions. Shallow, tropical reservoirs are identified as the highest GHG emitter owning to its relative large inundation area and humid weather[1 2 3].

Since 1990s, GHG emissions from hydropower reservoirs have become a topic of interest among many researchers. Oud (1993) and Rudd et al (1993) first shed light on the fake “climate-friendly” status of hydroelectric dams. Luiz Pingelli Rosa from Brail hydroelectric industry and Philip M. Fearnside, one of the most citied climate change scientists, later initiated a hot debate on the role of hydroelectric reservoirs regarding GHG emissions and its relative importance comparing to traditional thermal power plants (Rosa and Schaeffer 1994; Fearnside 1995; Rosa and Schaeffer 1995; Rosa et al. 1996; Fearnside 1997a; Fearnside 1997b; Rosa and dos Santos 2000; Fearnside 2002; Rosa et al. 2003; Fearnside 2004; Rosa et al. 2004; Fearnside 2005a; Fearnside 2005b; Cullenward and Victor 2006; dos Santos et al. 2006; Rosa et al. 2006). Researchers from Hydro Quebec, namely, Andre Chamberland, Eric Duchemin, Luc Gagnon, Joop F. van de Vate and Alain Tremblay, also made significant contributions to the knowledge base of GHG emissions from boreal region (Gagnon and Chamberland 1993; Duchemin et al. 1995; Chamberland and Levesque 1996; Gagnon and van de Vate 1997; Tremblay et al. 2004). Additionally, to date, Gwenael Abril, Robert Delmas, Corinne Galy-Lacaux and Frederic Guerin did the most comprehensive study of GHG emissions for a specific reservoir, Petit Saut in French Guiana, and the reservoir shares many common attributes with our subject, Nam Theun 2 in central Laos (Galy-Lacaux et al. 1997; Galy-

Lacaux et al. 1999; Delmas et al. 2001; Abril et al. 2005; Guerin et al. 2006; Kemenes et al. 2007). More recently, researchers such as Sergio Almeida Pacca and Arpad Horvath adopted a life cycle perspective to assess global warming impact of hydropower reservoirs (Pacca and Horvath 2002; Pacca 2007). Furthermore, United Nations Educational, Scientific and Cultural Organization (UNESCO) and International Hydropower Association (IHA) are trying to establish a set of standard methods to evaluate GHG emissions from dams.

Our subject, Nam Theun 2, is a 1070MW concrete gravity dam in central Laos on the Mekong tributary. The total terrestrial carbon in soil and vegetation prior to impoundment existing in the inundation area is about 5 Mt[4].

Here, a Life Cycle Assessment (LCA) approach is used to account for full energy-chain emissions of Nam Theun 2. Also, a time-specific methane Global Warming Potential (GWP) is employed to transfer methane contributions to carbon dioxide equivalent owning to the inconsistent emission pattern throughout the lifetime of the dam and two Monte Carlo simulations are conducted to simulate unknown parameters due to data unavailability and lack of field measurements.

2. Methodology

2.1. Life Cycle Assessment (LCA)

Life Cycle Assessment is so called “cradle to grave” analysis. It counts all the mass and energy inputs of a product’s entire life span. LCA extends the boundary of an environmental assessment from direct impacts to indirect impacts since sometimes indirect impacts surpass direct ones and they should not be neglected in energy comparisons or in policy decisions.

Since large amounts of materials and energy are required during the dam construction stage and the dam decommissioning stage, a LCA approach will better quantify the magnitude of actual GHG emissions associated with hydroelectric power plants and give out a fairer comparison with its thermal counterparts.

As noted, the manufacturing of the construction materials, the actual construction of the dam, the operation of the plant, and the decommissioning of the dam and reservoir at the end of its lifetime are some various stages of the life cycle process of a hydropower dam[5].

Life Cycle Assessment traditionally utilizes either a process-based methodology or an economic input-output approach[6].

Process Based LCA: SETAC-EPA

The process based approach was developed most extensively by the Society of Environmental Toxicology and Chemistry (SETAC) and the U.S. Environmental Protection Agency (EPA)[7]. It is a vertical bottom-up technique and it is resource- and time- consuming to draw the exact process flow since it attempts to go as far back in the flow as possible[8]. Process based approach has well-defined system boundary while the scope of the assessment is limited due to data availability and the infinite process loop.

The existing LCA inventories, such as the National Renewable Energy Lab (NREL) database created by U.S. researchers and the ecoinvent database developed by Swiss researchers, are based on the country specific data and are available to the public[9].

Economic Input-Output: EIO-LCA

In contrast, economic input-output life cycle assessment (EIO-LCA) methodology is a statistical top-down approach while not process oriented8. It is developed by Carnegie Mellon University and the most up-to-date version is based on 2002 U.S. economy data accounting for all the 428 sectors of the U.S. economy and determines environmental impacts associated with a dollar value of economic activity in each sector[6].

EIO-LCA is applied to assess the processes of secondary importance because this approach gives out general values instead of precise ones due to the approximate categorization and therefore, it is hard to locate all the hotspots. In this case, the construction phase GHG emissions of Nam Theun 2 may take an EIO-LCA approach since difficulties prevail in the tracing of exact material and energy inputs associated with dam construction.

Hybrid LCA

A hybrid approach combines the strengths from both techniques while reduces the uncertainty to minimum. Generally speaking, process-based approach is applied to where the major impacts occur and economic input-output one takes over the trivial and data shortage phases.

In the case of Nam Theun 2, the construction phase is supposed to be evaluated by EIO-LCA while the operation and decommissioning phase by process-based LCA. However, strictly speaking, the EIO-LCA developed by Carnegie Mellon University is U.S. economy based so it should not be utilized by projects from other countries. Also, the data availability in the construction phase of Nam Theun 2 does not meet the EIO assessment requirement. Thus, I can only obtain a fairly rough estimation of its construction stage.

System Boundary of Nam Theun 2 Hydroelectric Power Plant

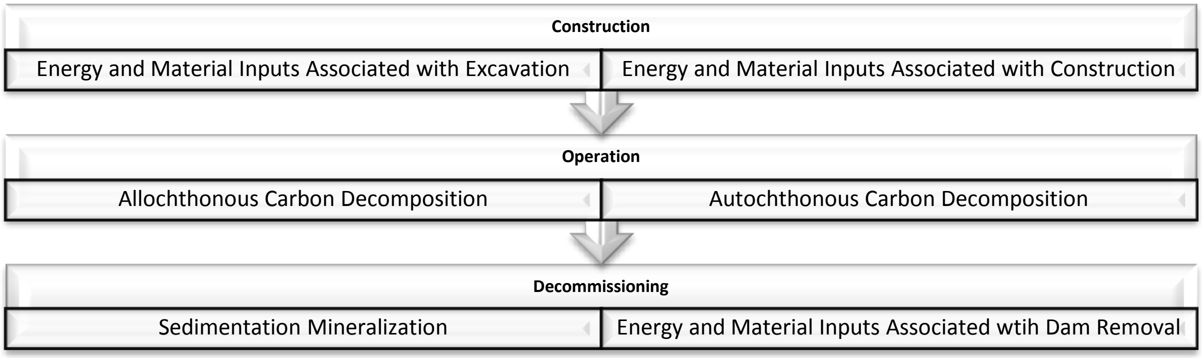


Figure 1 System Boundary

2.2. Global Warming Potential (GWP)

Global Warming Potential (GWP) Concept

Anthropogenic greenhouse gas additions to the climate system contribute to global climate change including increases in the extreme weather and the global temperature. A common gauge is needed to evaluate the magnitude and the sigh of the change. GWP hence acts as a common agent who takes into both the radiative forcing (RF) and the lifetime of greenhouse gas concentrations in calculating their impact on the global climate after a certain time.

The GWP of a certain GHG is defined as the ratio of the instantaneous radiative forcing of a unit mass emission of the GHG and that of carbon dioxide, the reference gas, integrated up to an arbitrarily determined time horizon. Thus, the unit of GWP is taken as CO_2 equivalent. And also, all GWPs have a sensitive time scale problem. The values in the International Panel on Climate Change (IPCC) reports are given out in 20, 50 and 100 years[1 3 10].

Reservoirs produce continuous emissions with temporal variations, and the greenhouse effect calculated over a given time, in this case 100 years[11], is the combined effect of all emissions within the period considered. Additionally, we also include the dam decommissioning process, which extend the dam process to 200 years.

To estimate the global warming impact of a hydroelectric reservoir, we have to take into account the time-specific GWP instead of employing a constant 100-yr GWP value into the calculation.

Mathematical Representation

The GWP of component i is defined by

$$\mathrm{GWP\ (t)} = \frac{\int_0^T \mathrm{RF_i\ (t)\ dt}}{\int_0^T \mathrm{RF_r\ (t)\ dt}} = \frac{\int_0^T \mathrm{a_i\ [Ci\ (t)]\ dt}}{\int_0^T \mathrm{a_r\ [Cr\ (t)]\ dt}}$$

Equation 1

which is based on the time-integrated global mean radiative forcing (RF) of a pulse emission of 1 kg of some compound (i) relative to that of 1kg of the reference gas CO_2.

In this equation, T is the time horizon, RF_i is the global mean RF of component i, a_i is the RF increase corresponding to per unit mass increase in atmospheric abundance of component i (radiative efficiency), $[C_i\ (t)]$ is the abundance of i at time t, and the corresponding quantities for the reference gas CO_2 (r) in the denominator[12].

Table 1 Lifetimes, Radiative Efficiencies and GWPs for CO_2 and CH_4[12]

Chemical Formula	Lifetime (τ, years)	Radiative Efficiency (W m^{-2} $ppbv^{-1}$)	20-yr GWP	100-yr GWP	500-yr GWP
CO_2	See CO_2 response function	$1.4*10^{-5}$	1	1	1
CH_4	12	$3.7*10^{-4}$	72	25	7.6

The CO_2 response function used in the IPCC (2007) report is based on the revised version of the Bern Carbon cycle model (Bern2.5CC; Joos et al. 2001) using a background CO_2 concentration value of 378 ppm. The decay of a pulse of CO_2 with time t is given by

$$a_0 + \sum_{i=1}^{3} a_i * e^{-t/\tau_i}$$

Equation 2

Where $a_0 = 0.217$, $a_1 = 0.259$, $a_2 = 0.338$, $a_3 = 0.186$, $\tau_1 = 172.9$ years, $\tau_2 = 18.51$ years, and $\tau_3 = 1.186$ years.

Assuming a constant radiative efficiency for CO_2 and CH_4, an exponential decrease of CH_4 atmospheric concentrations and an atmospheric lifetime of 12 years, the GWP can be given as

$$\mathrm{GWP}\ (t) = \frac{a_i \int_0^T (e^{-t/\tau})\ dt}{a_r \int_0^T \left(a_0 + \sum_{i=1}^{3} a_i * e^{-t/\tau_i}\right) dt}$$

Equation 3

Equation 3 can be integrated and expanded as

$$\mathrm{GWP}\ (t) = \frac{a_i}{a_r} * \frac{(-\tau e^{-t/\tau} + \tau)}{(a_0 t - \sum_{i=1}^{3} \tau_i a_i e^{-t/\tau_i}) + (\sum_{i=1}^{3} \tau_i a_i)}$$

Equation 4

Where $\frac{a_i}{a_r} = 72.7$ per unit mass according to table 1.

All the above equations denote direct GWPs and the calculated results of 20-, 100-, 500-yr GWPs are shown in Table 2.

Table 2 Direct and Indirect GWPs for CO_2 and CH_4

	20-yr GWP	100-yr GWP	500-yr GWP
(direct + indirect) value (IPCC 2007)	72	25	7.6
direct value (Equation 4)	52.1	18.2	5.5
(direct + Indirect): direct ratio	1.38	1.37	1.38

The indirect radiative effects of CH_4 are mainly due to its interaction with OH radicals, to ozone enhancements resulting from methane oxidation in the troposphere and to water vapor formation in the stratosphere. These process increase the GWP for CH_4 since tropospheric ozone and stratospheric water vapor are also efficient greenhouse gases1 [12].

Consequently, the total GWP (direct + indirect) for CH_4 becomes

$$\mathrm{GWP}\ (\mathrm{t})_{\mathrm{total}} = 1.38 * \frac{a_i}{a_r} * \frac{(-\tau e^{-t/\tau} + \tau)}{(a_0 t - \sum_{i=1}^{3} \tau_i a_i e^{-t/\tau_i}) + (\sum_{i=1}^{3} \tau_i a_i)}$$

Equation 5

If we substitute all the values into Equation 5, we will have

$$\mathrm{GWP}(\mathrm{t})_{\mathrm{total}} = 1203.91 * \frac{[1 - e^{(-t/12)}]}{[0.217 * t - 44.78 * e^{(-t/172.9)} - 6.26 * e^{(-t/18.51)} - 0.22 * e^{(-t/1.186)} + 51.26]}$$

Equation 6

Figure 2 presents the lifetime GWP values of methane in a 100-yr scale.

