Global Warming Effect Applied to Electricity Generation Technologies

by

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Abstract

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ABSTRACT GOES HERE

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LIST OF ACRONYMS

AFBC	atmospheric fluidized bed combustion plant
BOS	balance of the system
BC	black carbon
BCA	benefit cost analysis
BEA	Bureau of Economic Analysis
Btu	British thermal unit
CPI	consumer price index
EEI	energy efficiency index
EIO-LCA	economic input-output life-cycle assessment
ELN	Eletronorte
GHG	greenhouse gas
GWE	global warming effect
GWh	gigawatt-hour
GWP	global warming potential
HILDA	high latitude exchange/interior diffusion advection
IGCC	integrated gasification combined cycle
IPCC	intergovernmental panel on climate change
kWp	kilowatt peak – photovoltaic module capacity
LCA	life-cycle assessment
LEBS	low emission boiler systems
m-Si	mono-crystalline silicon
MCFC	molten carbonate fuel cells
MTC	metric tons of carbon
$MTCO_2Eq$	metric tons of carbon dioxide equivalent
MW	megawatt
NEA	net energy analysis
NREL	National Renewable Energy Laboratory
NSPS	new source performance standards
NTEL	National Energy Technology Laboratory
Pg	petagrams

p-Si	poly-crystalline silicon
ppb	parts per billion
ppm	parts per million
SETAC	Society of Environmental Toxicology and Chemistry
TAR	third assessment report from the IPCC
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
OMB	U.S. Office of Management and Budget
USBR	U.S. Bureau of Reclamation

LIST OF SYMBOLS

C	carbon
CH_4	methane
CO_2	carbon dioxide
N_2O	nitrous oxide
NO_x	nitrogen oxides
CuO	copper oxide
SO_2	sulfur dioxide

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Chapter 1: Introduction

Climate change is a global problem in a complex realm of interactions between climatic, environmental, economic, political, institutional, social and technological processes. Effects of climate change manifest over long time horizons and any action taken now will affect our sustainable development. Anthropogenic releases of greenhouse gases (GHGs) in the biosphere are the major cause for climate change, and electricity generation accounts for 2.1 Gt yr^{-1} (Giga metric tons of carbon per year) or 37.5% of total global carbon emissions [Metz 2001]. Lower GHGs emission scenarios require different patterns of energy development and there is no single path to a low emission future. This work proposes a framework to support the selection of the electricity generation technology with the lowest global warming effect (GWE) amongst a set of available, feasible alternatives. The intent is to reconcile local decisions with a global development path to minimize climate change.

The design of the research framework and the creation of a spreadsheet-based decision-support tool, intend to be transparent and flexible. The user is encouraged to change parameters and input the data that she understands is the most relevant for each analysis. By applying the framework, the users should not only be concerned with the final results but with the process itself. To facilitate that discernment, this work presents a systematization of the sources of problems and uncertainties embedded in each of the components of the framework.

Consequently, potential users of the GWE are analysts who recognize that the selection of electricity generation technologies to mitigate climate change involves a set of assumptions, choices, and uncertainties that affect the result of the assessment. Dealing with this set of variables is fundamental in any environmental policy analysis, and therefore, students who are getting engaged in quantitative policy analysis could benefit from the GWE framework.

Decision-makers interested in the mitigation of climate change may benefit from the GWE framework to initiate programs supporting technologies that reduce the burden of climate change over time frames tailored to their needs. Analysts working for agencies, development banks and foundations that solicit energy projects may benefit from the GWE to assess the performance of different proposed alternatives. The industry involved in the manufacturing of power plant components and electricity generation technologies may use the GWE framework to identify ways of improving the performance of their products and services. In summary, the GWE framework is designed to support the work of a range of users who are committed to the mitigation of climate change.

The present dissertation is organized into eight chapters. In Chapter 2, a brief literature review is presented followed by a discussion of the methods that are characterized as precursors of the life-cycle assessment (LCA) method, which is a component of the GWE. Methods focusing on energy use that were motivated by the oil crisis in the 1970s and lately evolved into energy payback calculations are reviewed. Methods that attempt to identify carbon dioxide (CO_2) emissions over the full fuel cycle of a power plant are also amongst the LCA precursors that have been applied to energy analysis.

Next, a more up to date alternative already focusing on climate change impacts and using current LCA methods is discussed. LCA is one of the pillars of the GWE method, which aggregates the fundamental systemic view of LCA into the time-integrated analysis derived from climate change science. The temporal dimension characteristic of the climate change science is incorporated into the GWE method as an alternative to time-dependent economic analysis. Indeed, if the concern is the comparison of power sources over time based on their global impacts, alternatively economic tools such as benefit-cost analysis (BCA) could be used. The chapter ends with a discussion of BCA applied to climate change and the problems associated with the use of this technique. A critique of BCA calls for the use of competing methods that are also able to compare the performance of technologies based on their environmental impacts over flexible analytical periods.

In chapter 3, the GWE framework is explained. It is proposed in this dissertation in order to compare electricity generation options based on their relative impact on global climate change is explained. The GWE intends to be transparent enough to reveal choices, assumptions, and uncertainties involved in the analysis. The method is composed of two well-established methods: LCA and Global Warming Potential (GWP). Because the framework aggregates different methods and these methods rely on other methods and models, there is a chain of problems that are discussed with clarity to validate the framework. A classification composed of three sources of problems is proposed:

1. problems related to the LCA method

2. problems related to the GWP method

3. problems related to the characterization of power plants

For each class a sub-classification is presented to help the user of the framework with the identification of choices and uncertainties involved with the adoption of the GWE framework.

In chapter 4, various electricity case studies involving the use of the framework are presented. The selection of different case studies aims to explore the variability associated with different electricity supply options. In terms of technologies, hydroelectric plants, solar photovoltaic (PV) modules, wind turbines, coal fired power plants, and natural gas fueled plants, are considered. Potentially, the application of the GWE can be extended to other electricity supply technologies and to any other technology currently in operation or expected in the future.

In chapter 5, the results from the case studies presented in chapter 4 are discussed and compared with the range of values identified in the literature for each of the electricity supply technologies.

In chapter 6, the adequacy of the GWE as a decision support tool is discussed emphasizing the use of the framework in environmental policy and management.

In chapter 7, the contribution of this research is presented.

In chapter 8, future work and research needs are described.

Chapter 2: Life-cycle Assessment (LCA) Precursors to Compare Electricity Generation Options

Frameworks for analyzing the performance of electricity supply options by looking at the complete life-cycle of processes have existed for some time. Most of these frameworks evolved from concerns with the oil shortage in the late 1970s, and attempted to reduce fossil fuel consumption over the life-cycle of power plants. The origin of such studies goes back to net energy analysis (NEA), a term coined to assess the energy input-output ratio of energy supply and conservation technologies. Usually these studies looked at more traditional sources of energy such as coal, oil, gas, hydro, and nuclear [Chapman 1974, Chapman 1975] but some also looked at renewable sources [Haack 1981, Herendeen 1981]. NEA aims to measure all energy flows associated with energy technologies during their different phases using either input-output techniques or process analysis. The adoption of such approach was recommended in the Non Nuclear Energy Research and Development Act of 1974 in the U.S. [Leach 1975].

Nevertheless, the definition of NEA was not precise enough to spur its application. Fuel cycle studies, which appeared in the late 1980s, are based on the same logic as NEAs. In addition to the concern with energy consumption, analysts became also concerned with the incorporation of environmental impacts, and the extension from energy to carbon emissions was natural since most energy sources rely on fossil fuels combustion that releases carbon dioxide.

Total fuel cycle studies capture the whole chain of carbon dioxide emissions during materials production, construction, operation and decommissioning of power plants [Meridian Corp.

1989, San Martin 1989, Uchiyama 1991, Uchiyama 1992]. Results are reported in metric tons of CO_2 per energy output (GWh) [Meridian Corp. 1989, San Martin 1989] Those studies were based on the identification of fuel consumption in each of the life phases of the project and its conversion to an environmental indicator such as CO_2 emissions. However, this method was unable to capture secondary impacts pertaining to the energy chain coupled to the generation of electricity [Meridian Corp. 1989].

The need for an analytical framework that broadens the operation of electricity production systems became fundamental for analyzing and comparing different alternatives. In the case of PV systems, the necessity to prove that they were net energy sources led to life-cycle based energy payback calculations including all direct and indirect energy inputs in the fabrication and installation of the systems. This assessment was broader, and included indirect energy used in the production chain of the modules and other parts of the PV systems. The energy payback time indicates the time necessary to match energy inputs in the facility with its energy yields [Alsema 2000].

$$\text{Energy Payback Time} = \frac{\text{Life-cycle primary energy consumed by the generation sytem (kWh)}}{\text{Annual power generation (kWh/yr)}} \qquad (1)$$

2.1 LCA in Energy Analysis

Presently, life-cycle assessment (LCA) is applied to address the consumption of energy and materials over the life of power plants [Uchiyama 2002, Gagnon 2002]. The goal of a LCA is to quantify material and energy resource inputs as well as waste and pollutants outputs in the production of a product or service. The method attempts to systematically quantify the environmental effects of the various stages of a product or process life-cycle: materials extraction, manufacturing/production, use/operation, and ultimate disposal (or end-of-life). The challenge is to map production processes so that they accurately represent current industry practices and trends. Several LCA tools provide process descriptions and flow diagrams, and libraries of data to users in order to help the execution of LCA [Gabi 3 2003, SimaPro 5 2003]. Existing studies differ in the number of environmental effects quantified, and in the scope of the analysis (where the boundary of the analysis is drawn). Currently, there are two major approaches to boundary setting: a process-based model developed most intensively by the Society for Environmental Toxicology and Chemistry (SETAC) and the U.S. Environmental Protection Agency (EPA) [Curran 1996], and an economic input-output analysis-based model called EIO-LCA [EIO-LCA 2003, Hendrickson 1998]. The SETAC approach has a more flexible boundary, which usually is selected at the discretion of the analyst and is molded based on a specific case study. The boundary of input-output based LCAs is predisposed by the boundary of the economic system from which data are extracted. One strength of the input-output analytical framework is its completeness regarding the coverage of the inputs in a given product or sector [Lenzen 2001].

In comparison, the SETAC-EPA approach divides each product into individual process flows, and strives to quantify their environmental effects. This LCA comprises four major components. First, the goal and scope definition establishes the objective of the analysis and what criteria best represent the performance of the assessed alternatives to accomplish the chosen objective. Second, the inventory analysis attempts to identify the major material and energy inputs associated with the production of the subject of the assessment. Third, during the impact assessment the effects arising from the use of each input in the production of the good are quantified and finally aggregated to yield the life-cycle impact of the object of the analysis. Fourth, results are interpreted by means of comparisons, rankings, sensitivity analyses, simulations, etc.

The inventory analysis of the SETAC-EPA method is constrained by the perceptionof the analyst on what is important to be quantified. For example, in the manufacturing stage of products, the analyst attempts to trace inputs as far back ("upstream") in the production chain as possible. This assessment is typically limited by data availability, time and cost, and includes the first tier (direct) suppliers, but seldom the complete hierarchy of suppliers, i.e., all the suppliers of suppliers (and thus the indirect effects). A problem defined as "truncation error" reflects the omission of some of the processes in the production chain and in the final results of the analysis from the boundary selection of this kind of LCA [Lenzen 2001].

In contrast, input-output based approaches essentially enclose all upstream production phases. The EIO-LCA model uses the 498x498 economic input-output commodity-by-commodity matrix of the U.S. economy (a general interdependency model) to identify the entire chain of suppliers (both direct and indirect) of a commodity. In this case, the boundary of the assessment is set at the national economy level. The 498x498 matrix is based on commodities such as cement, steel, coal, sugar, etc. To obtain the total (direct plus indirect) economic demand, final purchase (final demand) amounts are specified to the model. The results are then multiplied by matrices of energy use and emission factors calculated by economic sector level (e.g., energy use per dollar). The base year for EIO-LCA data is currently 1997. The EIO-LCA model has been applied to a number of product assessments [see, e.g., Lave 2000, Horvath 1998a, Horvath 1998b].