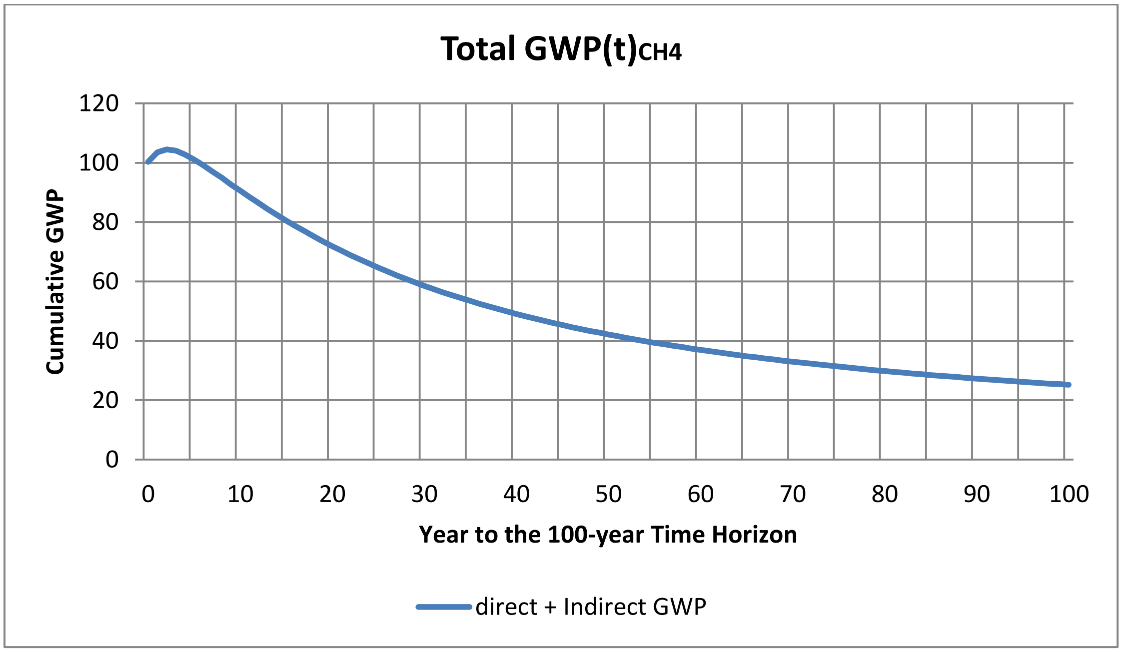


Figure 2 Total GWP for CH_4 in 100 Years

Figure 3 is reversed because lower GWP values will be applied to initial emissions since the earlier the emission, the higher portion of the atmospheric concentration will be consumed towards the end of the 100-year lifetime.

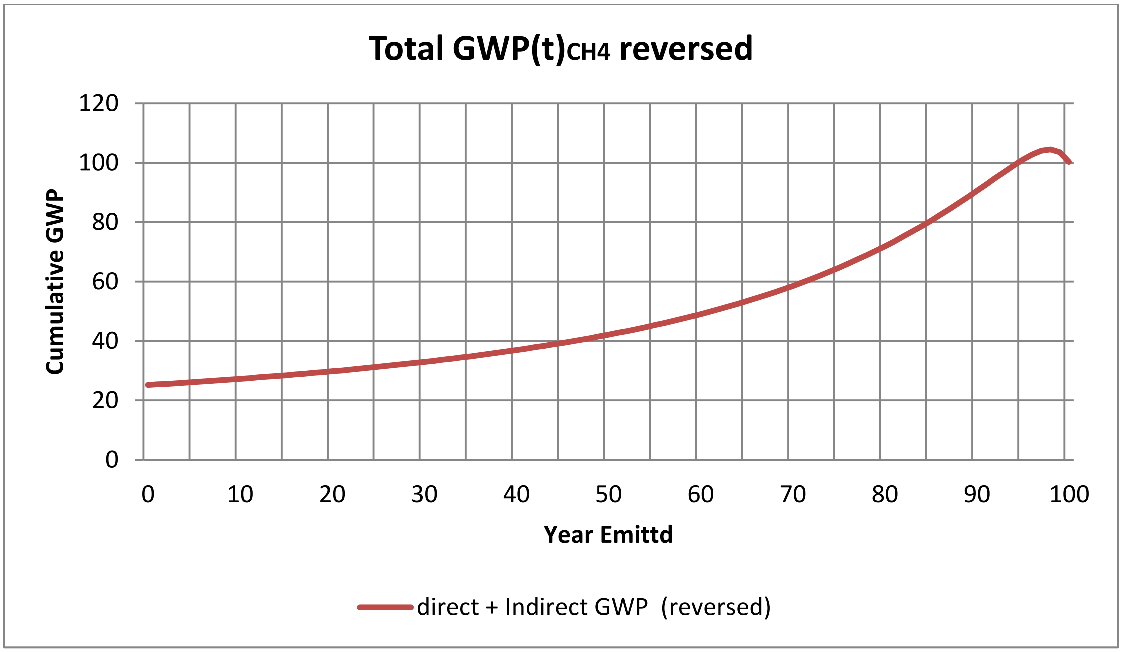


Figure 3 Total GWP for CH_4 in 100 Years (reversed)

2.3. Monte Carlo Simulation

Monte Carlo simulation models are probabilistic models that use random numbers to simulate chance events and to describe its consequences. It works when straightforward probability analysis if impractical or impossible.

In the Nam Theun 2 case, to date, since no standard methods exist for evaluating reservoir GHG emissions and no field measurement data allow public access, random variables obeying some kinds of distributions are assigned to simulate the probabilities of major parameters, namely, the percentage of original flooded biomass, decomposition e-folding time, the percentage of carbon dioxide emission in the total greenhouse gas emissions, carbon content in reservoir sediment and carbon mineralization percentage after the dam is no longer in service.

3. Nam Theun 2

3.1. General Condition

Nam Theun 2 hydroelectric power plant takes advantage of the difference in elevations between the Nakai Plateau and the Gnommalat plain and creates a 450km^2 reservoir corresponding to 40% of the plateau's total area and produces a net water head of about 350m. The project involves the construction of a 1070MW installed capacity power station and transmits 95% of the energy generated to Thailand while leaves 5% for domestic use.

The project area experiences a tropical monsoon climate with distinct wet and dry seasons. Since the river discharges are directly related to precipitation, drawdown of the reservoir normally occurs during the dry season, with filling typically occurring during the wet season. Full supply level (FSL) can be achieved during the periods of high inflow. The reservoir will discharge water to both the Nam Theun River and the Xe Bang Fai. Thus, the downstream impact should not be neglected.

In addition, the structure includes an aeration (re-oxygenation) weir of outflows entering the Xe Bang Fai which prevents low oxygen level in the water due to methane consumption and the anaerobic condition impairs the water quality. On the other hand, the aeration weir structure tends to release large amounts of methane to the atmosphere when the water is going through the turbines and spillways which would have significant impact on the global warming thanks to the high GWP value of methane[13] [14] [15] [16] [17].

Key Existing and Proposed Dams in Laos

Following is a map of the key existing and proposed dams in Lao PDR. Nam Theun 2 is circled with red ink.

Figure 4 Key Existing and Proposed Dams in Laos
Source: International Rivers 2008, Map of Key Existing and Proposed Dams in Laos; http://www.internationalrivers.org/southeast-asia/laos/map-key-existing-and-proposed-dams-laos-0

Nam Theun 2 Project Area Map

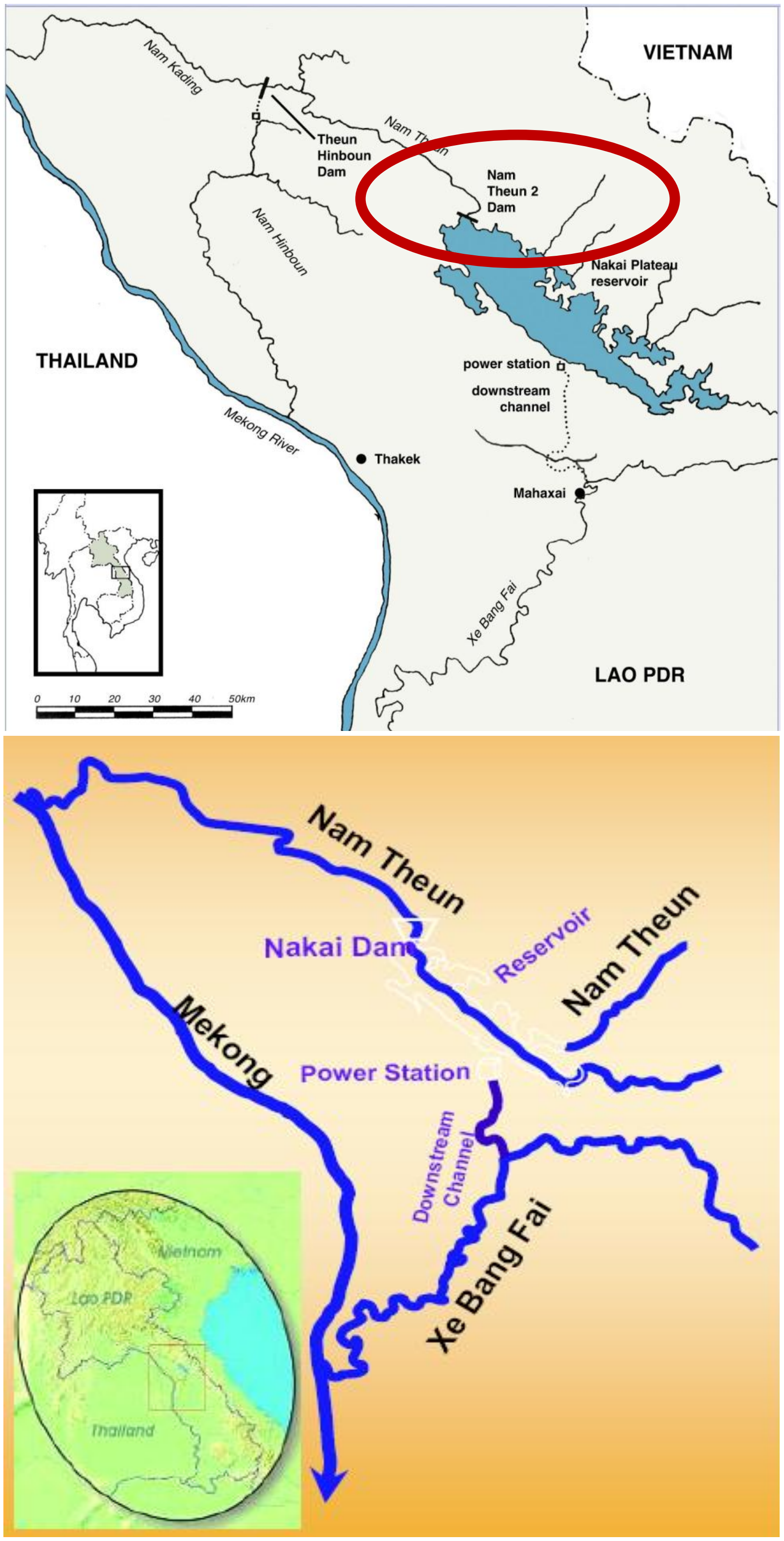


Figure 5 Project Area Map

Source: International Rivers, Map of Nam Theun 2 Project Area;

http://www.internationalrivers.org/southeast-asia/laos/nam-theun-2/map-nam-theun-2-project-area
World Bank, Nam Theun 2, a Project in the Heart of Laos.

Financing Schematic

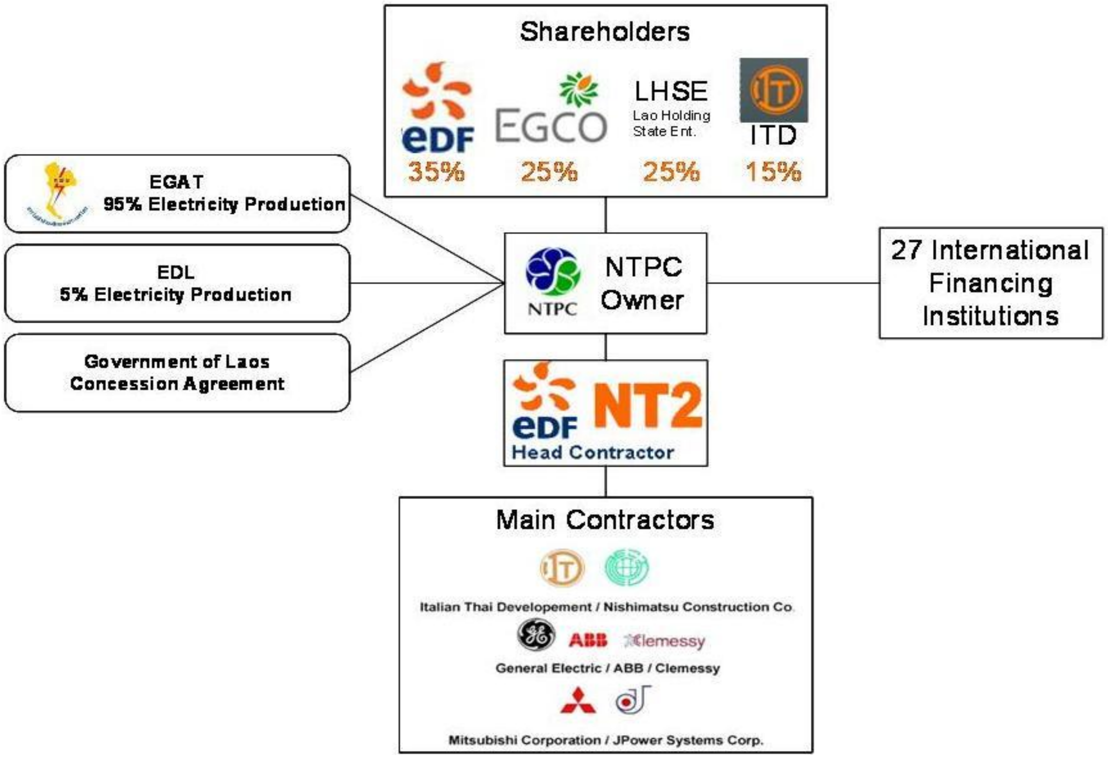


Figure 6 Project Ownership Schematic
Source: Nam Theun 2 Power Company.
http://www.namtheun2.com/images/stories/structure2.jpg

Milestones

Table 3 List of Important Dates of Nam Theun 2

1927	Nam Theun River's hydropower potential described in L'Eveil Economique de l'Indochine
1d89-91	World Bank feasibility study undertaken by Snowy Mountains Engineering Corp. (SMEC)
1993	GoL and NTEC sign Project development agreement in accordance with World Bank guidelines
1997	First series of environmental and social safeguards documents produced
September 2001	Shareholders Agreement signed
September 2002	NTEC and Lao Government create NTPC as a Lao company
October 2002	Concession Agreement signed
November 2003	Power Purchase Agreements signed with both EGAT and EDL
2004	Completion of safeguard documents and Project financing activities
May 2005	Financial Closure (FC) and beginning of full construction activities

November 2005	Nam Theun 2 Cornerstone Ceremony
2005	Construction activities commence and implementation of safeguards
April 2006-April 2008	Construction of resettlement villages and relocation of villagers to new homes
March 2008	Concreting of the diversion tunnel completed
April 2008	Diversion tunnel closed and impoundment begins
June 2008	Tunnel filling test
August 2008	Spillway gates closed on Nakai Dam
October 2008	First filling of hydraulic circuit; Third Stakeholder Forum in Thakhek
January 2009	Water releases from Nakai Dam for testing and commissioning
March 2009	Regulating Dam impoundment commences; energisation of 500 kV Transmission Lines & Substation
June 2009	Successful testing of first Francis Unit turbine and synchronisation with Thai national grid
April 2010	Commercial operations

Source: Nam Theun 2 Power Company.
http://www.namtheun2.com/index.php?option=com_content&view=article&id=49&Itemid=55

3.2. Site Parameters

I presented a table of the basic site information of the Nam Theun 2 project. It is located in tropical area with a power density of 2.38 W/m^2.

Table 4 Site Parameters of Nam Theun 2

Climate zone	Tropical
Location	Khammouane and Bolikhamsai provinces, Laos
Total project cost (US$)	1.45 billion
Project construction cost (US$)	1.3 billion[18]
Reservoir age (year)	1
Installed capacity (MW)	1,070
Capacity Factor	0.64
Flooded area (km^2)	450
Power density (W/m^2)	2.38
Electricity generation (GWh/yr)	6,000
Residence time (months)	6.2
Type of submerged biomass	Mixed deciduous evergreen forest Broadleaf coniferous forest[19] [20] [21]
Carbon density (vegetation) (t (C)/ha)	40
Carbon density (soil) (t (C)/ha)	70
Total original biomass without land-clearance(Mt)	4.95

Source: Nam Theun 2 Power Company. (2005). Environmental Assessment and Management Plan. Chapter 2 Project Description and Analysis of Alternatives.

3.3. Project Components and Technical Data

We can see from the project components map that when the Nakai Reservoir is elevated to its full supply level, much area will be inundated as well as the vegetation in the area.

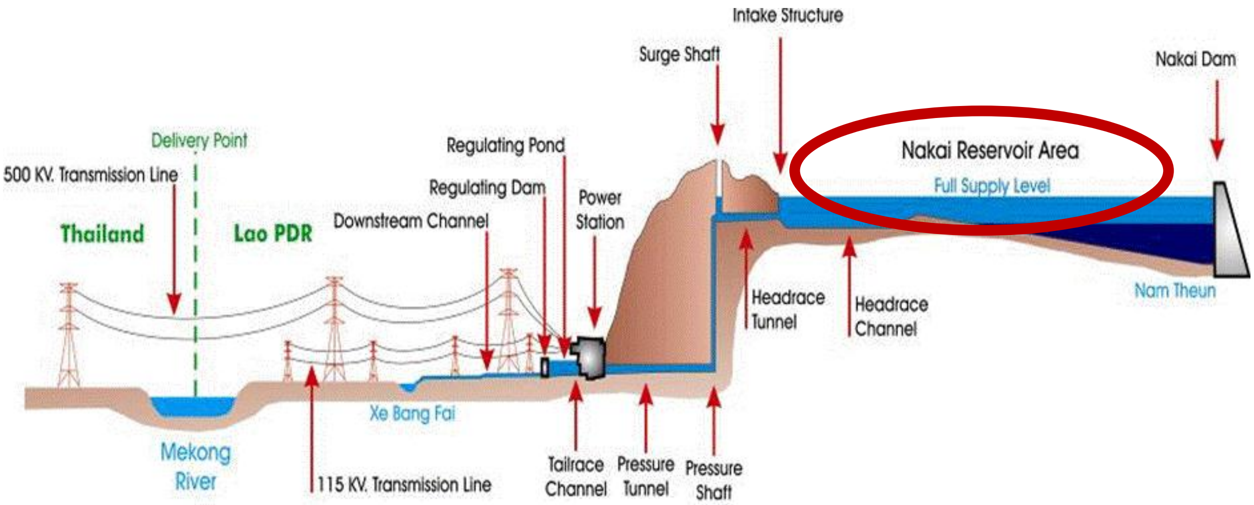


Figure 7 Project Components

Source: Nam Theun 2 Power Company.

http://www.namtheun2.com/index.php?option=com_content&view=category&id=43&Itemid=57

Table 5 Project Features and Technical Data

Project features		**Technical data**
Nakai Dam	Embankment Type	Concrete gravity (roller compacted concrete, RCC)
	Crest Level	El 541.5
	Crest Length	437 m
	Maximum Height	39 m
Saddle Dam	Number	14
	Embankment Type	Earth
	Crest Level	El 542.25
	Total Crest Length	4.4 km (approx.)
	Maximum Height	12.5 m
Reservoir	Catchment Area	4,013 km^2
	Average Annual Runoff	7,527 million m^3
	Maximum Volume	3,910 million m^3
	Minimum Volume	380 million m^3
	Live Volume	3,530 million m^3
	Full Supple Level (“FSL”)	El 538.0
	Minimum Operating Level (“MOL”)	El 525.5
	Surface Area at FSL	450 km^2
	Surface Area at MOL	82 km^2
	Average Depth	7 m
	Impoundment Length	195 km
Tunnels & Shafts		
Headrace Tunnel	Type	Concrete lined
	Length	1,499 m
	Diameter	8.80 m
Surge Shaft	Type	Concrete lined
	Height	115 m
	Diameter	8.80 to 13.00 to 42.00 m

Pressure Shaft	Type	Concrete lined
	Height	225 m
	Diameter	8.80 m
Pressure Tunnel	Type	Steel/concrete lined
	Length	1,141 m
	Diameter	7.15 to 8.80 m
Manifolds		
Francis Units	Length	55 m (approx.)
	Diameter	2 * 5.1 m to 4 * 3.6m
Pelton Units	Length	80 m (approx.)
	Diameter	1 * 2.5 m to 2 * 1.8m
Power Station	Structure type	External surface station
	Size	Length 128 m * Width 39m Height (substructure) = 34 m Height (superstructure) = 23m
	Volume of Concrete (substructure)	50, 000 m^3 (approx.)
	Francis Units	4 * 251.3 MW
	Pelton Units	2 * 42.7 MW
	Net Head (average)	348 m
Transmission Lines		
500 kV Transmission Line	Type	Double-circuit, AC
	Length	138 km in Laos, 168 km in Thailand
115 kV Transmission Line	Type	Double-circuit, AC
	Length	20 km
Tailrace Channel	Type	Open cut, shortcrete lined batters
	Length	340 m
	Bottom Width	70 m
Regulating Dam	Embankment Type	Earth
	Volume of Earthen Embankment	230,000 m^3
	Volume of Conventional Concrete	60,000m^3
	Crest Level	El 179.5 with rock bund to El 180.5
	Crest Length	396 m
	Maximum Height	24 m
Regulating Pond	Live Volume	8 million m^3
	Full Supple Level ("FSL")	El 178.0
Downstream Channel	Type	Open cut (lined & unlined) and tunnel
	Total length	27 km
Road & Bridge Works	Road Upgrading	82 km
	New & Relocated Roads	63 km
	New & Upgraded Bridges	Nam Theun, Nam Nian, Nam Kathang, Nam Gnom, Ban Itak, Huay Had, Tailrace Channel, Downstream Channel

Source: Nam Theun 2 Power Company. (2005). Environmental Assessment and Management Plan. Annex C: Project Key Technical Data. Nam Theun 2 Power Company. (2009). Summary of NT2 Major Project Components. Ball et al. (2005). Review of Nam Theun2 Hydroelectric Dam. Final Report to The Australian Government's Overseas Aid Program (AUSAID).

Aeration Weir

In addition the components listed in Table 5, a U-shaped aeration weir is installed in the downstream channel to improve the concentration of dissolved oxygen in the water and to elevate the water quality by reducing the methane and hydrogen sulphide concentration[4 15].

However, this kind of structure impairs the global warming mitigation aspect of the hydroelectric power plant as large amounts of methane is then emitted to the atmosphere through the aeration weir. Therefore, the methane emission catalyzed by the weir is another consideration when deciding whether to incorporate such a structure other than the water quality improvements.

3.4. Nam Theun 2 and Petit Saut Comparison

To date, only one study (Delmas et al. 2000) did assessment for GHG emissions from Nan Theun 2 based on Petit Saut reservoir (French Guyana) field data and their similarities and distinctions. The study extrapolated the information available on Petit Saut to estimate potential emissions from the Nakai Reservoir and considers principally the difference in carbon pool that will be subject to decomposition and the relative large drawdown area of Nakai Reservoir in comparison with Petit Saut. The large drawdown area suggests that more proportions of the organic matter will be released as carbon dioxide due to larger chance of aerobic decomposition. It is estimated that Nakai reservoir would produce 50% to 80% of the estimated GHG emission of the Petit Saut reservoir (a net of 30 million ton CO_2 equivalent and a gross of 42.3 million ton CO_2 equivalent in 100 years)[1 22].

I presented in Table 6 the comparison of site characteristics of Nam Theun 2, Petit Saut and also Buyo which was used to calculate the GHG emissions from Petit Saut due to their similarities in hydrological characteristics (water flow, residence time and type of vegetation) and the difference in impoundment year[2].

Table 6 Nam Theun 2, Petit Saut and Buyo Project Comparison

	Nam Theun 2	Petit Saut	Buyo
Impounding time	April 2008	January 1994	August 1980
Age (years)	1	15	30
Localization	Khammouane and Bolikhamsai provinces, Laos	60 km of Kourou	450 km south-west Abidjan
River	Nam Theun	Sinnamary	Sassandra
Installed capacity (MW)	1070	116	165
Water flow from turbines (m^3/s)	188-330	100-300	150
Surface area (km^2)	450	365	895
Maximum volume ($10^6\ m^3$)	3,910	3,500	8,300
Average annual runoff ($10^6\ m^3$)	7,527	8,420	12,551
Residence time (months)	6	5	8
Type of submerged biomass	Temperate forest	Equatorial forest	Equatorial forest
Vegetation carbon (Mg C/ha)	40	170	200
Soil carbon (Mg C/ha)	70	100	70
Organic carbon amounts (Mt)	4.95	9.861	24.2

Source: Galy-Lacaux et al. (1999). Long-term Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Forest Regions. Global Biogeochemical Cycles 13 (2): 503-517. Nam Theun 2 Power Company. (2005). Environmental Assessment and Management Plan.

3.5. Land-Clearance Plan Prior to Impounding

In the 2005 Environmental Assessment and Management Plan (EAMP) of the Nam Theun 2 Power Company (NTPC), it was said that vegetation would be removed before the inundation of the reservoir area and the clearance was not limited to valuable timber but also included non-commercially valuable timber collected for firewood. A biomass clearance assessment conducted by Aruna Technology (2004) for both within and outside the reservoir area concluded that forest cover within the area of the Nakai Plateau decreased 11% from 1973-2003 while forest cover within the inundation zone decreased 13% for the same period[4].

Other information for the land-clearance plan from International Rivers and Asian Development Bank indicated that area below minimum operating level (MOL) would be cleared as a priority with a total identified area of 3,000ha; and among the 3,000ha, a 1,500ha has already been substantially cleared[23] [24].