The EIO-LCA method is comprehensive and covers all commodities exchanged in a given economy. On the one hand, the selection of a national or regional economy establishes well defined boundaries for the calculation of emission factors. On the other hand, such emission factors are averages that correspond to a mix of agents (producers, service providers, etc) developing the same activity within the given economy. Averages do not represent the performance of a specific agent within an economic sector, who may be above or below the average performance of the sector, nor it represents the performance of a foreign producer that sells her products in the American market, which is modeled by the EIO-LCA. In order to deal with this particular problem, EIO-LCA assumes that imported goods are produced similarly to domestic goods.

Depending on the intent of the analyst the use of emission factors provided by EIO-LCA may lead to inaccurate emission factors for a given product. This is due to the aggregation level of the sectors modeled. Each specific sector modeled by the Bureau of Economic Analysis (BEA) is in fact a bundle of goods and services that in some cases are very disparate, and therefore, products or services within the same sector may actually lead to completely different emission factors.

In addition to a classification problem that averages the emission factors for products and services that involve different production chains and technologies, different emission factors for the production of the same commodity are also possible because of the technological heterogeneity amongst producers that manufacture a similar final product.

Knowledge about technology is also important because technology is dynamic and due to the time involved with data collection and information treatment there is always a time lag between the EIO-LCA data and the current technology. The magnitude of this problem varies according to the product and sector because some sectors are quite stable in terms of technological innovation, whereas other sectors change their technology more rapidly. Temporal changes also affect the use of emission factors from EIO-LCA because they are based on prices and prices are relative and change over time. Finally, the issue of technology spans over differences in scale between different firms. A given technology may be more adequate for a small sized firm with a small output but when the scale is larger another technology may be more appropriate.

The problems with the LCA part of the GWE framework are discussed in detail in section 3.2.1. In order to provide an organized view about problems arising from the use of LCA the following classification is proposed: data, temporal constraint, economic boundary, and methodological constraints. Data problems are associated with the collection and treatment of the information, temporal problems address the effects of time in the results from LCAs, economic boundary problems are related to the choice of economic transactions to intermediate the flows of commodities, energy and pollution within a specific territory, and methodological constraints are related with mathematical presumptions in the model such as linear relationships.

Even if the application of the EIO-LCA needs to be supported by knowledge on its limitations and the use of a process LCA has other sorts of problems, the structure of energy generation systems demands a life-cycle approach to reveal the potential of an alternative to achieve increased performance and reduce emissions [Nieuwlaar 1996]. Indeed, LCA is fundamental to assess any kind of technology, especially in the case of climate change because the location of the emission sources does not affect the potential impacts. That is, the global warming effect is global in comparison to effects from regional pollutants.

A LCA attempts to capture impacts from every phase of a process as shown in figure 1. Because energy is consumed in every step, some greenhouse gas (GHG) emissions are also associated with them.

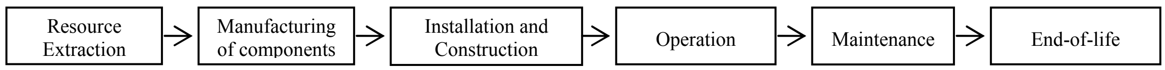

Figure 1: Phases of a Product or Service in a LCA

2.2 Comparison of Energy Technologies and Climate Change

The dilemma in climate change decision-making is to use GWE as an indicator and make a value judgement up front, which considers higher GWE worse than lower GWE, or to try to quantify the actual impacts from future climate change under different circumstances. The comparison of a plethora of impacts, which could be expressed in different terms, demands the translation to a common unit. Economic analysis could be used to ascribe monetary values to all sorts of impacts. On the one hand, quantification of all impacts in the same monetary basis allows welfare maximization. On the other hand, this method is controversial because human values and environmental characteristics vary across regions, either now or over time, and therefore, economic analysis is ill equipped to capture these nuances [O' Neill 1993, Bradford 1999].

Costs and Benefits included in a CBA should account for both market valued impacts and externalities. An externality arises when a value is not fully captured in the economic assessment of a production process. However, the problem is that usually there is a disconnection between the ones benefiting from the externality and the ones being affected. In the electricity sector externalities associated with production of pollution arise because the value of the damage caused by pollution elsewhere is not included amongst the costs of the electricity producer. The solution to this problem is in part associated with the establishment of property rights coupled to the elements affected by pollution. A subsidy for the electricity generator is another example of externalities for this sector. In this case the cost of an input used by the producer to generate electricity is below market prices. Tax and insurance differentiation, distortion in markets for labor, land, and energy resources also contribute for the production of externalities in the electricity sector. The existence of externalities distorts the prices, and therefore, the results of an economic analysis depend on how externalities are defined, identified, and evaluated. This is another drawback for the use of economics because it challenges the claim that economic analysis produces a unique and precise answer for any resource allocation problem. In the case of climate change the disconnection between the ones benefiting from the use of energy and the ones affected by the emissions of greenhouse gases and their impacts on the global climate is a temporal problem that can be framed as a intergenerational equity issue.

In this work I attempt to compare the global environmental performance of different electricity supply technologies over time using the GWE method. Alternatively, economic analysis could be used in the comparison and probably the causalities of climate change, which are discussed with some level of detail in this study, would be implicit in a Benefit Cost Analysis (BCA)-like analysis. Besides, if a BCA framework is chosen, instead of comparing the effect of GHGs over time I would be comparing economic values over time and one problem that would arise is the selection of an appropriate discount rate to compare alternatives over time. In short, similarly to what happens to GWE's formulation assumptions and uncertainties are also associated with BCA. These problems are briefly discussed in the next sections.

2.2.1 Benefit-Cost Analysis (BCA) Applied to Climate Change

BCA is the conventional economic approach to design public policy [Nordhaus 1999]. In addition, some economists claim that sustainability issues are addressed through BCA [Howarth 1995]. Accordingly, the use of economic analysis to evaluate outcomes from future climate change has been widely discussed by the Working Group III of the Intergovernmental Panel on Climate Change (IPCC) which was structured to assess "cross-cutting economic and other issues related to climate change." The IPCC second assessment report is not conclusive but acknowledges the difficulty to assess benefits and costs related to climate change effects in economic terms [Bruce 1996].

When economists deal with values in the future, which is the case with climate change, they look at the stream of future values in terms of their net present value. Therefore, the trade-off between consumption today and consumption in the future raises two central questions: first, how to think about this trade-off; second, what numerical value to attach to it. [Bruce 1996]. The first problem lies on the discussion of economic discounting, the second one relates to a pure valuation problem.

2.2.1.1 Economic Discounting

Economic discounting issues arise when economic outcomes associated with a stream of benefits and costs over time are compared using discount rates that translate future values into present values. This comparison is particularly important if we ponder that for economists sustainability is a matter of intergenerational equity or how resources are distributed between generations [Howarth 1992].

Discount rates embody different factors, which change the value of money over time, such as interest rates, inflation, and taxes. Interest rates are probably the most interesting component because they are intertwined with a great variety of forces, chiefly independent of the particular commodity and industry in question [Hotteling 1931]. Private interest rates reflect the anxiety of consumers and the marginal productivity of invested capital, and both of them depend on the equilibrium of the market economy.

In traditional BCA, the weight attributed to benefit and costs at different times is critical and is determined by the discount rate used. The higher the discount rate the lower future benefits and costs are when compared to present ones. The choice of market discount rates to deal with environmental problems steaming from energy use has been challenged because of some intricacies associated with the matter. The use of current market discount rates would reveal a myopic view of the distribution of benefits and costs over time because long time frames, which are not reflected in market discount rates, characterize natural processes associated with energy technologies [Lind 1982].

For example, in the case of nuclear power the use of a 10 % discount rate, as was specified by the U.S. Office of Management and Budget (OMB), converts high environmental costs such as the disposal of nuclear waste, to a negligible present value [Lind 1982]. A similar problem occurs with climate change because natural processes controlling the atmosphere, the oceans and ecosystems are characterized by long time frames, for example:

• decades to centuries are necessary to balance the climate system given a stable level of GHG concentrations,

• centuries are necessary to equilibrate sea level given a stable climate,

• decades to centuries are necessary to restore/rehabilitate damaged or disturbed ecological systems, and moreover, some changes are irreversible.

• decades to millennia are necessary to balance atmospheric concentrations of long-lived green-house gases given a stable level of GHG emissions,

As a matter of fact, a natural process, such as carbon dioxide decay in the biosphere entails a discount rate for capital, which is usually much less than is considered in economic appraisals of federal projects. The Appendix C of the Circular No. A-94 published by the Office of Management and Budget (OMB) of the White House stipulates real interest rates on treasury notes and bonds of specified maturities, which are used in cost-effectiveness analysis over a 30 year period to 3.2% per year [OMB 2003]. Figure 2 shows the effects of discounting over time using the discount rate prescribed by OMB and the persistence of carbon dioxide in the atmosphere, represented by a parameterized function [Watson 2000].

In addition, one could argue that future pleasures are ethically equivalent to present pleasures of the same intensity [Hotteling 1931]. Consequently, it would make sense to apply a zero discount rate to run policy optimization models to reflect this postulate since future generations are the ones who bear the costs of environmental degradation from climate change.

Recent analyses of impacts from climate change have shown that the pursuit of sustainable development requires low discount rates to evaluate environmental services [Howarth 1992, Howarth 1995]. Sustainability requires equitable distributions of resources between present and future generations; however, traditional economic analysis incorrectly treats efficiency and equity [Howarth 1990]. While a mathematical framework identifies the most efficient point on the utility possibility frontier, which optimizes the social use of resources, the result depends on the initial allocation of resources. A competing initial allocation, which takes into account a more equitable distribution of resources, leads to a distinct optimum point; therefore, sustainability is a matter of resources distribution across generations [Howarth 1992].

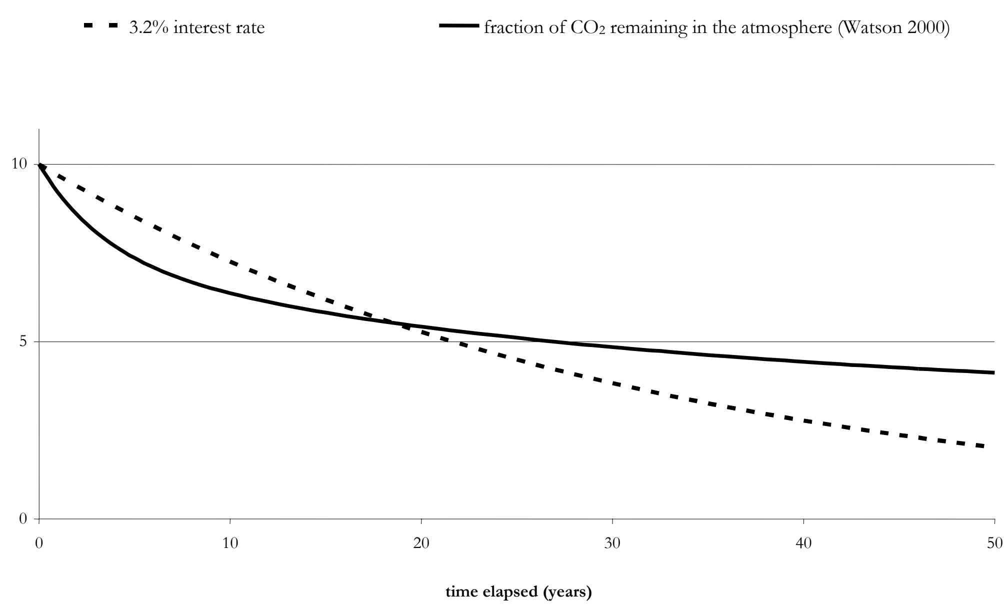

Figure 2: Changes in Value and Atmospheric Concentration of Carbon Dioxide

Concerned with equitable welfare distribution, Howarth and Norgaard built an overlapping generation model to illustrate that initial property rights determine the equilibrium and distribution of welfare in a market economy. In their model, consumption and investment levels are controlled by two generations that overlap, that is, old individuals of the earlier generation and young individuals of the next generation live part of their lives together. In addition, they assume that GHGs, which are associated with energy use in the economy, have a negative impact on production [Howarth 1992]. Other ordinary economic assumptions are made, such as diminishing marginal utility across all consumption goods, and positive marginal time preference. Besides, the government operates capital transfers between generations, which allow equitable welfare distribution and sustainable development.