The actual biomass removal was less than planned (at least 3,000ha) according to another report by International Rivers (IRN). Field trip by IRN found that only less than 5% of the biomass had been cleared from the reservoir area due to pool planning and failure to commit sufficient resources[25]. Leaving the biomass in place of the inundation area would cause severe water quality problem and release considerable amounts of GHG emissions from aerobic and anaerobic decomposition.

4. Greenhouse Gas (GHG) Emissions

Lots of uncertainties and unaddressed concerns exist in the estimation of GHG emissions from hydroelectric reservoirs. Among them, the issues of relative importance are listed below.

The choice of what emissions to count or not to count, and the decisions made, by default or by design, on how emissions are treated when they occur at different places and at different times influence the final result of estimated GHG emissions[14].

Gross vs. Net Emissions

The unaffected ecosystem prior to impoundment might be a carbon sink or a carbon source as well. Consequently, separating out anthropogenic additions from natural emissions is crucial in the calculation of GWP and the comparison with alternative generation techniques. However, the pre-impoundment emissions can only be estimated through literature data since few field measurements have been conducted on GHG emissions prior to reservoir filling because the cost of the campaign prevents its conduction.

Delmas et al. (2001) concluded that the net emission flux is lower than the gross flux by 15-42% if the previous terrestrial ecosystem uptakes carbon dioxide and functions as a carbon sink[1].

In addition to the displacement of a potential terrestrial carbon sink, reservoir sedimentation blocks particulate carbon from entering the ocean through natural river flow and therefore eliminates the oceanic carbon sink function. This impact will be revealed after the dam decommissioning and through sediment carbon mineralization[7].

Consequently, Rosa et al. (2004) noted that it was necessary to carry out an emissions assessment study prior to building a dam, so as to compare the emissions measured after its construction, and in order to identify the anthropogenic element in these emissions[26].

Annual vs. Total Emissions

The ultimate contribution is the difference between the carbon stocks in the forest prior to inundation and that in the reservoir when once the forest has decayed and the equilibrium is reached. It is easier to estimate compared to annual emission pattern since less parameters are involved in the estimation[27]. However, since the GWP value of a certain GHG is time-specific instead of constant throughout, the assessment of precise climate impact of hydropower dams requires annual balance pattern which should be come from experimental campaign.

Reservoir Surface vs. Turbines and Spillways Emissions

GHG emissions not only come from reservoir surfaces but are also release when the water is passing through turbines and spillways due to sudden pressure drop. Since, water intakes are located well below the water surface and methane concentration quickly increases with depth, most of the dissolved methane is promptly degassed and the methane release percentage through turbines and spillways can be as high as 80%[28 29].

The inclusion of an aeration weir in the spillway design of Nam Theun 2 may further catalyze the methane releases.

Permanently Flooded vs. Seasonally Flooded Zone

Part of the reservoir is alternately exposed and flooded as water levels fluctuate between the minimum operation level (MOL) and full supply level (FSL) and it is called the drawdown zone[28]. The drawdown zone will likely become covered by terrestrial vegetation tolerant of temporary inundation and produce large quantities of autochthonous biomass[4]. The amount of the autochthonous biomass grown in the reservoir after the inundation and its carbon release through respiration are also difficult to count.

Permanent Addition vs. One-time Release

The reservoir may not stop emitting GHGs after having reached its initial equilibrium after 20 years or more. The initial pulse of intensive decomposition happens over a relatively brief period of time, decaying exponentially in just a few years within the easily biodegradable part of submerged biomass (e.g. leaves) while the refractory part (brunches and trucks) may decompose slowly and adding their emissions to the atmosphere throughout the entire lifetime of the reservoir[30 31].

Moreover, the permanent addition also comes from autochthonous carbon pool whose quantities will not be affected by the reservoir age.

Depth and Age

Depth: Methane fluxes at the reservoir surface, as well as through turbines and spillways, is smaller in deeper water because they have a higher probability of being oxidized before reaching the water-air interface28. Consequently, shallow reservoir will emit more methane and cause greater global warming impact after a period of time.

Age: GHG emissions reveal a correlation with the age of the dam as the initial rapid release gradually decreases.

4.1. Construction Phase

I wish to use Economic Input-Output Life Cycle Assessment (EIO-LCA) approach to evaluate the construction phase GHG emissions caused by material and energy input. Unfortunately, due to data availability of the amounts of the construction materials used and the per unit cost, only a very rough result of construction phase GHG emissions can be obtained from previous literature data.

I presented in Table 7 the outcomes in previous studies.

Table 7 Empirical GHG Emission Values from Hydroelectric Power Plant Construction Phase

Source	Chamberland and Levesque (1996)	Tahara et al. (1997)	van de Vate (2002)	van de Vate (2002)	Oud (1993)	Pacca (2002)
Project	general study	based on Japanese data for a 10MW hydroelectric power plant	earth/ rock storage reservoir	large concrete storage reservoir[32]	a proposed southern Africa dam	Glen Canyon Dam
Construction phase GWP (gCO2 eq/kWh), 100-year lifetime	0.03	0.17	0.1-1	1-5	1.1[33]	1.2[34]

Also, in van de Vate (2002), it is estimated that the contribution to the total GHG emission factor from the often lengthy (1000 km or more) power lines connecting the plant to the grid is about 1 gCO_2 eq/kWh (100-year lifetime). In our case, Nam Theun 2 transmission lines consist of a 306-km-long, double-circuit 500-kV to the Thai grid and a 28-km-long, single-circuit 115-kV to Lao's domestic grid.

Therefore, I propose a GHG emission factor associated with construction phase be 2-3 gCO_2 eq/kWh (normalized by 100-year lifetime) including the transmission lines contribution and with a mean of 2.5 gCO_2 eq/kWh. The estimated value is relatively small compared to the operation phase emission and agrees with previous studies.

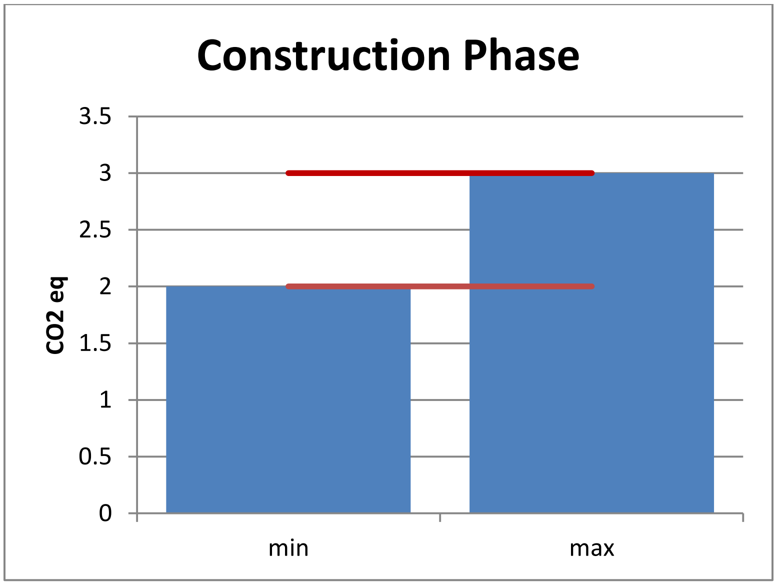


Figure 8 GWP Range for Construction Phase

Although I cannot conduct the EIO-LCA of the construction phase GHG emissions, I present below the process of data collection and calculations if detailed construction contract are provided for Nam Theun 2 hydroelectric project.

Energy and Material Input

GHG emissions associated with the construction of hydroelectric power plant are mainly related to the construction materials (concrete, cement and steel) and with energy used (fuel combustion) for material transportation, excavation and construction of dam and other infrastructure. The material used is decided by the composition of dam. Nam Theun is a gravity dam built by roller compacted concrete and GHGs related to structural steel and concrete are the major contributors (some 60%) to the construction associated emissions.

The construction phase GHG emission can be denoted as the following equation

$$\mathrm{GHG} = \sum_{i=1}^{n} \frac{I_i * E_i}{L}$$

Equation 7

I_i = input (g)

E_i =GHG intensity of each input (g CO_2 eq /g)

L = lifetime energy production (kWh)

Table 8 is an example of material quantity and dam volume data of some other dams with certain amount of data available to represent the kind of data needed for Nam Theun 2. Ideally, more categories of materials and more detailed descriptions should be added into the rows.

Table 8 Material Quantity and Dam Volume Data

Project name	**Nam Kai Dam**	**Nam Theun 2 Regulating Dam**	Victoria Dam	Proposed southern Africa Dam
Type	Roller compacted concrete gravity	Earth embankment	Roller compacted concrete gravity	Roller compacted concrete gravity
Height above foundations (Maximum height)	39 m	24 m	52 m	
Crest length	437 m	396 m	285 m	
Crest width			8.8 m	

Volume of the dam				4,000,000 m^3
Volume of earthen embankment		230,000 m^3		
Volume of conventional concrete		60,000 m^3		900,000 m^3
Volume of roller compacted concrete			121,000 m^3	4,100,000 m^3
Volume of concrete facing elements			13,500 m^3	
Volume of excavation for foundations			100,000 m^3	
Mass of steel				30,000 t

Source: http://www.watercorporation.com.au/d/dams_victoria.cfm. Oud. (1993). Global Warming, a Changing Climate for Hydro. International Water Power & Dam Construction 45 (5): 20-23.

Table 9 is the values of E_i in the Equation 7 from literature data.

Table 9 Greenhouse Gas Emission Factors of Greenhouse Gas Intensive Materials Used in Full Energy Chains (gCO_2eq/g):

Materials	van de Vate (1995)	Frischknecht et al. (1994)	EUR Commission (1995)	Fritsche et al. (1995)	NIRE (Tahara et al. 1997)
High alloyed steel		7.21			
Low alloyed steel	2.0-2.2	3.03	2.4	3	
Unalloyed steel		2.44			
Cement	0.76-0.9	0.96	0.16		0.719
Concrete	0.14	0.16	0.16		0.099
Reinforced concrete	1.95				
Copper	3.5-4.9	5.4	2.7	8.8	1.304
Aluminum	13-34	23		2.5	2.035
Aluminum (recycled)		1.3			
Glass	0.9-1.2	1.2		1.9	1.928
Plastics	2.0-7.9	1.37-5.45	2.4 (GRP)	6	
Nitric acid	1.4	0.61			
Fertilizer	12				
Silicon	181				86.241

Source: van de Vate. (1997). Comparison of Energy Sources in Terms of Their Full Energy Chain Emission Factors of Greenhouse Gases. Energy Policy 25 (1): 1-6.

Additionally, The density of concrete is 2400 kg/m^3[35].

LCA-EIO Estimation

The EIO-LCA method was used to estimate the amount of each GHG emissions from the construction and operation of power plants based on the amounts and costs of the materials and energy inputs.[36]

The newest version of EIO-LCA is based on 2002 economic data and therefore we also need to find out the customer price index (CPI) of 2005 compared to 2002.

Table 10 is an example form for LCA-EIO estimation if all data are available.

Table 10 Major Construction Inputs and GHG emissions for Nam Theun 2 Hydroelectric Power Plant (100-year)

Inputs	Volume (m^3)	Mass (g)	Unit cost (2002 $/g)	Total cost (2002 $)	GHG emissions (gCO_2 eq/kWh)			
					CO_2	CH_4	N_2O	Total
Concrete								
Steel								
Copper								
Aluminum								
Turbines and turbine generator sets								
Power distribution and transformers								
Total								

EIO-LCA can be conducted through Carnegie Mellon University website (http://www.eiolca.net/).

4.2. Operation Phase

Gases

Carbon dioxide and methane are two major GHGs and also two crucial emissions from hydropower reservoirs. Carbon dioxide is produced through aerobic decomposition while methane is released through anaerobic decay. In tropical reservoirs, methane represents about 85% of the total global warming contribution due to warmer temperatures which favor oxygen consumption and therefore anaerobic conditions[2].

Sources

There are two kinds of sources of the carbon load into the reservoir and artificial impoundments affect the dynamics for both sediment sources:

1) Autochthonous: from respiration of vegetables and planktons grown within the reservoir, especially in the drawdown area;

2) Allochthonous: from the original flooded-biomass, from seasonal flooding from upstream water shed, from organic material and eroded soil washed into the water from the land, rivers and streams that feed it, and from dissolved organic carbon that enters the river from ground water[28 37].

Pathways and Processes

There are three pathways from which GHGs release into the atmosphere:

1) Diffusive: major emission pathway for carbon dioxide, mainly dominates in boreal and temperate reservoirs;

2) Ebullition: major pathway for methane releases in tropical reservoirs;

3) Degassing: intense methane release from turbines and spillways due to instant pressure drop; the presence of an aeration weir built in order to eliminate methane from water to prevent the consumption of oxygen by methane oxidation in the water will significantly increase methane degassing.

The major pathway of greenhouse gases from tropical reservoir surface is from methane bubbles and from turbines and spillways from methane degassing.

Factors

Wind forcing, weather condition (sunlight) and the length and depth of the ice cover (boreal reservoirs) are three major factors influencing GHG emissions from reservoirs.

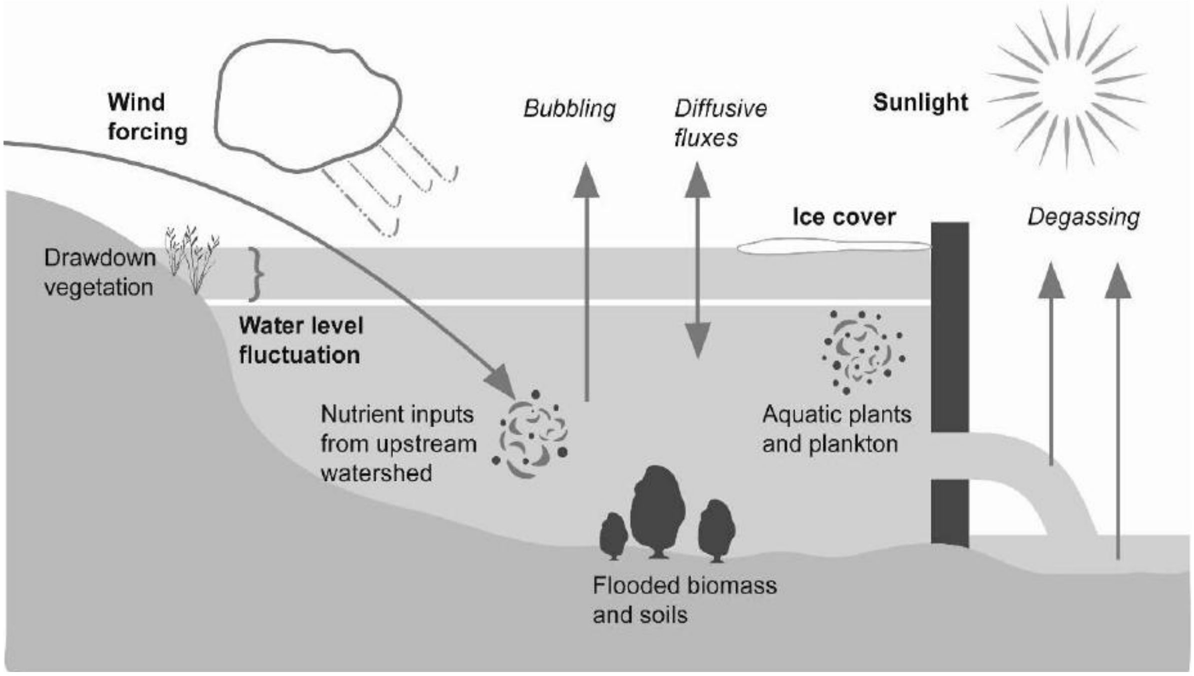
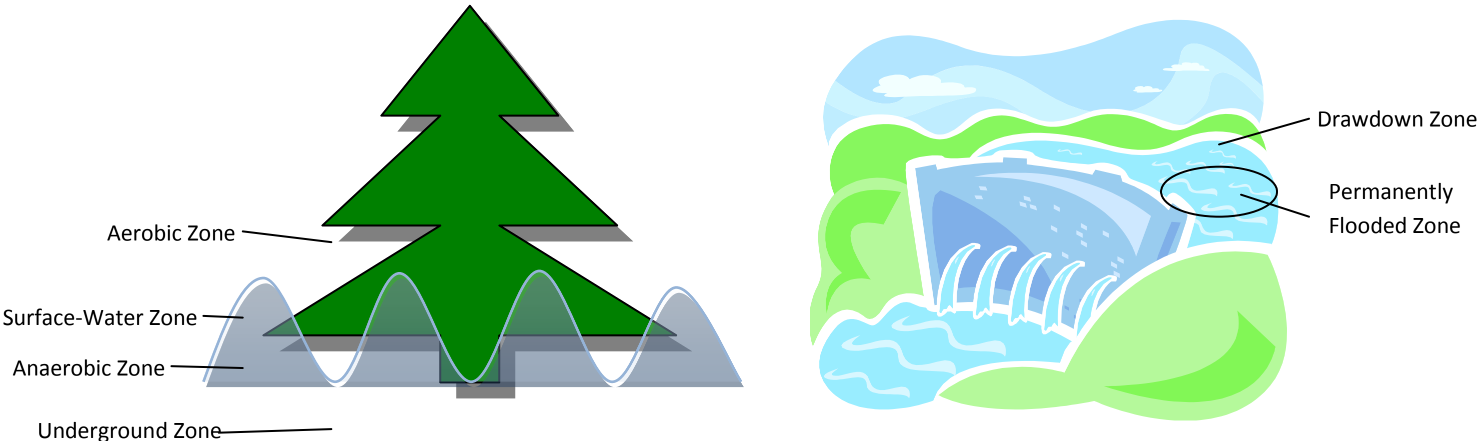


Figure 9 Factors Influencing GHG Emissions from Reserviors
Source: Mäkinen and Khan. (2010). Policy Considerations for Greenhouse Gas Emissions from Freshwater Reservoirs. Water Alternatives 3(2): 91-105. McCully and Pottinger. (2006). Fizzy Science: Loosening the Hydro Industry's Grip on Reservoir Greenhouse Gas Emissions Research. International Rivers. Soumis et al. (2005). Hydroelectric Reservoirs as Anthropogenic Sources of Greenhouse Gases. Water Encyclopedia.

Zones for Distribution of Biomass in Reservoirs

In a reservoir, permanently flooded zone represents areas that are always filled with water while drawdown zone is the peripheral areas that are inundated in full supply and dried in low supply. Hence, for plants in the reservoir, the vertical hierarchy is separated as underground, anaerobic, surface-water and aerobic zone as indicated in Figure 10.



Vertical Zones

Horizontal Zones

Figure 10 Zones for Designating Distribution of Biomass in Reservoirs
Source: Fearnside (1995). Hydroelectric Dam in the Brazilian Amazon as Source of Greenhouse Gases. Environmental Conservation 22: 7-19.

Measurement techniques

Diffusive fluxes: floating static chambers;

Bubbling emissions: polyethylene funnels;

Degassing fluxes downstream of the dam: determine by using average gas concentration in the water column and daily total water flow through turbines and spillways.

Original Flooded Biomass

Carbon loads from various sources into the reservoir, however, in this case, only the original flooded biomass carbon pool will be considered because no field measurement data of GHGs from Nam Theun 2 are available to the public as well as other sources of carbon input may not be considered as anthropogenic impact due to inundation.

According to the Environment Assessment and Management Plan (EAMP) of Nam Theun 2, the total original biomass amount in the impoundment area (assuming the area equals to the reservoir area at Full Supply Level (FSL)) was 4.95 Mt.

If we assuming an exponential decomposition pattern with an e-folding time of b years and a original flooded biomass percentage a, the biomass amount left at time t (Mt) will be

$$\mathrm{N} = 4.95 * \mathrm{a} * \mathrm{e}^{-\mathrm{t}/\mathrm{b}}$$

Equation 8

Using an unit convertor of 1Mt = 1.67 g/kWh (100-year energy generation is $6*10^{11}$kWh) and taking the negative derivative of Equation 8, we can get the carbon emission at time t (g/kWh)

$$\mathrm{C}\ (\mathrm{t}) = 1.67 * \left(-\frac{\mathrm{dN}}{\mathrm{dt}}\right) = 1.67 * \frac{1}{\mathrm{b}} * 4.95 * \mathrm{a} * \mathrm{e}^{-\mathrm{t}/\mathrm{b}}$$

Equation 9

The carbon will be released as CO_2 and CH_4 through aerobic and anaerobic decomposition, respectively. Assuming a CO_2: CH_4 ration c:(1-c), the emissions of both GHGs can be given as follows

$$\mathrm{CO_2(t)} = \frac{44}{12} * \mathrm{C(t)} * \mathrm{c}$$

Equation 10

$$\mathrm{CH_4(t)} = \frac{16}{12} * \mathrm{C(t)} * (1 - \mathrm{c})$$

Equation 11

Then the total global warming potential of both CO_2 and CH_4 at time t should be

$$\mathrm{Total\ GWP(t)_{CO_2+CH_4}} = \mathrm{CO_2(t)} + \mathrm{CH_4(t)} * \mathrm{total\ GWP(t)_{CH_4}}$$

Equation 12

If we integrate that up to 100 years lifetime, the cumulative total GWP of both CO_2 and CH_4 becomes

$$\text{Cumulative total GWP}_{CO_2+CH_4}\ (100\ \text{years}) = \int_0^{100} \text{Total GWP(t)}_{CO_2+CH_4}\,\text{dt}$$

Equation 13

Finally, substituting all the values into Equation 13, it should be calculated as

$$\text{Cumulative total GWP}_{CO_2+CH_4}\ (100\ \text{years}) = \int_0^{100} \left\{ 30.25 * \frac{ac}{b} e^{-t/b} + \frac{13243.03 * (1-c)a * e^{-t/b} * [1 - e^{(t-100)/b}]}{b * \left[0.217 * (100-t) - 44.78 * e^{(t-100)/172.9} - 6.26 * e^{(t-100)/18.51} - 0.22 * e^{(t-100)/1.186} + 51.26\right]} \right\} dt$$

Equation 14

The Monte Carlo simulation is used to estimate the cumulative total global warming potential from greenhouse gas emission in the operation phase. The variable distributions and characteristics are listed in Table 11 and graphed in Figure 11.

Table 11 Distributions and Characteristics of the Random Variables

r.v.	distribution	min value	most likely value	max value
a (original flooded biomass percentage)[38]	triangular	0.976	0.982	0.988
b (e-folding time, years)[39]	triangular	40	50	60
c (CO_2 emission percentage)[40]	triangular[41]	0.7	0.85	0.9

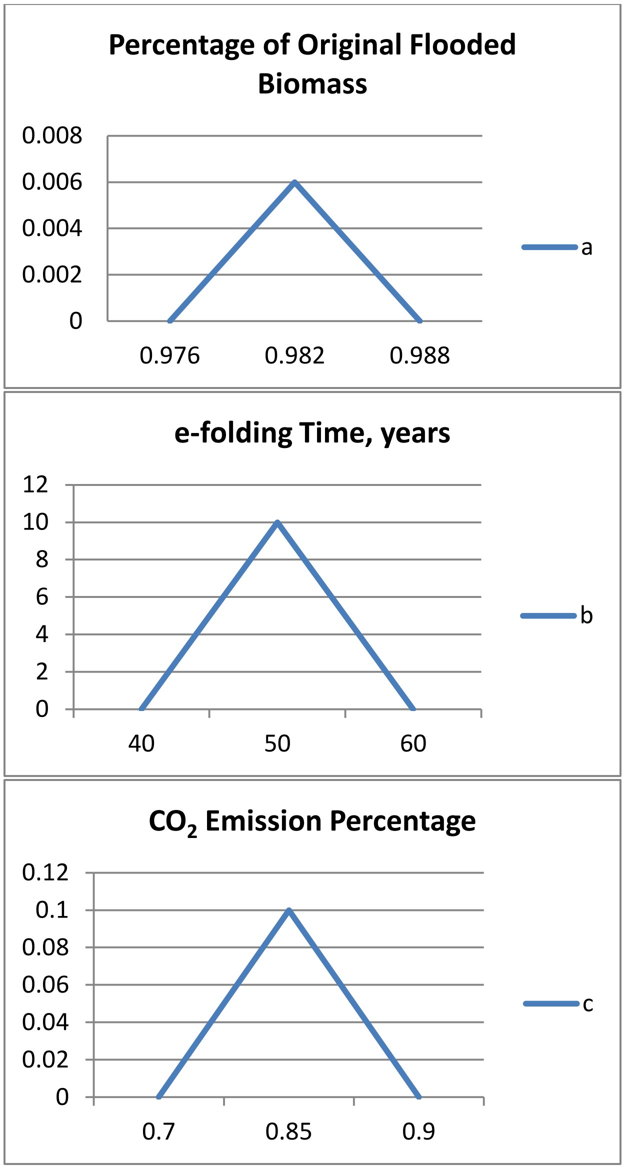


Figure 11 Distributions of the Random Variables in the Operation Phase

If assigning all the random variables the most likely value, we can get the most likely scenario for operation stage and a Cumulative total $GWP_{CO2+CH4}$ (100 years) value of 77.09 gCO_2 eq/kWh by integrating the emission path from Figure 12.