Consequently, the equilibrium of the model and the value of all variables are function of transfers between generations. The result is that the more assets are transferred to the next generation, the lower is the discount rate; moreover, higher values are assigned to environmental services. In short, they prove within the economic framework that the adoption of low interest rates is part of a value judgment concerning an equitable distribution of welfare between generations, and not an issue of pure mathematical efficiency [Howarth 1998].

In summary, long time scales associated with climate change make discounting critical and the literature shows that lower rates, which give more weight to long term benefits should be considered. However, there is still no consensus on long term discount rates, even if it is accepted that they should be distinguished from private market discount rates [Metz 2001].

2.2.1.2 Economic Valuation

The second problem associated with economic impact valuation is the quantification of climate change impacts or how changes in the concentration of GHG in the biosphere are translated into socioeconomic impacts. The use of economics presupposes that we know the value of environmental services now and in the future, which are either already incorporated in the market or are converted into monetary values by the person in charge of the BCA. The assertion that from economic perspective sustainability is a matter of intergenerational equity is based on the assumption that values and preferences don not change over time, which is not the case. Personal and societal choices are dynamic and something that is accepted today may not be tolerated in the future.

Nonetheless, international development agencies are addressing sustainability through environmental valuation [Howarth 1992]. In the case of climate change assessment, environmental valuation requires a chain of steps beyond the assessment of the correspondent GWP, and involves information acquisition, modeling, and evaluation. Consequently, decision-making for climate change requires knowledge on a chain of issues that finally are compared on a common basis. Usually, the conversion of a comprehensive set of knowledge into money is difficult and several considerations are left aside during this process.

Further, long time scales intrinsic to climate change cause unpredictable impact evaluations. For instance, climate impacts will be imposed on future generations on different communities with different value systems compared to values pertaining to present evaluators. In economic terms this could mean variations in the elasticity of utility with respect to consumption and income [Schelling, 1995]. Consequently, it is possible that adverse climate impacts in the future will be incommensurable based on monetary compensations established in the present. Moreover, outcomes valued as benefits may be challenged depending on who benefits from such outcomes. In short, it is unlikely that we can be completely successful assigning money values to climate change impacts [Bradford 1999].

A BCA of climate change impacts is usually conducted based on top-down models of the energy socioeconomic system [Bruce 1996], and balance marginal costs of climate change mitigation against marginal benefits from avoided emissions. The same economic rationale could be extended to the assessment of different electricity production options; that is, alternatives would be compared through the quantification of the socioeconomic impacts produced by each one. Nevertheless, it would be still necessary to rely on economic evaluations of hard to value impacts, and heterogeneity in time and space could make the analysis impossible.

Flaws in the economic analysis led to models that evaluate electricity sources independently of environmental economic evaluations, and the pros and cons of alternative institutions for the attainment of consensual environmental obligations have become more and more accepted [Howarth 1990].

As a result, it could be more appropriate to use alternative physical units in environmental assessments, which represent concentration of pollutants as the unit of analysis [Nyborg 2000]. The choices of physical units to compare alternatives is interesting because they are a more direct result from scientific assessment models and bypass problems associated with the economic quantification of the final impacts.

One environmental evaluation method that uses this type of correlation is the intake fraction method [Bennett 2002]. The idea is that the risk posed by pollution is assessed through the fraction that is inhaled by a population living on a certain area over a given period of time divided by the amount released at the source. One of the objectives of the intake fraction method is to consolidate a consistent and transparent way to compare emissions-to-intake studies performed by different researchers, helping the communication of the results.

The ecological footprint is another evaluation method that also follows the rationale of correlating causes and consequences through a non monetized indicator. The method's goal is to find out how much land is necessary to support various human activities [Rees 2003]. Everyone has an idea about land dimensions, and therefore, one of the method's strengths is that the magnitude of the results is easily communicated even to lay people. Another similarity between the GWE and the ecological footprint is that it was proposed as an alternative to economists' argument that the idea of carrying capacity is irrelevant to our society. Instead of asking the question: how many people can be supported by a given land area? The ecological footprint seeks the opposite: how much land is needed to support a given population? The calculation of the footprint is based on the continuous supply and assimilation of all the resources demanded by a stipulated population.

In the same vein of reasoning, the framework proposed in this work uses GWE as an indicator, without incurring into the evaluation of actual socioeconomic and detailed environmental impacts. As other studies it assumes that more GWE harms earth's economy. [Howarth 1990, Nordhaus 1999].

On the one hand, if an intermediate indicator such as GWE does not address the non linearity between temperature changes and climate change impacts and costs, and may only become valuable after the establishment of links in the chain of consequences which goes from emissions to atmospheric concentrations, climate forcing, changes in climate parameters (such as global average surface temperature), climate change impacts, and finally, economic costs of climate change damages [Shackley 1997, Smith 2000, O'Neill 2000]; on the other hand, the use of GWE decoupled from ultimate damages of climate change could benefit its applicability since less assumptions and uncertainties are incorporated in the assessment, and besides they can be more clearly presented to a broad audience. Moreover, GWPs are intended for use in studying relative rather than absolute impacts of emissions, and correspond to specific time horizons [Houghton 2001]. The same idea is extended to the use of GWEs.

Despite these two sorts of problems (discounting and valuation) related to the calculation of benefits and costs associated with climate change outcomes and policies, a BCA of climate change impacts favors climate stabilization over a business as usual scenario [Horwarth 2003], which makes eminent the need for actions to reduce current GHGs emissions.

Chapter 3: Assessment Method and Approach

The framework used in this work is supported by the idea that climate change is a global problem, and therefore, there is no need to assess regional and local impacts of climate change if alternatives are scrutinized based on global compromises. However, this approach does not deny the legitimacy of regional/local assessments of other sorts of problems; even if it is conclusive when climate change impacts are at stake.

One advantage of the GWE method is its flexibility to accommodate different analytical periods for the comparison of the alternatives. As a result, in the analysis the lifetime for each electricity generation technology may be extended through routine maintenance, retrofits, and upgrades following the idea that obsolescence is also dictated by social factors [Lemer 1996].

The GWE method combines two well established methods LCA and Global Warming Potential (GWP) and is discussed below.

3.1 The Global Warming Effect (GWE) Method

The quantification of the GWE for each facility is obtained through a hybrid LCA that draws both on process based LCAs and economic input-output based LCAs and combines the advantages of both methods. The input-output data are obtained from a model of the U.S. economy developed by a team of researchers at Carnegie Mellon University – EIO-LCA [Hendrickson 1998]. In the case of fossil fueled power plants information from the U.S.

Energy Information Administration (EIA) was used to find out fuel consumption rates and emission factors during the operation of the facilities.

The first step to assess GHG emissions from the construction of the power plants is to identify the major energy and materials consumed by each facility and how much is consumed over its life-cycle. This step parallels the inventory phase of the SETAC LCA, and the information used is usually available in construction contracts and various published sources, as noted throughout this work.

The EIO-LCA method was used to estimate the mass (*M*) of each GHG emissions (CO_2, CH_4, N_2O) from constructing and operating power plants based on the amounts and costs of the materials and energy inputs. The construction assessment included material (extraction, processing, and transportation) and energy (extraction/generation, processing, and transportation) inputs, and equipment use in construction activities (fuel combustion). For the operation stage of the fossil fueled power plants, fuel inputs are quantified in each year of the service life, and air emissions are estimated from the fuel extraction, transportation, and combustion phases.

The effects of different GHGs on climate change are determined using the Global Warming Effect (GWE), which is the sum of the product of instantaneous GHG emissions (*M*) and their specific time-dependent GWP. The GWP for a GHG and a given time horizon is [Houghton 2001]:

$$GWP = \frac{\int_0^{TH} a_x \cdot \left[x_{(t)}\right] dt}{\int_0^{TH} a_r \cdot \left[r_{(t)}\right] dt} \qquad (2)$$

where:

a_x is the radiative efficiency of a given GHG, which represents the radiative forcing divided by the change in its atmospheric concentration prior to the industrial revolution up to 1998 (the base year of the EIO-LCA data is 1997). The Radiative forcing measures the magnitude of a potential climate change mechanism. It represents the perturbation to the energy balance of the atmosphere following a change in the concentration of GHGs.

a_r is the radiative efficiency of CO_2, which is assumed to 1 because all other GHGs are compared to CO_2.

$x(t)$ in the numerator is an exponential decay function using a GHG-specific atmospheric lifetime.

$r_{(t)}$ in the denominator represents the CO_2 response function used in the latest IPCC reports to calculate GWPs, which appears in a footnote of IPCC Special Report on Land Use, Land-Use Change and Forestry [Watson 2000].

$_{TH}$ is the time horizon between the instantaneous release of the GHG and the end of the analysis period.

Therefore, the global warming effect (in metric tons of CO_2 equivalent**,** $MTCO_2Eq$) is:

$$GWE = \Sigma M_j \ . \ GWP_{j,\,TH} \qquad (3)$$

where:

M_j is the amount in metric tons of the instantaneous emission of each GHG "j"

$GWP_{j,\,TH}$ is the global warming potential for each GHG "j" calculated using equation *(2)*

For example, the GWE of CH4 emissions over 20 years is equal to the amounts of releases in years 1, 2, 3, …20 multiplied by methane's GWPs when the $_{TH}$ is 20, 19, 18, …1 years and summed for the total. In the case of a emission that is constant every year there is no need for the calculation of GWPs, and only the calculation of a GWP corresponding to the total time period multiplied by the annual emission gives the radiative forcing produced by the annual release of the GHG. However, if emissions vary from year to year then the calculation of specific GWPs is necessary.

Therefore, the global impact of each technology over time is a function of the fraction of gas remaining in the atmosphere in the future compared to the effect of CO_2. In addition, in the case of CH4, it is assumed that after atmospheric decay, all CH_4 oxidizes into CO_2, which is not included in the GWP calculations for CH_4, and thus is accounted for as additional CO_2 [Houghton 2001]. The CO_2 response function is used to determine the future concentration of carbon in the atmosphere. The life time of a facility depends on the obsolescence of its structures and technology. Consequently, the analysis periods depend on upgrades, changes in technology, human values, resource availability, etc.

According to the GWE the temporal scale of emissions is more important than their spatial distribution, and the method captures this component very well. Another advantage of the method is that it works with relative comparisons instead of the ultimate/absolute impacts because it is based on GWP computations that compare the effect of GHG emissions to the emission of a similar amount of CO_2 over a chosen time horizon [Houghton 2001]. The choice of an intermediate indicator to compare alternatives is interesting because it eliminates the problems associated with the quantification of the final impacts caused by climate change and provides a standardized method to compare alternatives [Lenzen 2002]. Such characteristics are also present in other environmental evaluation methods such as the intake fraction method [Bennett 2002]. The final result of the assessment is a ranking of the compared alternatives according to their GWE, which is a relative measure with no compromise with the absolute impacts of each alternative.

3.2 Problems and Uncertainties Associated with the Assessment Method

Because the framework combines two methods it also adds the problems from each one. Besides that, there are also problems with the characterization of comparable power plants to produce electricity. Thus, problems with the method are classified in three categories:

1. Problems associated with the LCA method
2. Problems associated with the GWE (GWP) method.
3. Problems associated with dimensioning of power plants according to site specific characteristics and technological options.

3.2.1 Problems with LCA

The LCA method used in the GWE assessment entails different problems. Some of these problems have been already characterized as uncertainties in input-output analysis [Lenzen 2001]. While some of these problems may be characterized within a range of variable known values and analytical choices, others go beyond this characterization and add uncertainty to the assessment. Figure 3 presents a classification of problems within the LCA method. Four main categories are proposed: data, temporal constraint, economic boundary, and methodological constraint.

Data problems arise during data collection and interpretation. Problems such as incomplete data and missing data are recognized by the EIO-LCA team.

> ***"Incomplete data**: While the eiolca.net strives to include comprehensive data, some sources are incomplete. For example, the toxics release inventory only is required for some industrial sectors and only for plants above administratively defined threshold sizes. As a result, the toxics emissions are likely to be underestimated.*
>
> ***Missing data:** The eiolca.net software does not include all environmental effects. For example, habitat destruction for manufacturing plants is not included. Similarly, the external costs of production are limited to health effects of conventional air emissions due to lack of data on the valuation of other effects."* [EIO-LCA 2000].