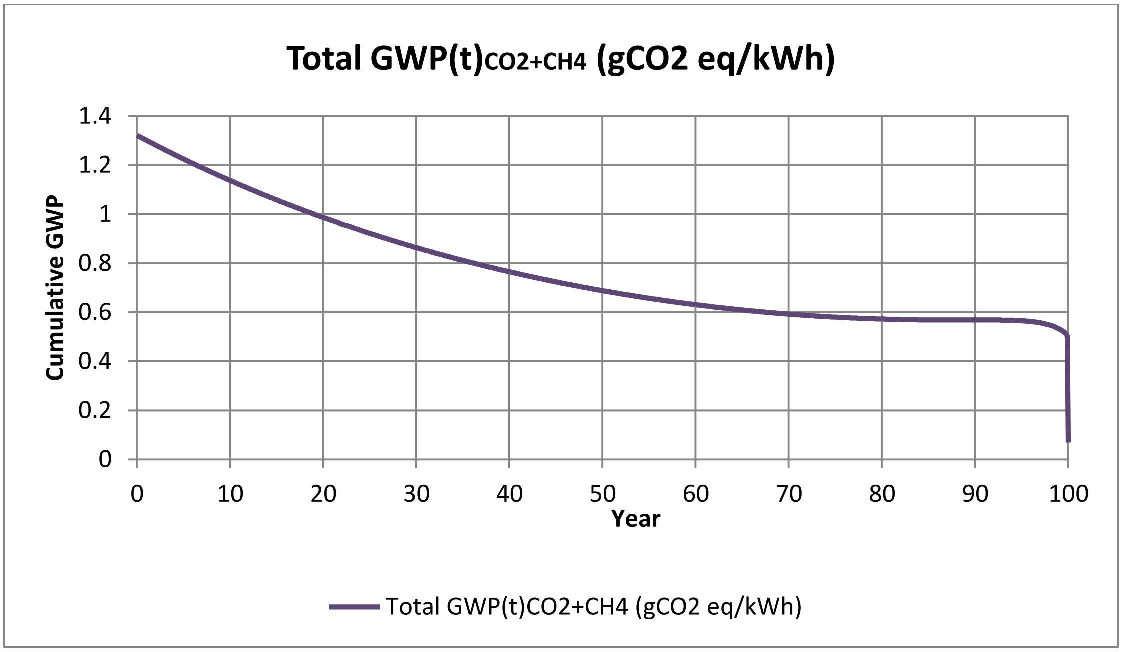


Figure 12 Total GWP of CO_2 and CH_4 at Time t in the Most Likely Scenario

The stochastic model diagram for the operation phase is as follows.

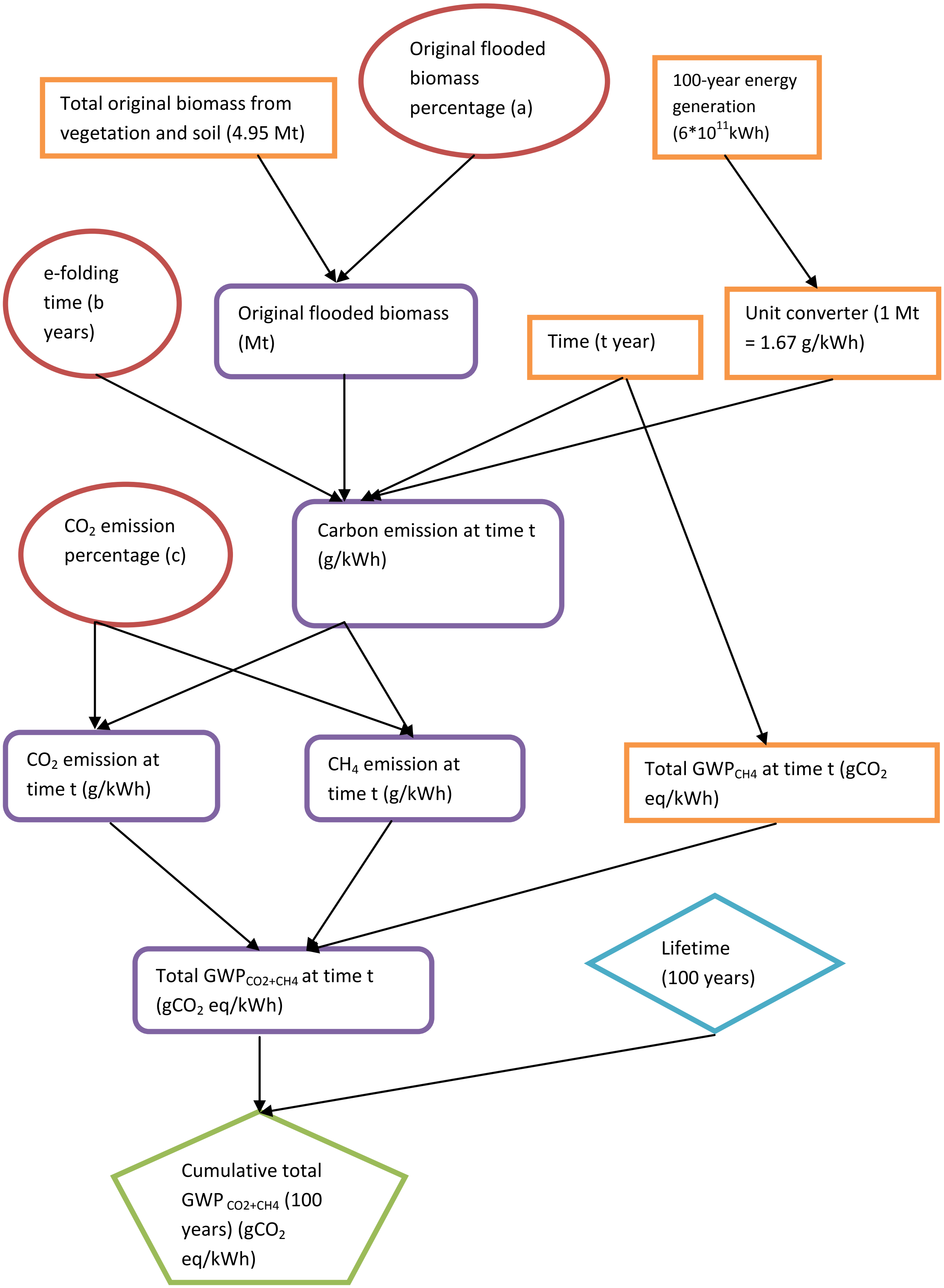


Figure 13 Monte Carlo Simulation Operation Model Diagram

Table 12 Descriptive Statistics for Operation Simulation (gCO_2 eq/kWh)

Mean	89.17
Median	87.14
Standard Error	0.42
Standard Deviation	13.34
Confidence Level (95.0%)	0.83

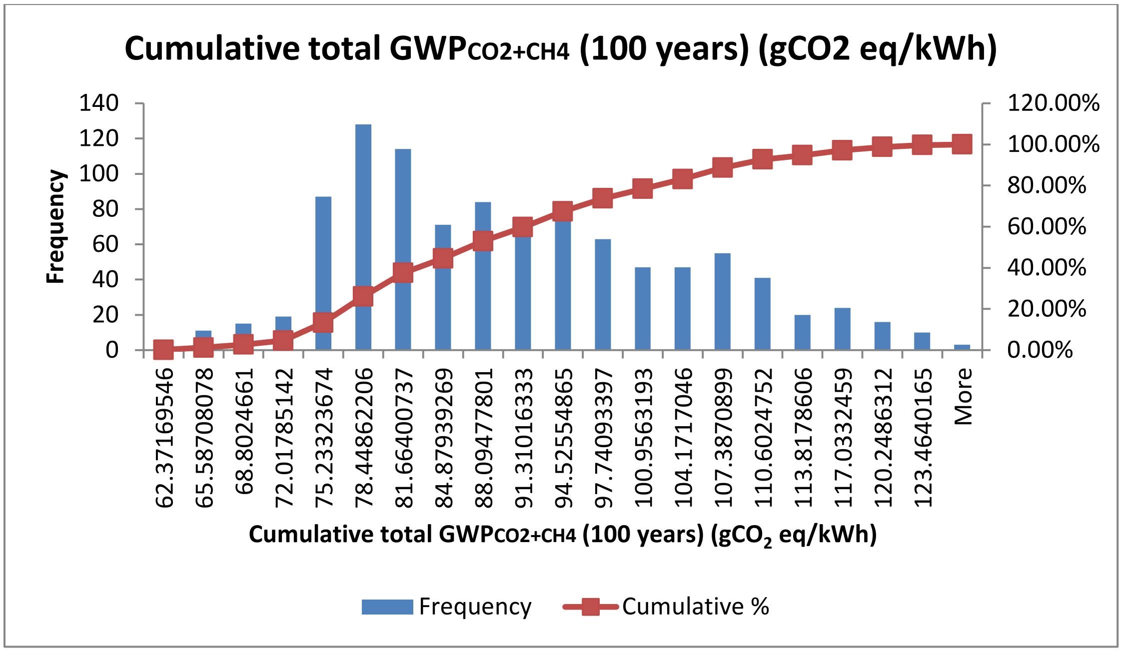


Figure 14 Probability Density Function (PDF) and Cumulative Density Function (CDF) of Cumulative Total GWP for CO_2 and CH_4 in 100 Years (Operation Phase)

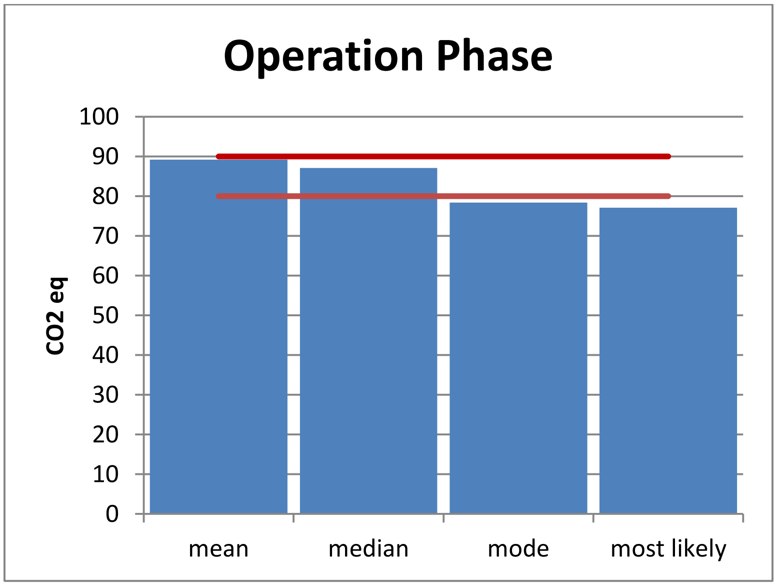


Figure 15 GWP Range for Operation Phase

The statistical mean for the operation simulation is 89.17 gCO_2 eq/kWh while the median is 87.14 gCO_2 eq/kWh. However, from the PDF above, we can tell the mode is around 78.45 gCO_2 eq/kWh, in agreement with the most likely scenario value, 77.09 gCO_2 eq/kWh. Therefore, the operation global warming potential will take a value around 80-90 gCO_2 eq/kWh indicated in Figure 15.

Net Ecosystem Production (NEP) Balance

Besides the flooded biomass GHG emissions, the filling of the reservoir displaced a previously balanced ecosystem, temperate forests in the Nam Theun 2 case, and resulted in a change of Net Ecosystem Production (NEP), which should be considered as an anthropogenic addition or subtraction depending on the sign of the change.

NEP is the difference between net primary productivity (NPP), which absorbs carbon from the atmosphere, and heterotrophic respiration, which releases carbon to the atmosphere[36]. A positive NEP suggests a carbon sink while a negative NEP indicates a carbon source.

It is defined as

$$\mathrm{NEP} = \mathrm{NPP} - \frac{\mathrm{C}}{\tau}$$

Equation 15

Where C is the amount of carbon stored in the terrestrial ecosystem, τ is the average turnover time, which is calculated as:

$$\tau = 42.8 * \mathrm{e}^{-1921*\left[{}^{1}/_{(283.15-139.4)} - {}^{1}/_{(\mathrm{MAT}-139.4)}\right]}$$

Equation 16

Using 297.95K[42] for the local mean annual temperature (MAT), annual NPP of 0.56 kg (C)/m^2[43] and a carbon density of 11 kg (C)/m^2 (vegetation + soil); we can get an annual NEP of -334 g (C)/m^2.

The negative value represents a carbon source instead of a carbon sink of the temperate forests before the formation of the Nakai reservoir. The 100-year emission is -0.92 gCO_2 eq/kWh while timing by entire reservoir area and dividing by annual energy generation as well as assuming all are released as CO_2. The value is far from significant compared to the original flooded biomass GHG emissions. Therefore, the creation of the reservoir does not have much influence on the NEP balance and it is neglected in the final estimation.

4.3. Decommissioning Phase

Sedimentation Rates

Snowy Mountains Engineering Corp. (SMEC) made an assessment of sediment loads in 1991 and the sedimentation of the reservoir is expected to be minimal. Studies suggest that if the sedimentation rates measured in the 1990's were to continue, it would take 1,800 years for the reservoir to fill with sediment. If sedimentation were to increase by 25 times, its effects would not be measureable until after 50 years and would be an unlikely case for generation to cease for a few hundred years after that. If sedimentation were to be 70 times present levels there would be a measurable reduction in electricity production of 11% at the end of 50 years. This would not impact on the present economic assessments and it would still not be a cause for decommissioning. Such extreme scenarios can be readily avoided and the Nam Theun 2 safeguard measures have bone to some lengths to ensure they are avoided[17 44].

While the reservoir sedimentation rates are too slow to result in any negative impact, a major concern would be the widening of the Xe Bang Fai downstream due to increased discharge and would result in local sedimentation, from bank collapse, into the stream. The new channel bed and banks are expected to restabilize after several flood seasons, but in the short-term seasonal sediment slugs are anticipated to occur in the Xe Bang Fai[17].

Project Decommissioning

The decommissioning of Nam Theun 2 hydroelectric project could involve removal of the Nakai Dam and power station and returning river to its original situation. However, depending on the slow rates of sedimentation and the length of service, the reservoir may have established a new valuable ecosystem and decommissioning of the project could therefore merely involve the removal of the power station and closure of the underground works[15].