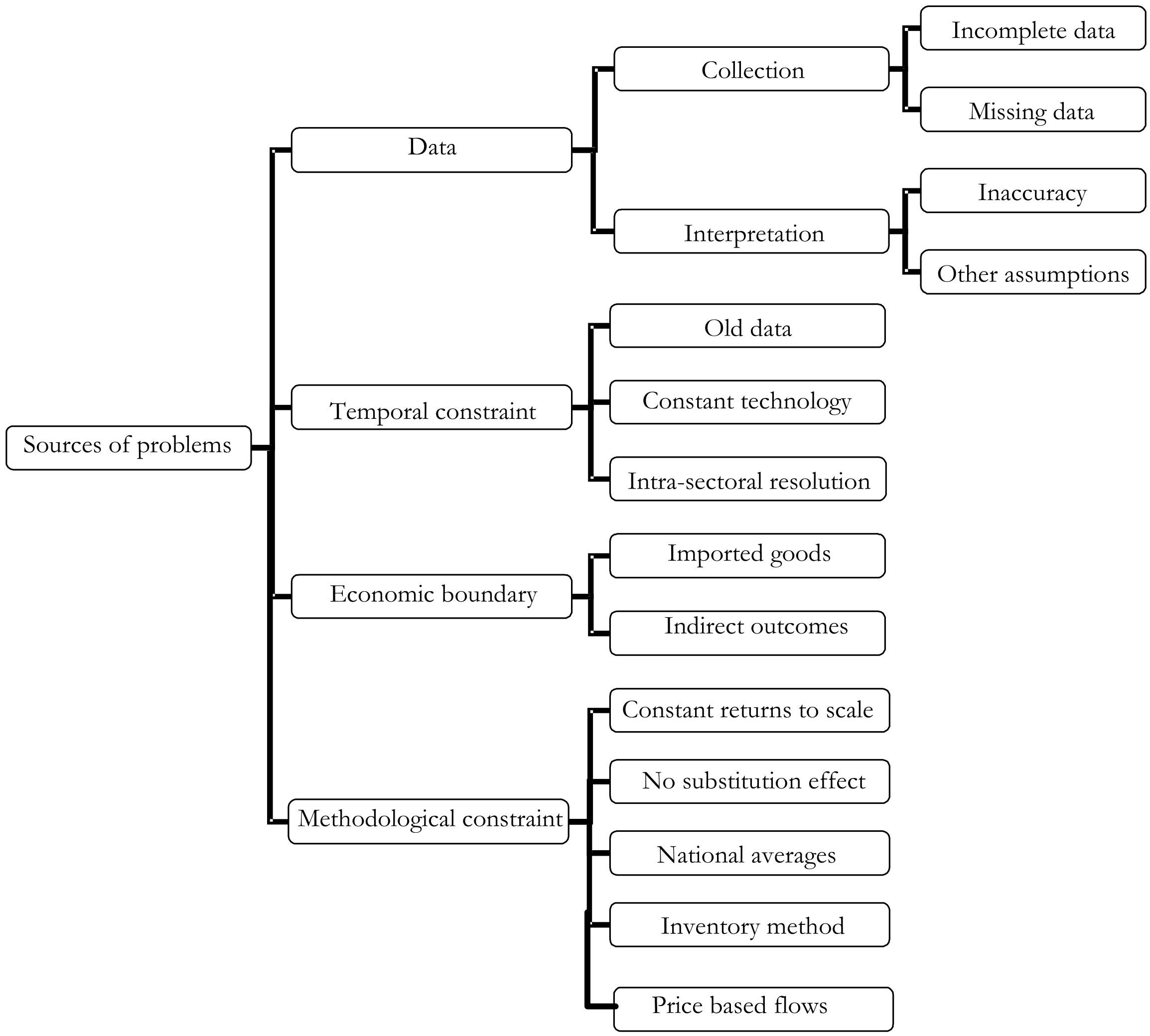

Figure 3: Problems with LCA

While coping with incomplete data is beyond the capacity of the EIO-LCA team who works with various self-reported public datasets, missing data limitation is also a question of preferences. That is, the stressors selected to portray the environmental burden of products and processes depend on how such stressors are valued by the analysts.

It is difficult to provide exact information on the accuracy of data sets; however, it is possible to estimate basic standard errors for the elements of all basic input-output tables based on the knowledge of the survey data sources [Lenzen 2001]. Although precautionary steps are taken during collection, processing, and tabulation of the data to reduce errors in the U.S. economic census, no direct measurement of the error is made [U.S. Census 2003].

Data interpretation is also a problem in generic LCA methods. This problem spans from measurements at the emitter level up to the information treatment at the analyst level. That is, the emitter may not report all the emissions that are released by its activity or two analysts may use divergent conversion factors to transform economic values into physical units that generate conflicting outcomes. For example, the average real price of coal ($ per short ton) delivered to electric utilities has decreased 32% between 1991 and the year 2000 (Real prices are in 1996 dollars, calculated using implicit Gross Domestic Product price deflators. Average prices are based on the cost including insurance and freight) [EIA 2002]. If someone uses the 2000 price to find out the amount of coal consumed by the electric utilities in the U.S. in 1996 it results in a value 32% higher than the actual value. Conversely, if someone uses a price higher than the actual price she underestimates the amount of coal consumed. Consequently, all major assumptions involved in the preparation of the emission factors per dollar of output for each sector should be disclosed so that the user traces back parameters, and estimates the effect of alternative assumptions on the final emission factors.

The input-output method is also constrained by time. The data are specific to a given year, and it takes sometime to tabulate 500 by 500 data tables for the whole U.S. economy. Therefore, it is likely that data are outdated in comparison with the information required as part of the analysis. Usually, input-output tables available from the U.S. Department of Commerce are published with a 5 year delay. In addition, there is a lag in data supply from environmental agencies as well [EIO-LCA 2000]. Consequently, recent technological changes are not captured by input-output methods. Although some sectors are quite stable in terms of technological innovation, other sectors change more rapidly. One example is water consumption data that was last time reported in 1982. Meanwhile, end-use water technologies for different sectors have evolved leading to substantial water savings, even if the economic output of the sector has grown over the same period [Gleick 2000].

Besides historical technological variability in the case of electricity production not only power generation technology varies temporally but it also varies regionally because of the diversity in terms of resources availability. In addition, depending of the scale of the "power plant" the technology may be different. For example, solar energy may be harnessed by PV modules at a small-scale level but it may be more appropriate to use a thermal solar electric generator to produce power at a large-scale level [Kreith 1990].

Intra-sector resolution corresponds to the level of aggregation within a given sector. For example, the sector "Turbine and Generator Sets" encloses disparate sub-sectors such as:

- Gas turbines, mechanical drive
- Governors, steam
- Hydraulic turbines
- Solar powered turbine-generator sets
- Steam engines, except locomotives
- Steam turbines
- Tank turbines
- Turbine generator set units, complete steam, gas, and hydraulic
- Turbines steam, hydraulic, and gas-except aircraft type
- Turbo-generators
- Water turbines

- Wind powered turbine-generator sets
- Windmills for generating power

Although they are all turbines and energy related the technology of a gas turbine is quite different than the technology of a wind turbine. Even if EIO-LCA includes 500 sectors, sometimes more detailed information on specific products or processes is needed. This problem is classified under temporal constraints because usually the number of sectors, and sometimes their classification, which are determined and reported by the U.S. Department of Commerce, changes for each new report.

The use of an economic boundary yields limitations and advantages. A consequence of the use of the national economy as a boundary is the lack of information on imported goods [Lenzen 2001]. EIO-LCA assumes that imported goods are produced similarly to domestic goods. Thus, if steel is used by a US company, the environmental effect of steel is expected to be comparable to those made in the US. To the extent that overseas production is regarded as more or less of an environmental concern, then the factors presented by EIO-LCA should be adapted. For example, the energy efficiency index measures the energy input necessary to produce a given amount of product. The more efficient the sector in a country, the lower is its energy efficiency index. The best practice level selected as a marker corresponds to 100% [Houghton 2001]. In the case of steel, for example, it is known that the energy efficiency index in the U.S. is higher than several exporting countries (figure 4). Thus EIO-LCA overestimates life-cycle energy consumption if imported steel is used in the manufacturing of a good in the U.S.

The aggregate energy efficiency index (EEI) is calculated as:

$$EEI = (\Sigma_i P_i \cdot SEC_i)/(\Sigma_i P_i \cdot SEC_{i,BP}) \qquad (4)$$

Where:

P_i is the production volume of product "i";

SEC_i is the specific energy consumption for product "i";

$SEC_{i,BP}$ is a best-practice reference level for the specific energy consumption for product "i".

By applying this approach a correction is made in order to account for structural differences between countries in each of the industrial sectors considered. A typical statistical uncertainty for these figures is 5% but because of statistical errors higher uncertainties may occur in individual cases.

Another problem that affects EIO-LCA is that indirect outcomes and their respective environmental burden are not always included in the analysis. For instance, if the method is used to assess carbon dioxide emissions from a labor intensive process, and most of the employees of the firm spend a long time commuting back and forth to their work. Emissions from employee's automobiles are not included because the fuel is purchased with their salaries, and such economic transaction is exogenous to the industrial process assessed by EIO-LCA. Therefore, if the transportation of employees represents a considerable amount of pollution, it is ignored by the method. A way to correct such discrepancy would be to find out how much labor is associated with the production of the commodity and combine such value with travel distance, per capita fuel consumption, carbon content in the fuel, carbon dioxide airborne fraction, etc.

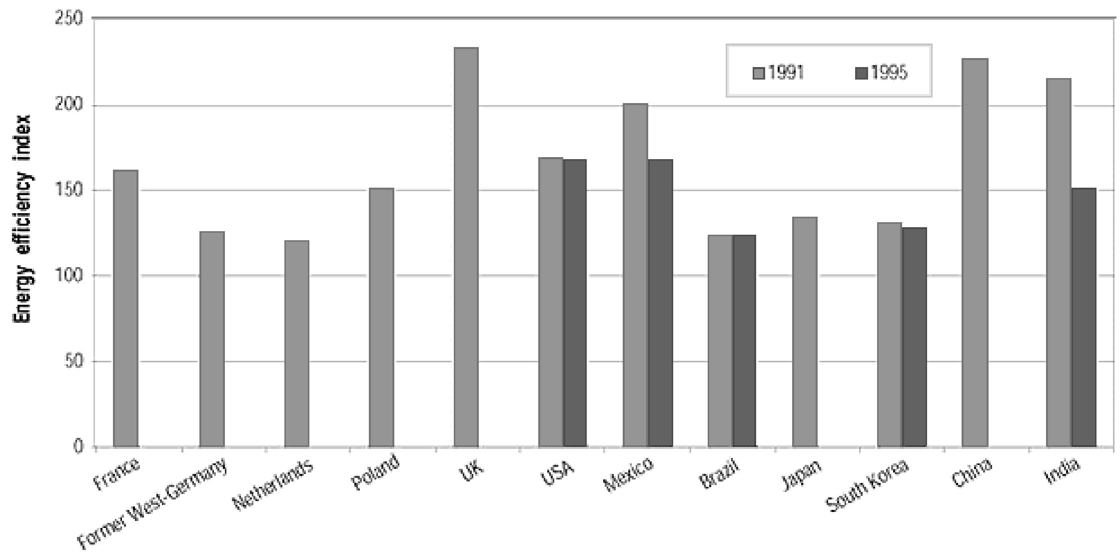

Figure 4: Energy Efficiency Index for Iron and Steel Production [Metz 2001].

Because only commodities used in the fabrication of other commodities or services are captured in input-output methods some consequences associated with other phases of the life-cycle of a product may be ignored. For example, the end of life of a product may entails serious impacts that need to be quantified separately [Lenzen 2001].

A similar problem, which also ignores part of the impacts posed by a product or activity, spawns from the inventory method applied to identify emissions. Indeed, it is hard to be comprehensive and identify all emission sources for a given compound, therefore, only the major ones should be pursued but sometimes it is very difficult to quantify major GHG emissions associated with human activities. For example, nitrous oxide emission estimations in EIO-LCA are based on the assumption that 10% of the oxides of nitrogen (NO_x) emissions are converted to nitrous oxide (N_2O) [EIO-LCA 2000]. Oxides of nitrogen emissions are reported by the U.S. U.S. EPA based on fuel consumption [U.S. EPA 2002].