The cost of decommissioning is estimated to be $300 million as in 2004 dollar and if assuming a discount rate of 17.1%, after the passage of the lifetime of the dam (100 years), the value of the initial $300 million will drop to only $20 and therefore the decommissioning cost will have no impact on present economic evaluations [17].

Carbon Mineralization

The average annual sediment load in the Nam Theun was estimated at 231,530t by SMEC (2003) based on suspended sediment sampling at Ban Thalang (447 samples from 1988 to 2002) and at the Nakai Dam site (299 samples from 1994 to 2002). In addition, SMEC assumes that all the sediment load of the Nam Theun will be trapped by the reservoir due to the high capacity-inflow ratio 0.52[4].

Assuming d be the carbon content of the sediment, e be the carbon mineralization percentage after 100 years dam lifetime when the project is decommissioned, a total carbon emission per kWh energy generated in 100 years will be

$$\text{Total C (g/kWh)} = \frac{(2.3153 * 10^{13}) * \mathrm{d} * \mathrm{e}}{(6 * 10^{11})}$$

Equation 17

As in the operation stage, the CO_2 emission percentage is denoted as c, we can have the total CO_2 and the total CH_4 emission from carbon mineralization from reservoir sediment

$$\text{Total } CO_2 \text{ (g/kWh)} = \frac{44}{12} * \text{Total C} * \mathrm{c}$$

Equation 18

$$\text{Total } CH_4 \text{ (g/kWh)} = \frac{16}{12} * \text{Total C} * (1 - \mathrm{c})$$

Equation 19

Consequently, the total GWP of both GHGs is given as

$$\text{Total GWP}_{CO_2+CH_4}\text{(100 years) (g}CO_2\text{eq/kWh)} = \text{Total } CO_2 + \text{Total } CH_4 * \text{total GWP(100)}_{CH_4}$$

Equation 20

Substituting all the values into Equation 20

$$\text{Total GWP}_{CO_2+CH_4}\text{(100 years) (g}CO_2\text{eq/kWh)} = 141.49 * \mathrm{d} * \mathrm{e} * \mathrm{c} + 1286.28 * \mathrm{d} * \mathrm{e} * (1 - \mathrm{c})$$

Equation 21

The distributions and characteristics of the random variables of Monte Carlo simulation are listed in Table 13 and graphed in Figure 16.

Table 13 Distributions and Characteristics of the Random Variables

r.v.	distribution	min value	most likely value	max value
d (carbon content)[45]	uniform	0.02	n.a.	0.03
e (carbon mineralization percentage)[46]	triangular	0.03	0.07	0.11
c (CO_2 emission percentage)[47]	triangular	0.7	0.85	0.9

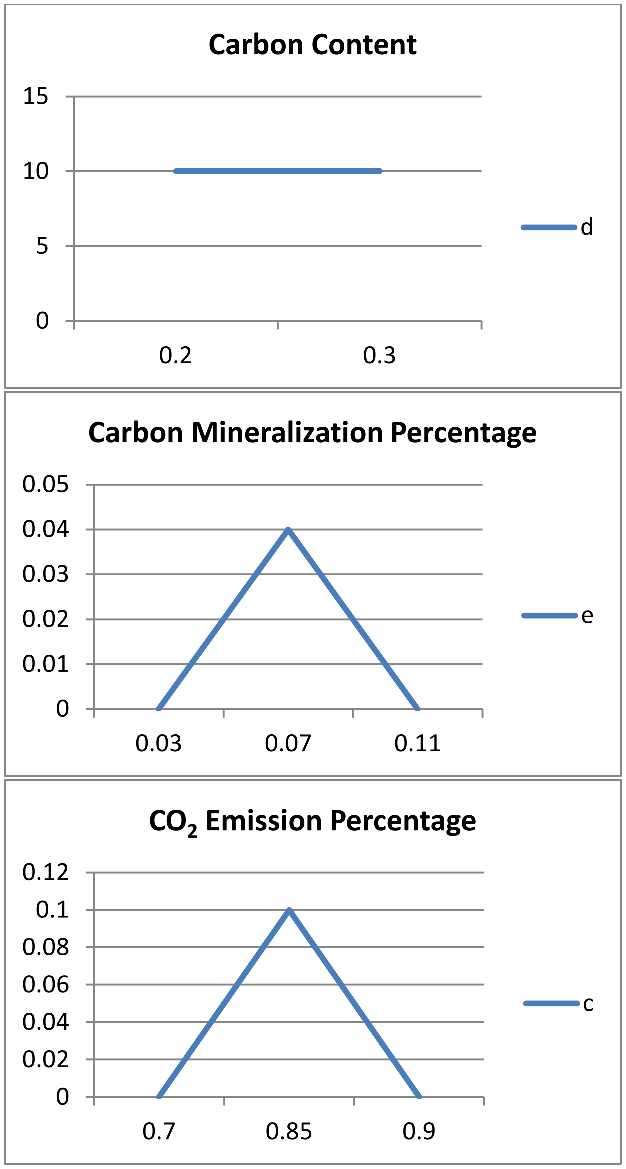


Figure 16 Distributions of the Random Variables in the Decommissioning Phase

If most likely value taken for r.v d, e and c, the total GWP for CO_2 and CH_4 is as follows

Total $GWP_{CO2+CH4}$ (100 years) (gCO2 eq /kWh) = 0.55.

Figure 17 presents the stochastic model diagram.

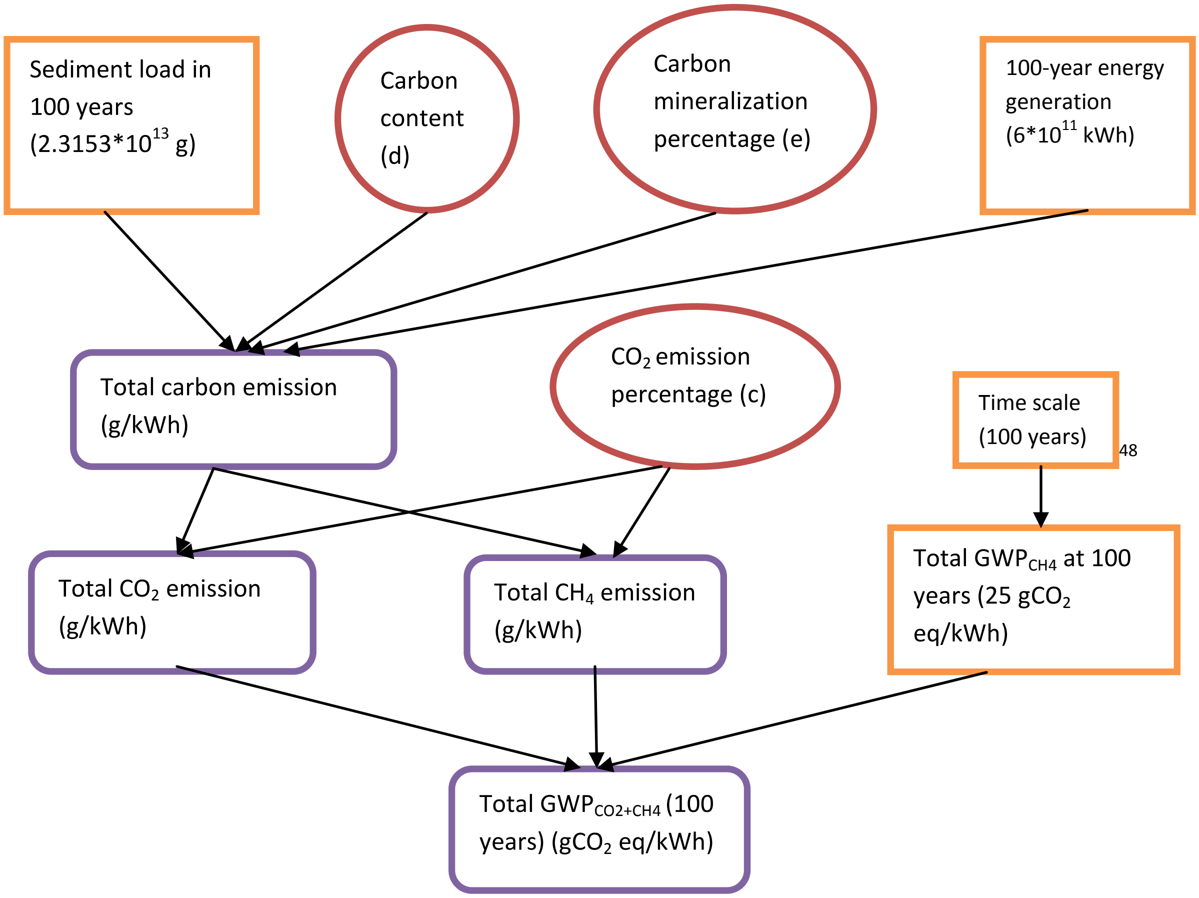


Figure 17 Monte Carlo Simulation Decommissioning Model Diagram

Table 14 Descriptive Statistics for Decommissioning Simulation (gCO_2 eq/kWh)

Mean	0.64
Median	0.62
Standard Error	0.006
Standard Deviation	0.18
Confidence Level (95.0%)	0.01

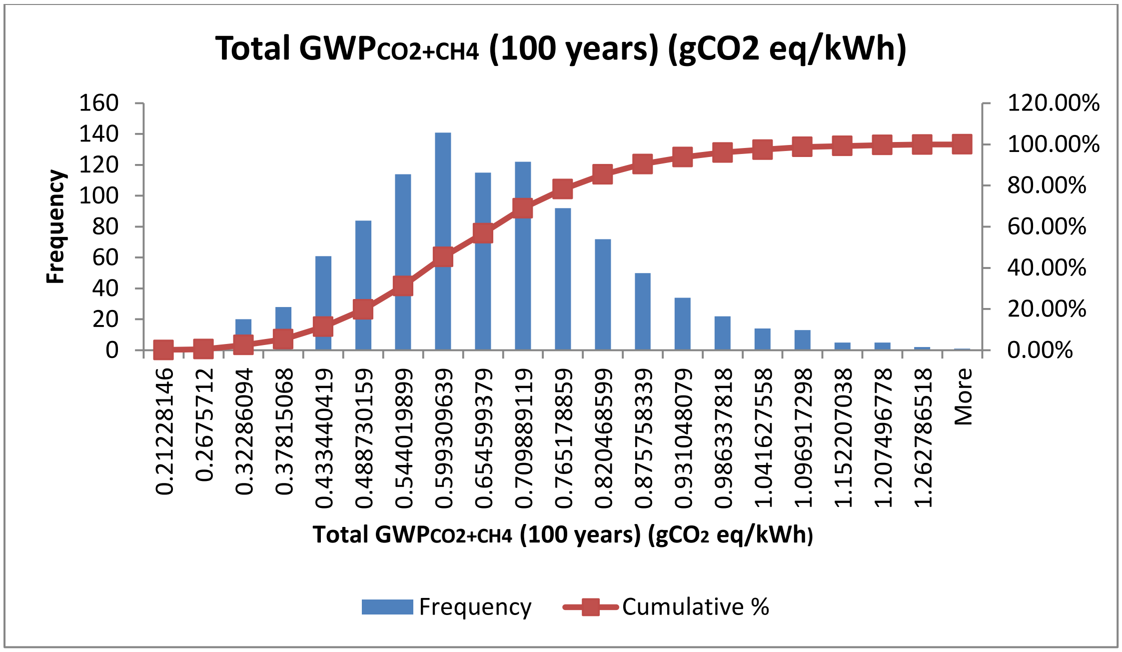


Figure 18 Probability Density Function (PDF) and Cumulative Density Function (CDF) of Total GWP for CO_2 and CH_4 in 100 Years (Decommissioning Phase)

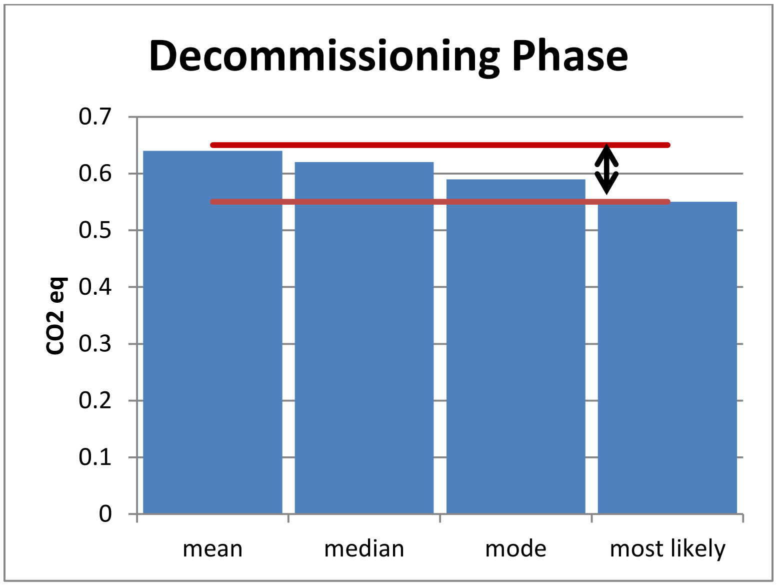


Figure 19 GWP Range for Decommissioning Phase

The statistical mean for the decommissioning simulation is 0.64 gCO_2 eq/kWh while the median is 0.62 gCO_2 eq/kWh. However, from the PDF above, we can tell the mode is around 0.59 gCO_2 eq/kWh, in agreement with the most likely scenario value, 0.55 gCO_2 eq/kWh. Therefore, the operation global warming potential will take a value around 0.55-0.65 gCO_2 eq/kWh indicated in Figure 19.