However, it is recognized that a more significant amount of anthropogenic N_2O comes from agricultural soils [Houghton 2001]. Actually, over 65% of atmospheric N_2O comes from soil as a result of nitrification and denitrification [Bouwman 1990]. Therefore, if there is a concern with nitrogen oxides emissions it makes sense to identify the area of crops which are necessary to sustain a given industrial activity and the effects of cultivation practices on the balance of nitrogen between soil and air.

Constant returns to scale and the inability to substitute inputs in a given process are amongst the most well known limitations of input-output analysis [Levinson 1979]. The constant returns to scale assumption means that given the resources needed to produce one unit of a given commodity, it is just a matter of scaling up these amounts to find out how much is necessary to produce 1,000 units. However, if a manufacturer faces increasing returns to scale, that is, the larger is its total output, less input is demanded per unit of output, such efficiency gains are not captured by EIO-LCA.

Substitution effects do not fit in the EIO-LCA method as well. if we consider the example of a producer that faces high electricity costs and decides to build its own wind power plant, and we are concerned with the level of emissions associated with its final product, then, we should consider the effects of the substitution of grid electricity for self-supply power because electricity generated by different systems is likely to produce different air emissions. In the case of input-output based LCA, the use of emission factors in a different region should take into account carbon dioxide intensities pertaining to the electricity generation mix in that region [Lenzen 2002].

In addition, EIO-LCA method represents all transactions within the U.S. economy, and aggregates singular performances within the same sector. Consequently, EIO-LCA indicators represent the average performance of a myriad of producers within a sector. On the one hand, the use of such values could require some adjustments to become more precise, on the other hand, they are opportune to assess generic projects and products within a given sector and hold comparisons based on the relative effect of alternative options. Moreover information from the EIO-LCA database is readily available and free.

Finally, the characterization of physical flows through the input-output method is based on money flows. The problem is that prices vary both over temporal and spatial scales, and therefore, proportionality between prices and physical quantities does not hold. Prices for the same good are also different depending on the consumer (consumer discrimination). For example, electricity in the same region and at the same moment can be sold at different prices for industrial and residential consumers [Lenzen 2001].

A methodological distinction when doing a LCA is the difference between choices and uncertainty. While some criteria applied to the analysis are to the discretion of the analyst, others reflect the incomplete knowledge about the true value of a parameter. An imprecise measurement aggregates uncertainty to the analysis in the same way that estimations of parameters that are difficult to assess with precision also constitute a source of uncertainty. Although sometimes the analyst is forced to assume some values for parameters that are not precisely defined, this practice is completely different than ignoring something that is known or selecting alternatives among a set of available possibilities.

Only when the range of uncertainty is know or at least a given distribution can be associated with this range it is possible to use some computational frameworks to analyze the consequence of such variability in the final results of the assessment. Monte Carlo simulation is an alternative to cope with uncertainties that propagates known parameter fluctuations into an uncertainty distribution of the output variable.

Monte Carlo simulation is used to reveal the effects of uncertainties in the final results, which requires the selection of specific statistical distribution functions for the uncertain parameters. The logical association of the parameters is also selected by the analyst and the output of the simulation produces a range of possible scenarios. A sensitivity analysis targeting parameters independently can be used to find out which parameters pose the greatest effect on the final results.

3.2.2 Problems with the Global Warming Potential (GWP)

The GWE draws on the climate sensitivity parameter that is proposed based on the relationship between the effects of changes in GHGs concentrations on the global average temperature. The scientific basis of the GWE is the same behind the GWP, and therefore, problems associated with the GWP also manifest with the use of the GWE.

The use of GWPs is challenged because they are not able to capture all the complexity inherent to the global climate system. Changes in ice cover and land use, which affect the albedo, are left aside, sea level changes are left aside, precipitation changes are left aside, and natural phenomena such as the action of volcanoes and changes in solar incoming radiation are left aside (Figure 5). Besides all these external sources of problems there are also some problems inherent to the GWP formulation.

The calculation of global warming potentials comprises five parameters. The first is the choice of the time horizon, which is driven by the goals of the analysis. The time horizon is selected based on the analyst's judgement on how pressing is the escalation of GHGs concentration in the atmosphere and its effects on climate change. This is not a source of uncertainty but a simple circumstantial choice.

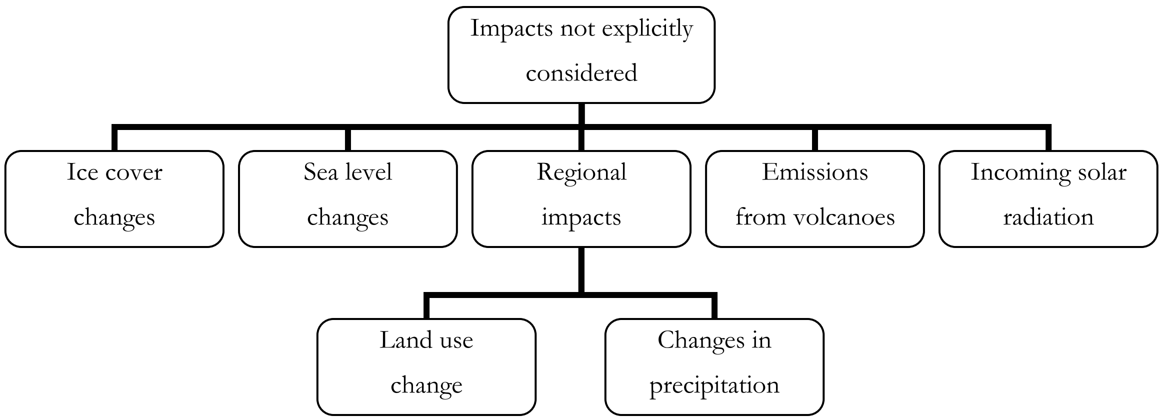

Figure 5: Global Climatic Features not Explicitly Treated in the GWP Method

Next, two parameters represent the potential impact on global radiative forcing. One is the radiative efficiency of the GHG that is compared to carbon dioxide, and the other is the radiativie efficiency of carbon dioxide itself. The radiative efficiency measures the change in the average global temperature triggered by the change in concentration of a specific GHG, which is defined as the radiative forcing for that GHG, normalized by the change in concentration for that GHG since the pre-industrial period (circa 1750). Although both the radiative efficiencies of carbon dioxide and the GHG that is compared to carbon dioxide are assumed to be constant, they depend on the concentration of these gases in the atmosphere, and actually change over time. The definition of GHGs concentration over time depends on future scenarios that involve a set of independent variables such as: energy policy (what are the future energy sources: fossil or renewables?), economic growth, population growth, technology (what electricity supply options will be available in the future?), etc. Accordingly, the radiative forcing of GHGs is also affected by the outcomes of the models used to calculate the atmospheric concentrations of the GHGs and the consideration of chemical reactions between different compounds in the atmosphere.

Finally, the last two parameters represent the residence time of carbon dioxide and the other GHG in the atmosphere. The turnover time of GHGs depend on mechanisms and feedbacks that are not precisely modeled; in addition, in the case of carbon dioxide, prognoses of future atmospheric concentrations are affected by the global carbon cycle model used to calculate future CO_2 concentrations, and concurrent carbon models present different degrees of complexity [Oeschger 1983].

In summary, the GWP is an index used to compare the relative importance of different GHGs in terms of they climate forcing. The numeraire for the GWP is the forcing of carbon dioxide integrated over the period of analysis, which corresponds to the effect of a given amount of carbon dioxide released to the atmosphere on the global mean temperature [Houghton 2001]. This value is the denominator of the GWP formula *(2)* and is obtained through the product of the remaining concentration of carbon dioxide in the atmosphere times its radiative efficiency. Therefore, two basic parameters in the GWP method are the radiative efficiencies and the factors affecting the balance of GHGs in the atmosphere.

3.2.2.1 Problems with Radiative Efficiency

The radiative efficiency is the radiative forcing normalized by the change in concentration of the species of interest, which are usually well mixed gases. Well mixed gases such as CO_2, CH_4, and N_2O are characterized by residence times long enough to remain well mixed in the troposphere. The radiative forcing concept is consistent with the assumption that there is a relationship between the global average forcing and the global average temperature. Accordingly, the radiative forcing denotes an externally imposed perturbation, natural or anthropogenic in the radiative energy budget of the earth's climate system. One example of a natural perturbation are emissions from volcanoes that are estimated as 0.02 to 0.05 Pg C yr^{-1} Anthropogenic or human perturbations have been much more significant over the last 100 years and include fossil fuel burning (6.3 Pg C yr^{-1}) and land-use change [Houghton 2001]. Nevertheless, these two sources of carbon contribute to the increase in carbon dioxide concentration in the atmosphere and equally contribute to an increase in the global radiative forcing of the earth.

The adjective radiative is used because the idea is similar to the assessment of radiation from the decay of different radioactive substances that generate compounds, each one with different characteristics (life-time and radioactive emissions) and responsible for a certain share of the total radiation produced [Smith 1993]. A parallel idea holds for the effect of different GHGs on the global climate. That is, the radiative forcing of species with characteristic residence times in the atmosphere is combined in a global radiative forcing.

The climate sensitivity parameter (λ) measures the ratio between the global mean temperature response (ΔT) and the change in radiative forcing (ΔF). It is a global parameter, and in current one-dimensional models, such as the old Arrhenius model [Arrhenius 1896], λ is a almost constant for various radiative forcings and corresponds to 0.5 $K/(Wm^{-2})$, which denotes a possible universality for the relationship between forcing and global temperature changes [Houghton 2001]. Such universality is a strong reason to take λ as a central element in global climate models and define a set of possible outcomes such as changes in ice cover, sea level, etc as functions of changes in raditive forcing, which implies a proportional change in the global average temperature. The problem is the circularity in these definitions because changes in ice cover should also affect the global forcing.

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Nevertheless, although the value for climate sensitivity varies across different models, within each model it is found to be constant for a wide range of perturbations. Even more complex models, which involve three-dimensional experiments, show that radiative forcing continues to be a good estimator for global mean temperature changes.

"The invariance of λ has made the radiative forcing concept appealing as a convenient measure to estimate the global, annual mean surface temperature response without taking the recourse to actually run and analyze, say, a three dimensional Atmosphere-Ocean General Circulation Model (AOGCM) simulation" [Houghton 2001]

Furthermore, different radiative forcing precursors are all assumed to affect the global climate in the same way [Houghton 2001], and it is difficult to isolate the radiative forcing due to one precursor within the set of possible components that affect the whole system. Actually, other components besides GHGs also affect the global radiative forcing; however, the current knowledge about their effects is still limited (Figure 6).

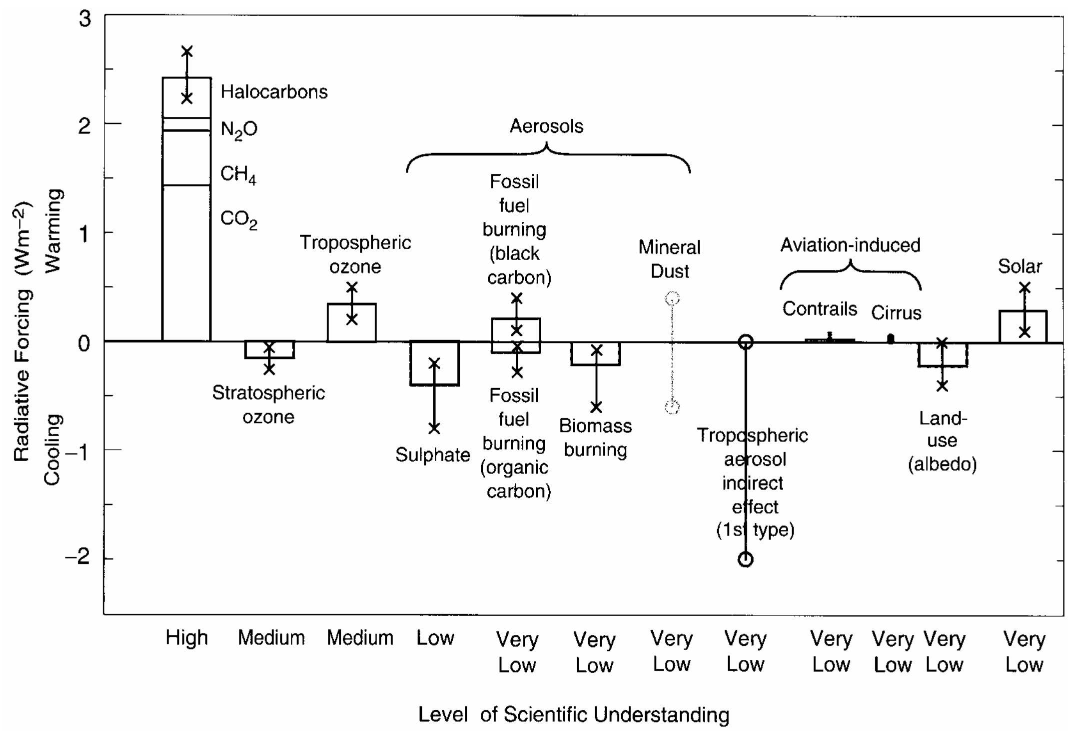


Figure 6: Global and Annual Mean Radiative Forcing (1750 to present) [Houghton 2001].