4.4. Results and Discussion

In summary and not surprisingly, the operation phase dominates the greenhouse gas emission from a hydropower dam and if we consider the original flooded biomass decomposition, it should have a GWP value of around 80-90 gCO_2eq/kWh, which is much higher than the previous estimated that takes a value around 10 gCO_2eq/kWh. And actually, lots of literatures also point out the fact that hydroelectric generation is not as "clean" as we thought before.

Table 15

CO_2 and CH_4 emission (gCO_2eq/kWh)	
Construction phase	2.5±0.5
Operation phase	75±5
Decommissioning phase	0.60±0.05
Total CO_2 and CH_4 emissions per kWh (g CO_2eq/kWh), 100 years	78.1±5.55

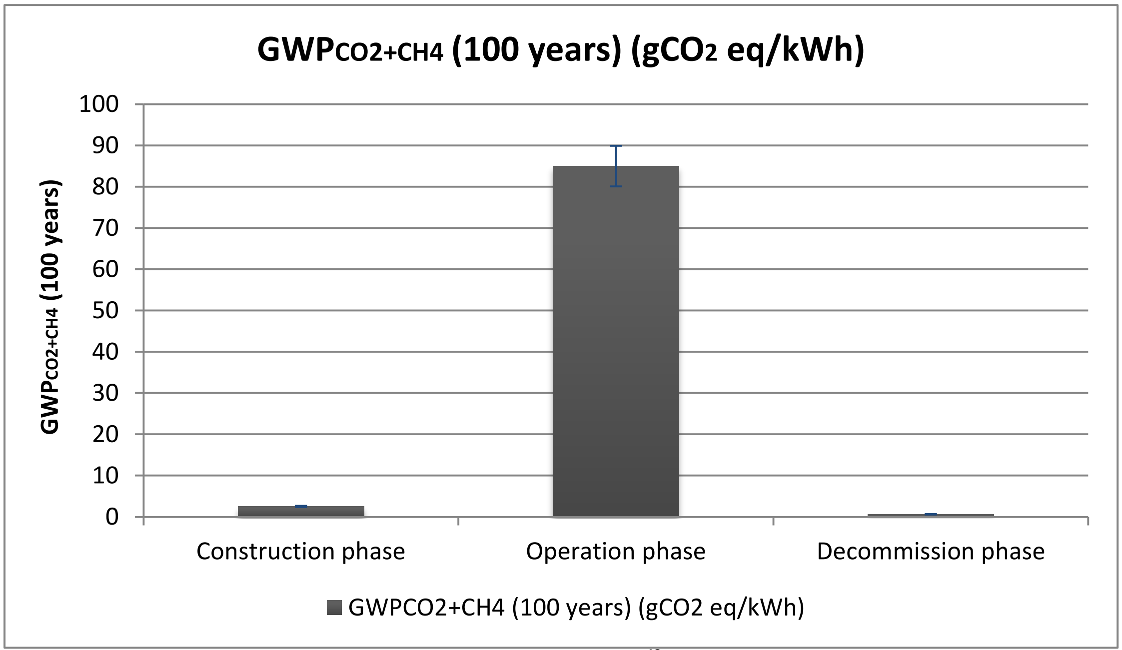


Figure 20 Estimated GWP for Life Cycle Emissions of Nam Theun 2[49]

Figure 21 gives out previous estimations of life cycle GHG emissions of various conventional and renewable energy generation approaches. The hydro GWP value calculated in our study is presented as the red column.

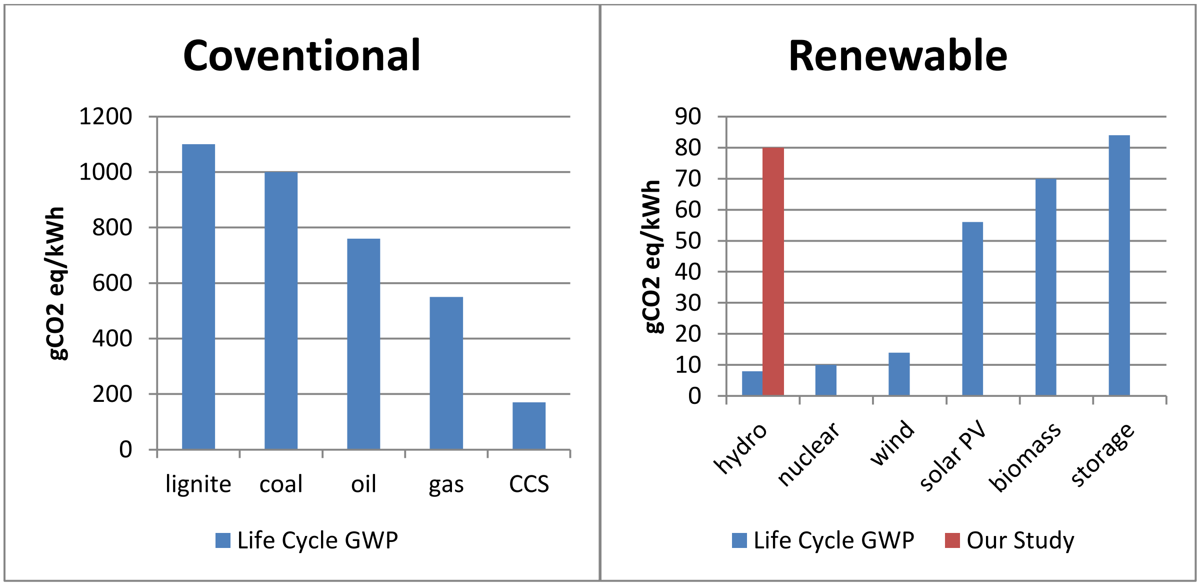


Figure 21 Summaries of Life Cycle GHG Emissions for Selected Power Plants[8]

5. Mitigation Recommendations

5.1. Planning

First of all, in order to reduce the global warming impact from reservoir emissions, we need to prevent low power density (the ratio between installed capacity and the reservoir area, less than 0.1 W/m^2) and take advantage of building deep reservoirs. Also, the planning of a multi-purpose reservoir including flooding control, irrigation and drinking water supply could mitigate the negative impact of the construction and operation.

Secondly, clearing of biomass prior to inundation not only improves the water quality but also benefits the global climate as less initial carbon load is subject to decomposition. The compliance with the land-clearance plan in the environmental assessment reports should improve both conditions while failure to stick to the plan may cause degraded water quality and severe climate change impact.

Finally, infrastructure modification can be involved to mitigate GHG emissions. According to Bambace et al. (2007), through the use of simple and inexpensive solutions and accurate environmental impact analysis, even during the post-construction phase, it is possible to reduce the environmental impact of hydroelectric reservoirs. If the installation of an aeration weir is a must for water quality purpose, light metal structures or even membranes as barriers, associated with buoys and anchors, could be used to control the position of spillways and turbines relative to the water surface to ensure only shallow, methane-depleted waters reach the intakes of them instead of deep, methane-rich ones[28].

5.2. Construction

The Head Contractor should comply with the existing construction schedule, otherwise if the inundation occurred before the transmission lines and other structure were installed and the reservoir remained full without any drawdowns, the reservoir turns anaerobic and resulting in fish kills and severe anaerobic decomposition within the reservoir that emits large amounts of high GWP value methane[4].

5.3. Monitoring

It is particularly important to develop and implement an entire set of standard methods for GHG measurement and monitoring. The United Nations Educational, Scientific and Cultural Organization (UNESCO) and International Hydropower Association (IHA) have initiated a GHG Research Project Workshops[50] aiming at better understanding the process and key parameters leading to the emission of methane from hydropower reservoirs and the standardization of measurement techniques.

In the Nam Theun 2 case, GHG will be monitored through ad hoc procedures with the support for EDF experts with similar experience on South American tropical reservoirs[23]. In addition, the Aquatic Environment Laboratory has begun testing greenhouse gas emissions from the reservoir as part of long-term research effort on the impacts of tropical reservoirs on climate change, but it is too early to build a picture of results[51].

Compared to GHG monitoring, water quality measurement in fresh water reservoirs is a more common procedure to comply with environmental safeguards and therefore the incorporation of water quality measurement with GHG monitoring can lead to more efficient use of equipment and labor resources.

5.4. Operation

During the operation of a hydropower dam, as to avoid substantive global warming impact, improvements in overall plant efficiency (capacity factor) and the resulting promotion in lifetime energy generation is crucial to further normalize the total GWP.

Hydro management should also be carefully executed to ensure the full supply reservoir water level in wet season and the drawdowns in dry season since in faster decomposition condition during humid weather, deep waters will increase the chance of methane oxidation through its going up to the surface and reduce methane production relative to carbon dioxide release.

5.5. Utilization

New studies of GHG emissions from hydropower reservoirs begin to examine the possibilities of transforming existing methane stocks of tropical reservoirs into a clean, renewable energy source although the purification of the recovered biogas might be a matter of concern due to the mix of carbon dioxide in methane[28 52].

The proposed CH_4 recovery strategy is based on the transport of methane-rich, pressurized, deep waters to surface ambient conditions through the use of a gate-buoy and a degassing system, as noted in the infrastructure modification, where the dissolved gas can be extracted by bubbling or by spraying droplets into a sealed vessel with a recovery efficiency of 79%[28].

The dynamics of gas-liquid separation is modeled in Bambace et al. (2007). From this model, for given methane concentration in the water, optimal operating conditions (maximum methane output, for example) may be derived[53].

5.6. Erosion and Sediment Control

Erosion and sediment control is crucial not only to GHG mitigation but to a series of environmental impacts. To mitigate against any impacts associated with reservoir erosion, the Head Contractor would prepare and implement an erosion and sedimentation plan according to Environmental Assessment and Management Plan for Nam Theun 2 including drainage works, sediment traps and other structures designed to improve water quality and also the Head Contractor would minimize working during wet season to further minimize any erosion[4]. The compliance with these plans regarding the construction of any dams is important to GHG mitigation.

Notes and References

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[39] According to the Nam Theun 2 Power Company. (2005). Environmental Assessment and Management Plan. Chapter 3 Assessment of Environmental Impacts., one study (Delmas et al. 2000) has attempted to evaluate the potential GHG emissions from the Nakai Reservoir using estimated emissions from the Petit Saut Reservoir in French Guyana (said to share similar characteristics as the Nakai Reservoir), therefore, I assume the e-folding time of biomass decomposition of the Nakai Reservoir be similar to that of the Petit Saut Reservoir. In terms of the Petit Saut Reservoir, "in 10 years, about 22% of the 10 Mt C flooded was lost to the atmosphere" (Abril et al. (2005). Carbon Dioxide and Methane Emissions and the Carbon Budget of a 10-year Old Tropical Reservoir (Petit Saut, French Guiana). Global Biogeochemical Cycles 19: 1-16.), corresponding to an e-folding time of 40 years; and also in 20 years, 3.2 Mt of the 10 Mt C was released (Galy-Lacaux et al. (1999)). Long-term Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Forest Regions. Global Biogeochemical Cycles 13 (2): 503-517.), corresponding to an e-folding time of 50 years. Therefore, I assume a minimum value of 40 years, a most likely value of 50 years and a maximum value of 60 years.

[40] In the Petit Saut Reservoir case, 85% of carbon emission was released as CO_2 in 20 years. So I take a most likely value of CO_2 emission percentage 0.85. In addition, according to Rosa and Schaeffer. (1995). Global Warming Potentials: the Case of Emissions from Dams. Energy Policy 23 (2): 149-158, 10-30% of carbon was subject to anaerobic decomposition, which gave the minimum value of 0.7 and the maximum value of 0.9.

[41] Triangular distribution in Monte Carlo Simulation is used to describe random variables (r.v.) for which there is little information and the uniform distribution is not appropriate.

[42] According to Nam Theun/Cading http://flood.dpri.kyoto-u.ac.jp/ihp_rsc/riverCatalogue/Vol_03/06_Lao-4.pdf, the annual average temperature Nam Theun/Cading is 297.95K.

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[46] In the Pacca. (2007) paper, a GHG emission analysis from decommissioned hydroelectric dams was done and it was calculated 3-11% sediment pool might be mineralized after the project lifetime. Here we assume a minimum value of 3% and a maximum of 11% with a most likely value of 7%.

[47] Same distribution and characteristics as in the operation phase.

[48] The 100 year time scale chosen is arbitrary. There is no consensus on the time frame within which the global warming potential be assessed after the dam is decommissioned. Choosing a 100-year GWP_{CH4} value is to agree with the operation lifetime, which is also assumed to be 100 years. As a result, including the decommissioning phase into the dam life cycle extends the total evaluation lifetime to 200 years.

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