Critics of GWPs highlight that global mean forcing estimates are not necessarily indicators of the regional impacts of climate change. Actually, regional responses to variant forcings can differ from homogeneous forcing responses, and changes in other parameters such as ice cover, precipitation, land use change, and sea level, which are all related to global climate change, are not included in radiative forcing formulations. Consequently, advocates of more complex models rely on three-dimensional atmosphere-ocean general circulation models (AOGCM) that are composed by three-dimensional atmospheric general circulation models (AGCMs) integrated to ocean general circulation models (OGCMs), which include sea-ice interactions and terrestrial models. The resolution of such models is much greater than the model used to calculate GWPs, and they allow the modeling of regional outcomes in a much smaller scale.

In any case, climate change science is always evolving, and even the methods to calculate radiative forcing are changing over time. Such changes, in part, attempt to internalize knowledge based on the output from more complex models. In the IPCC 2001 report, the CO_2 radiative forcing, which corresponds to a doubling in the concentration of CO_2 in the atmosphere, ranges from 3.5 to 4.1 W m^{-2}; and its variation since the pre-industrial era corresponds to 1.46 W m^{-2} [Houghton 2001]. Such values are slightly different from the previous IPCC report, and reflect the inclusion of stratospheric temperature adjustments and, short wave forcing in the computations of radiative forcing. That is, even if the GWP does not deal explicitly with a series of factors that affect the global climate, many of those manifestations are included by changing the value corresponding to the radiative forcing of a given GHG.

In addition, the radiative forcing of carbon dioxide is time dependent because it depends on the current CO_2 concentration in the atmosphere; thus different formulations have been proposed to estimate the radiative forcing for CO_2 based on its atmospheric concentration (Table 1).

The first row in table 1 lists an expression with a form similar to Houghton (1990) but with newer values for the constants. The second row is a more complete and updated expression similar in form to that of Shi (1992). The third row expression is from WMO (1999), based on Hansen et al. (1988). The symbol “C” is CO_2 in ppm, and the subscript “0” denotes the pre-industrial concentration, which is assumed to be 278 ppm in the year 1750 [Houghton 2001]. The constant in the simplified expression on the first row is based on radiative transfer calculations with three-dimensional climatological meteorological input data [Myhre 1998]. For the second and third rows, constants are derived with radiative transfer calculations using one-dimensional global average meteorological input data from [Shi 1992] and [Hansen 1998], respectively [Houghton 2001].

Table 1: Simplified Expression for Calculation of CO_2 ΔF in W/m^2 [Houghton 2001]

Expressions	Constants
$\Delta F = \alpha \ln (C/C_0)$	$\alpha = 5.35$
$\Delta F = \alpha \ln (C/C_0) + \beta(\sqrt{C} - \sqrt{C_0})$	$\alpha = 4.841$, $\beta = 0.0906$
$\Delta F = \alpha(g(C)) - g (C_0)$	$\alpha = 3.35$
where $g (C) = \ln (1+ 1.2C+ 0.005C^2 + 1.4 \times 10^{-6}C^3)$	

The existence of different propositions to calculate the radiative forcing for carbon dioxide indicates that the valuation of this parameter encloses some uncertainty. For example, assuming a carbon dioxide concentration of 365 ppm the carbon dioxide radiative forcings calculated using the three formulas yields the following results in W m^{-2}: 1.46, 1.54, and 2.74. These values are fundamental in the calculation of the GWP and GWE because they affect the relative value of other GHGs compared to carbon dioxide.

Along the same lines, specific expressions are proposed for calculation of radiative forcings of other GHGs, and they are always a function of their present concentration in the atmosphere (Table 2).

Table 2: Simplified Expression for GHGs ΔF calculations in W/m^2 [Houghton 2001]

Trace gas	Expressions	Constants
CH_4	$\Delta F = \alpha(\sqrt{M} - \sqrt{M_0}) - (f(M,N_0) - f(M_0, N_0))$	$\alpha = 0.036$
N_2O	$\Delta F = \alpha(\sqrt{N} - \sqrt{N_0}) - (f(M_0,N) - f(M_0, N_0))$	$\alpha = 0.12$
CFC-11	$\Delta F = \alpha(X - X_0)$	$\alpha = 0.25$
CFC-12	$\Delta F = \alpha(X - X_0)$	$\alpha = 0.32$

The expression on the third row in table 2 is used for all CFCs and CFC replacements, but with different values for α i.e., the radiative efficiencies. The subscript "0" denotes the unperturbed concentration (pre-industrial), and the function used in rows 1 and 2 is:

$$f_{(M,N)} = 0.47 \ln[1+2.01\text{x}10^{-5} (MN)^{0.75}+5.31\text{x}10^{-15} M(MN)^{1.52}] \qquad (6)$$

Where:

M is CH_4 in ppb

N is N_2O in ppb

X is CFC in ppb

Although the total climate feedback is treated as being invariable for the homogeneous global system, individual feedbacks have different strengths. Besides direct effects some compounds modify the radiative balance through indirect effects relating to chemical transformations or change in the distribution of other active species. This calls for adjustments on radiative forcings depending on the understanding of their stocks and flows in the atmosphere.

3.2.2.2 Problems with the Modeling of Stocks and Flows of Greenhouse Gases (GHGs)

The modeling of GHGs is important to provide a function that represents the amount of gas in the atmosphere after some air emissions occur. This function is integrated over a given time horizon to produce the integrated forcing of the GHG, which is part of the GWP calculation. In the case of carbon dioxide the function is derived from a run of a carbon cycle model and represented by the pulse response function, whereas in the case of other well mixed gases the function is a simple exponential decay function.

$$F_{(t)} = e^{-\frac{t}{\tau}} \qquad (7)$$

where:

t is time in years;

τ is the characteristic residence time of the gas.

Although simple exponential functions are used in the GWP calculations the complexity of the atmospheric chemistry and the deepening of its understanding affect the choice of characteristic residence times for well mixed gases. For example, the decline of the ozone layer over the last two decades has increased the penetration of ultra-violet radiation and led to changes in the dissociation of hydroxyl (OH), which regulates the lifetimes of methane (CH_4), carbon monoxide (CO), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC), nitrogen oxides (NO_x), sulfur dioxide (SO_2). Moreover, as the lifetime of the compounds is affected, their radiative efficiency is also affected (Table 2).

The lifetime of methane is also affected by several processes in the atmosphere. However, most studies assume that its climate forcing remains constant within the foreseeable future [Lelieveld 1993]. Industrial emissions, soil removal and chemical reactions in the biosphere govern the lifetime of methane, and wetlands are a significant source of methane, which are responsible for 23% to 40% of natural emissions. Reactions with hydroxyl (OH^-) destroy about 90% of the methane in the atmosphere [Lelieveld 1993], which then oxidizes into carbon monoxide. Carbon monoxide has a residence time of months and is ultimately converted to carbon dioxide [Crutzen 2001]. Therefore all CH_4 emitted to the atmosphere ultimately is converted to CO_2.

Changes in scientific understanding affects the parameters used in GWP calculations. The lifetimes of CH_4 and N_2O that were 12.2 and 120 years respectively in the 1995 IPCC report [Houghton 1995] were adjusted to 12 and 114 years respectively in the 2001 IPCC report due to feedbacks of emissions on lifetimes [Houghton 2001].

Although calculations involving CH_4 mixing ratios and its instantaneous forcing are subject to assumptions and uncertainties, the IPCC 2001 report assumes that the radiative forcing for CH_4 is 0.49 W m^{-2}, its pre-industrial concentration is 700 ppb, and its concentration in 1998 is 1,745 ppb [Houghton 2001]. However, the calculated radiative efficiency of methane is 4.69×10^{-4} W m^{-2} ppb^{-1} and not 3.7×10^{-4} Wm^{-2} ppb^{-1} as indicated on table 6.7 of the same report. The radiative efficiency of methane combined to its characteristic residence time, the radiative efficiency of carbon dioxide, and the function representing the behavior of carbon dioxide in the atmosphere plus a given time horizon are the five parameters used in the calculation of GWPs for CH_4. The CH_4 GWP values reported in the third assessment report TAR of the IPCC based on 20, 100, and 500 years are 62, 23, and 7, respectively.

Beyond assumptions and uncertainties associated with methane, approaches to carbon dioxide, which is the numeraire for GWP, are also controversial. For example, it is difficult to establish a singular residence time for carbon dioxide in the atmosphere since this GHG is not removed by chemical decay from the atmosphere and is constantly transferred to different pools, which are regulated by different processes [Bruhl 1993, Lashof 1990, O'Neill 2000]. Carbon cycle models, which are the source for the parameterized pulse response function (PRF) to calculate the integrated amount of carbon dioxide in the atmosphere over time are discussed next.

3.2.2.3 Carbon Cycle Models and Pulse Response Functions (PRFs)

The utility of models rely on different kinds of calculations as a function of time. For example, forward modeling involves the prescription of specific emission profiles (Q(t)) to find out atmospheric concentration levels in the future whereas inverse modeling calculates the emissions that lead to a given concentration level (C(t)). Another use of models is the calculation of pulse response functions that are used in the calculation of GWPs.

The spectrum of climate change models is rich and stems from simple concentration extrapolation models to atmosphere-ocean general circulation models (AOGCM). The mechanics embedded in OGCMs is derived from fundamental physical and chemical principles [Enting 1994]. Concurrent representations of the carbon cycle, which balance the carbon budget over time, lead to different future atmospheric concentration levels for a specific projection of future carbon emissions [Bruce 1996].

Basically, global carbon cycles represent two types of forcings: anthropogenic forcing and responses to such forcings, which feedback in the exchange rates between different boxes of the model. Anthropogenic forcing results from GHG emissions due to fossil combustion, and land use change. The response to such forcings reflects on changes in atmospheric concentrations, carbon uptake by oceans and terrestrial ecosystems. The partitioning between carbon dioxide uptake by oceans and land is not an issue that is already resolved and remains a source of uncertainty in all proposed models independently of their resolution or degree of complexity.

Terrestrial carbon models use discrete compartments that represent leaves, branches, litter, roots, and soil carbon. Carbon is stored in each of these compartments and the turnover time represents the amount of time that an atom of carbon stays in the compartment.

The atmospheric carbon budget as a function of time is represented by the following equation that represents carbon flows [Enting 1994]:

$$2.123\frac{d}{dt}C = Q_{foss(t)} + D_{n(t)} - S_{ocean(t)} - S_{fert(t)} - S_{resid(t)} \qquad (8)$$

where:

2.123GtC ppm^{-1} refers to the size of the atmosphere in moles times the mass of one mol of carbon

C is the atmospheric CO_2 concentration in ppm

$Q_{foss(t)}$ is the fossil emission rate

$D_{n(t)}$ is the net release from land use change

S_{ocean} is the net carbon uptake by the ocean

S_{fert} is the net flux associated with higher CO_2 concentrations

$S_{resid(t)}$ is a residual term associated with neglected processes

In this formulation, anthropogenic forcing terms are composed of fossil fuel emissions ($Q_{foss(t)}$) and net carbon releases from land use change $D_{n(t)}$. Variations of the same fundamental parameters are part of every modeling effort undertaken.

The High Latitude Exchange/Interior Diffusion Advection (HILDA) model used by the IPCC for simulating the transport of CO_2 between the ocean, the atmosphere and the biosphere is the source for the PRF that is used in the calculation of the GWPs by the IPCC. HILDA, which is also known as the Bern model has a structure with six boxes (Figure 7).

HILDA is already a parameterized model formed by simplified descriptions that are present in more complex models. Six boxes are part of the model. One box represents the biosphere or everything pertaining to the terrestrial ecosystem. Another box represents the atmosphere, which corresponds to a layer with an average height of 12 km. Four boxes represent the ocean that is differentiated according to different latitudes. Out of these four boxes two represent the superficial layer up to 75 m deep, which is divided in low latitude (LS) and high latitude (HS) boxes. The remaining 2 boxes represent the deep waters (3,800 m) and are also divided according to their latitude. An advective circulation oceanic current and a depth dependent eddy diffusion coefficient, which captures flows between each subjacent box, are also part of the ocean model. Actually, the limiting process for carbon dioxide uptake by oceans is the internal mixing in the ocean. Flows in the model represent the carbon exchange between the boxes and affect the atmospheric concentration of CO_2.

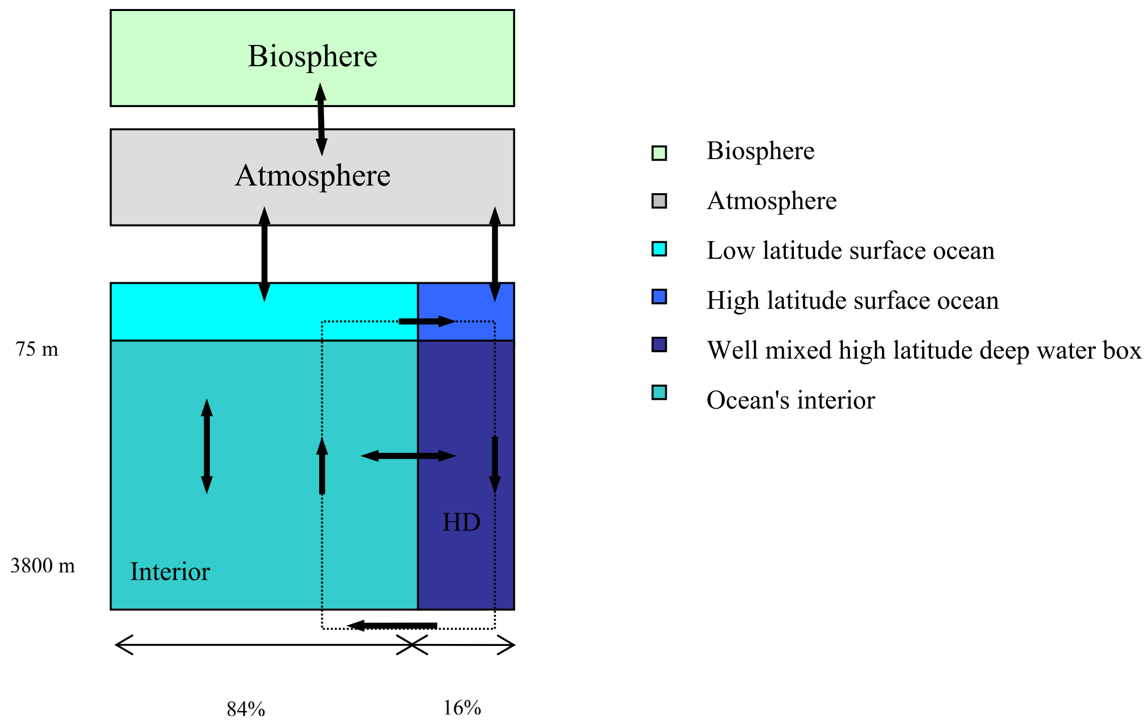


Figure 7 : HILDA Model [Siegenthaler 1992]

Parameterized models are simplified descriptions of more complex models used to link emissions to atmospheric concentrations. In the case of the calculation of GWP an even simpler parameterized representation of the removal of CO_2 from the atmosphere is used. The function used is the pulse response function (PRF), which is a parameterized exponential expression, obtained through a run of the HILDA model that includes a specific future emissions scenario. In the case of the function provided by the IPCC the background CO_2 concentration profile used as a reference assumes a constant concentration of 353.57 ppm from 1990 onwards and a 11Gt carbon flux from deforestation between 1980-89 [Joos 2003]. The PRF describes the behavior of the atmospheric carbon dioxide concentration after a unique perturbation, which equals to 10 Gt of carbon injected in the atmosphere in the year 1995.

Usually PRFs are obtained either assuming a background with zero emissions, which relates to pre-industrial concentrations, or a background corresponding to emissions leading to a given future stabilization level (353.57 ppm).

The response function Ga(t) is evaluated as [Enting 1994]:

$$F[CO_2(t)] = 2.123[C(t) - Cb(t)]/10.0 \qquad (9)$$

Where C(t) is the concentration of carbon in the atmosphere and Cb(t) is the background concentration, which depends on the future emission scenario selected. The factor 2.123 GtC ppm^{-1} is the size of the atmosphere (box) in moles times the molecular weight of carbon.

The approximation of the output of the HILDA model, which is used in the GWPs calculations for the 1995 and 2001 IPCC reports, corresponds to the following parameterized response function [Watson 2000]:

$$F[CO_2(t)] = 0.175602 + 0.137467e^{-t/421.093} + 0.185762e^{-t/70.5965} + 0.242302e^{-t/21.42165} + 0.258868e^{-t/3.41537} \qquad (9)$$

Where F is the fraction of CO_2 remaining in the atmosphere and “t” is the time after the pulse was emitted in years. This function is based on results running the HILDA model assuming a background concentration of 353.57 ppm.

The pulse response function used in the denominator of the GWP depends on the results of the carbon cycle model used to calculate the fate of carbon dioxide emissions in the atmosphere. Therefore, problems embedded in the carbon cycle model affect the coefficients of the pulse response function, and a discussion on the choices and uncertainties embedded in the model enhances the validity of the results obtained with the model.

Uncertainties in the model are classified in:

1. model error
2. imprecise calibration
3. budget uncertainty

The existence of different models demonstrates the existence of different model structures and parameters. However, the variability amongst current models is not an indicator of the actual uncertainty in the predictions. It is possible that a small group of models does not capture the full range of uncertainty. Moreover, some key process could be missing in every model [Enting 1994].

In a reasonable model the parameters used should be expected to hold in the future, and the validation of carbon cycle models is fundamental to give credibility to the projections. One concern is that different sorts of models would present different results if they run similar input data. This has been dismissed by a recent comparison of two different models predicting the future global climate [Zwiers 2002].

Uncertainties in predictions made with the model affect the PRF that already contains uncertainty from its ability to represent in a single function actual observational data. The estimation that the current CO_2 concentration is growing at a rate of 3.2 ± 0.1 PgC yr^{-1} during 1990 to 1999 [Houghton 2001] reflects this kind of uncertainty. The variability in land

and ocean uptake may explain why in 1992 the growth rate was 1.9 PgC yr^{-1} and in 1998 it was 6.0 PgC yr^{-1}.

The information used to calibrate the model needs to report both past carbon dioxide concentrations in the atmosphere and emissions. Direct measurements of CO_2 concentration started in 1957 and to extend back the historical series of CO_2 researchers rely on indirect measurements based on physical and biophysical principles. For example, tree ring records, corals, lake sediments, and ice core samples are used to reconstruct the past CO_2 concentration record over past geological ages. It turns out that part of the emissions are associated with land use change and there is a considerable amount of uncertainty related with the past land use changes and its effect on carbon emissions [Enting 1994].

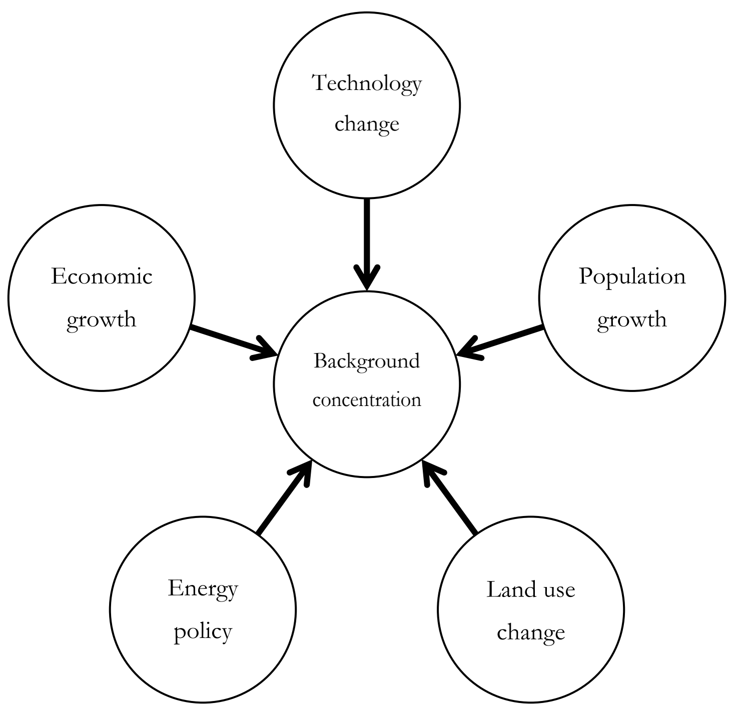


Figure 8: Independend Variables Affecting Projected Carbon Background Concentrations

In addition to uncertainties the use of the model requires different choices about some of the parameters. Because the model is also used to predict the future climate (forward calculations) different emission scenarios, which affect the future carbon budget, may be used as the input in the model. Various parameters that can be modeled independently affect the future carbon background concentration (Figure 8)

In the IPCC 2001 report four different emission scenarios and their respective future carbon concentrations are presented. Each scenario refers to an emission pathway associated with specific policies and is characterized by storylines (0). The use of these background concentrations as the background for the calculation of the PRF produces different outcomes.

The pulse response (PR) model that is a simplification of the HILDA model is documented and is written in Fortran code [Joos 2003b] Based on these four scenarios from TAR and their predicted future carbon emissions, the PR model is used to calculate four future carbon concentration scenarios (Figure 9). The comparison between the output from the PR model based on one of the four emissions scenario and the output based on the same emissions scenario with the addition of a pulse of CO_2 in the year 1995.5 yields four PRFs that can be used in the GWP calculations (Figure 10). The intent of such calculations is to assess the effect of different expectations about future emissions on the calculation of GWPs.

Table 3: Scenarios Storylines

A1	• rapid economic growth, • low population growth, • rapid introduction of efficient technologies.	• convergence among regions • capacity building, • increased cultural and social interactions, • reduction in regional differences in per capita income
A2	• Fragmented per capita and economic growth • high population growth • Regional economic development	• heterogeneous world. • self-reliance and preservation of local identities
B1	• low population growth • service and information economy – less materials • clean and resource-efficient technologies	• Global solutions to economic, social, and environmental sustainabiliby • equity
B2	• moderate population growth • intermediate levels of economic development	• Local solutions to economic, social, and environmental sustainability

Different pulse response functions can be calculated using the outcomes predicted by the four different scenarios and running the PR model. The PRFs based on the four IPCC 2001 scenarios tend to stabilize at a concentration level of 450 ppm because of the characterisitics of the future emission scenarios used in the PR model whereas the PRF used by the IPCC assumes a background concentration of 353.57 ppm (Figure 10).

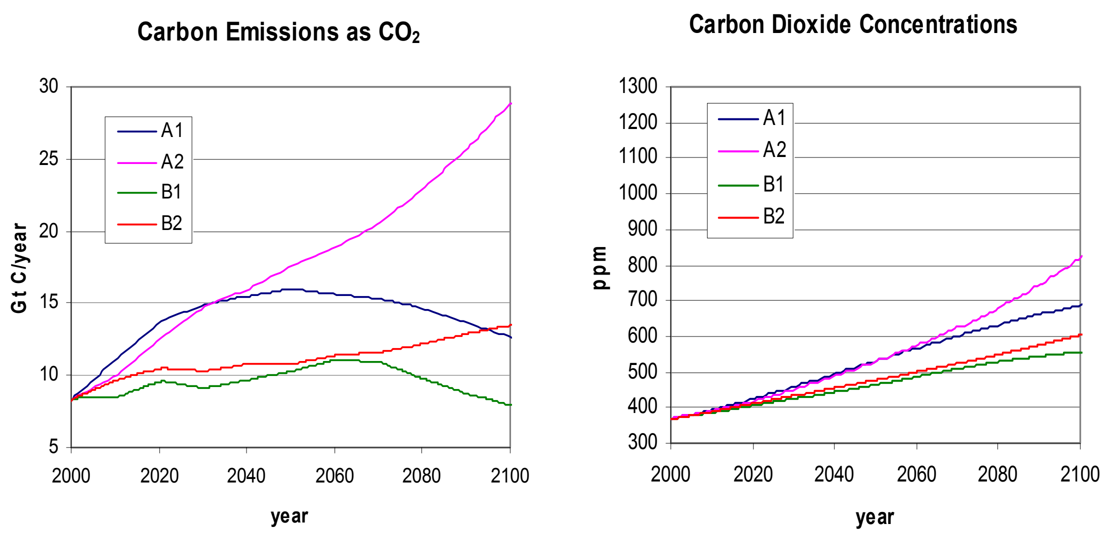


Figure 9: Future Carbon Emissions and Carbon Dioxide Concentrations

The use of the A1 scenario as the background for the definition of the PR model is more realistic than an approach that considers a constant backgroud. Moreover, any scenario that attempts to predict future emissions reveals the increasing importance of CO_2 relative to other GHGs and aerosols as CO_2 accumulates in the atmosphere [Hayhoe 2002].

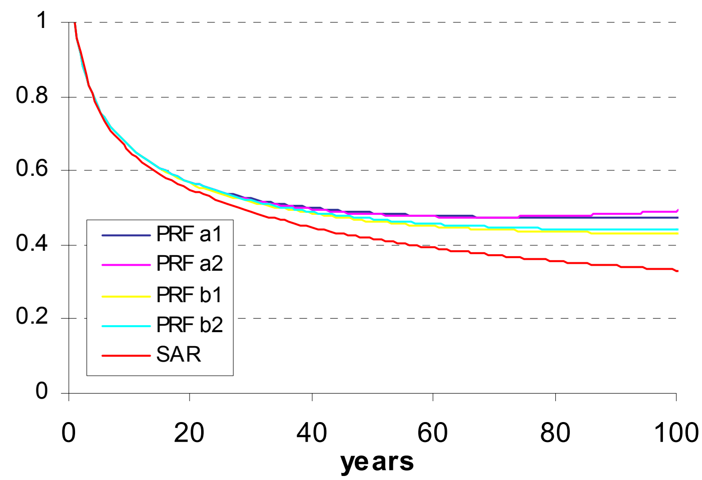


Figure 10: PRFs Based on TAR Scenarios and PR Model Used in the Calculation of GWP.

Independently of the data set describing future GHG emissions all projections of future global change show that the warming is likely to continue, and short term models are necessary to develop strategies for coping with climate change over the typical two-decade planning horizon, which is more adequate for developing policy, and mitigate or adapt to climate change. Moreover, a centenary time frame obscures the message that there is consensus on warming projections for the next couple of decades regardless the particular model or emission scenario used [Zwiers 2002].

The use of a global model representing the behavior over time of carbon dioxide in the biosphere is convenient to compare the impact of alternatives in terms of GWE by means of a future estimation of impacts based on carbon dioxide emissions equivalent. Because climate change is linked to the build up of GHGs in the atmosphere and not to any ephemeral event, the sum of emissions over time best characterizes the potential impacts on the global climate [Metz 2001].

3.2.2.4 Parameters Used in the Calculation of GWPs and GWEs

The calculation of GWP/GWE is a simplification of complex interactions and models. Because the ultimate GWP value comprises time integrated climate forcings for the major GHGs over time, three time dependent factors affect the GWP calculation:

- instantaneous direct climate forcing of GHG, which is calculated for a given period of time.
- residence time of GHGs in the atmosphere,
- indirect effects through chemical feedbacks [Lelieveld 1993].

These factors are intertwined, and the conditionings, which define their values, constantly change. In the actual GWP/GWE calculations the instantaneous direct climate forcing of a GHG is based on a steady state situation and is considered constant over the integration interval. That is, in the GWP calculations, the concentration of the GHG changes over time but its radiative forcing is invariable. All these issues also affect the GWE, which is derived from the GWP.

The IPCC adopts the following procedures in the calculation of GWP:

1. a constant radiative forcing for CO_2 (0.01548 Wm^{-2} ppm^{-1}) is adopted for the GWP calculations [Houghton 2001].

2. The reference pulse occurs in 1995 and corresponds to 10 Gt of carbon.

3. HILDA, the model described by Siegenthaler and Joos (1992) is adopted as the reference case.

4. A background concentration of 353.57 ppm of CO_2 is selected from 1990 onwards for running HILDA [Joos 2003].

5. the net release from land use change ($D_{n(t)}$) is tuned to 1.6 Gt C yr^{-1} over the 1980s.

In order to provide temporal flexibility to the GWE framework, the calculation of GWPs is easily done using an electronic spreadsheet. The CO_2 removal is represented by the PR model using information from the future emission scenarios published in TAR IPCC or by the PRF function used in the same report. Discrete time intervals corresponding to one year each are used in the calculations, which allows the selection of different time horizons at the discretion of the analyst. The flexibility of the GWP's calculation in a spreadsheet allows for a better understanding of the limitations of the method and adds transparency. For example, the summary table with the GWPs for 20, 100, and 500 years published in the Third Assessment Report of the IPCC has a typo in the radioactive efficiency of methane. The explicit discussion of what is behind the GWPs makes the GWE method much more reliable and robust for decision-making and in the future the creation of a carbon cycle model that could run in an interface that is more transparent to users would add a lot to the method even if some simplifications would make it less accurate.

Despite the debate over the effectiveness of GWP, and consequentially the extension of such issues to GWE and its ability to evaluate impacts and support decision-making, the method seems appropriate to compare different energy technologies when the concern is climate change. Even if current trends are assumed constant and projected over different time horizons, the same presumptions are applied to all alternatives considered. The GWE method equally weights ultimate climate effects up to some time horizon, which is advantageous if we assume that future generations have the same rights as the present; therefore, the ultimate impact from emissions today is similar as the impact from emissions tomorrow.

In short, the GWP method embodies assumptions and uncertainties as part of the aggregation of a couple of GHGs into a single indicator. Besides that, GWP is calculated based on climate forcing for various GHGs over a definite time, and supposedly is not affected by changes in their mixing ratios. This simplification is unreal; however, the problem is minimized if expected impacts from global warming are within the time horizon of the GWP formulation [O'Neill 2000]. Or vice-versa the selection of a given time horizon is conditioned to the expectation of impacts within that time frame.

Chapter 4: Electricity Generation Case Studies

Independently of the energy source used, the conception of an electricity generation system follows certain criteria. An initial step in the case of renewable energy projects, including hydroelectric plants, is the definition of the project's purpose. In the case of PVs, for example, this means the option for a centralized plant or a collection of dispersed systems integrated onto existing buildings. In the case of hydro, it relates to the share of water allocated to power generation compared to other uses that are directly or indirectly beneficial to society. Water supply or irrigation are among the directly important water uses while the preservation of aquatic life such as salmon in the northwest of the U.S. serves as an example of an indirect water use. Defining the purpose of the project is intertwined with the identification of the resources available to run the power plant. The more choices and parameters associated with alternative power options are explicitly included in the GWE framework, the better the result of the assessment will be because it allows the performance of sensitivity analysis based on different parameters explicit in the framework.

Nonetheless, the GWE is a consistent method that is not only useful to conduct the assessment of particular case studies with original data, but is also useful to standardize comparisons between previous LCAs available in the literature. Indeed, some published LCAs disclose a list with the amounts of materials and energy used over the life-cycle of the alternatives that potentially serves as input to the GWE method.

The application of the method has been already demonstrated [Pacca 2002], and as a complement to the results reported in this chapter a literature review for each technology with LCAs that have at least quantified CO_2 emissions normalized by energy output is presented.

4.1 Hydroelectric Plants

The energy potential of a hydroelectric plant is a function of the volume of water that is harnessed in the watershed and accumulated in the reservoir combined with the *head* of water. The head is the difference between the level of the water in the reservoir, and the elevation of the turbine shaft. This parameter associated with the expected operation flow is important to decide which type of turbine best fits the plant [Egre 2002]. Local geography and topography are strategic to determine the best design to maximize the energy output of a hydroelectric plant. Indeed, not all hydroelectric plants are the same; each one should be assessed based on its own characteristics [Koch 2002].

One choice that affects the design of the power plant is the timing of the use of the electricity. *Base load* and *peak load* power supply characterize two different electricity supply modes of a hydroelectric plant that affects the plant's design. Hydroelectric plants with storage capacity can regulate the amount of energy delivered over time and deliver energy concentrated over a limited amount of time (peak load) or produce a constant amount of energy over time (base load). The basic difference between the two schemes is also explained through the *capacity factor* of the plant that is the ratio between the period (in hours) the plant is producing energy over the total number of hours in a given period. Thus, peak load hydroelectric plants tend to present a smaller capacity factor than base load plants that operate during a longer period to supply base load energy. A reservoir with a fixed storage capacity can have its capacity factor reduced and its installed capacity augmented with the installation of extra turbines. Depending on the value of the energy at a given period of the day, this option renders more revenues than producing the same amount of energy over a longer period of time.

The storage of a reservoir is also used to regulate the flow of rivers, which is important to control flows, supply water for irrigation, and synchronize the operation of a chain of power plants on the same river to maximize the benefits from power production. Although the presence of a reservoir offers a precious energy storage option that can be combined to other benefits associated with the lentic environment, it is also a source of various environmental impacts that became apparent after various problems instigated the manifestation of a critical mass. Alternatively, run-of-river projects demand only a small reservoir to divert part of the river flow to the intake.

Impacts from a reservoir are created by the construction activities necessary to building the dam, by the presence of support infrastructure such as roads, power lines, by changes in the natural river flow, and by direct impacts from the reservoir that floods a terrestrial environment and becomes a barrier [Egre 2002]. The installation of a reservoir changes completely the fluvial regime in a watershed. Such effect is not only local, but regional, and possibly global. The volume stored by the largest reservoirs in the world correspond to seven times the water volume of natural river water. Dams affect the re-oxygenation of surface waters, and sediment transport [Vorosmarty 1997].

With respect to climate change, not only does the construction of the reservoir contribute to emissions of GHGs, but the flooding of land (which previously constituted a repository of carbon in the vegetation, litterfall, and soil) produces both CH_4 and CO_2 emissions [Rudd 1993, Gagnon 1993, Svensson 1993, Rosa 1994].

In addition, damming as any other human made modification on natural aquatic ecosystems affects the capacity of freshwater to mobilize and exchange carbon with the atmosphere. Similarly to dry terrestrial ecosystems, reservoirs also have the potential to sequester carbon and store organic compounds in the bottom sediments. The quantification of such potential depends on the understanding on how damming affects both biotic and abiotic carbon pathways between terrestrial ecosystems, streams, reservoirs, aquatic organisms, sediments, etc.

4.1.1 Carbon Balance Between Air and Reservoirs

Even if the global contribution of carbon exchanges between reservoirs and the atmosphere is not as significant as other anthropogenic induced activities and their respective feedbacks, the individual contribution of a reservoir is salient in a comparison with fossil fuel sources. However, a generalization whether reservoirs are sinks or sources of carbon is not yet possible. This is not only a matter of lack of knowledge on processes affecting the carbon balance but also a matter of variability in terms of the environmental conditions intrinsic to each case.

The two basic phenomena affecting carbon exchange between reservoirs and the atmosphere are the decay of flooded biomass and the net ecosystem production (NEP). The net contribution of both processes depends on the assessment of the NEP pre and post the reservoir filling. The net productivity of the reservoir after the filling spans the conditions in the reservoir and also depends on the flow of nutrients and sediments from the upstream watershed into the reservoir. The residence time of the water in the reservoir is also a parameter that affects the NEP.

4.1.1.1 Potential Emissions from Decomposition of Flooded Carbon

The contribution of reservoirs as a source for carbon emissions has an become object of investigation for researchers concerned with the comparison between hydroelectric plants and fossil fueled power plants as competing electricity supply options [Rudd 1993, Gagnon 1993, Rosa 1994]. Production of CH_4 and N_2O is triggered by anoxic conditions, microbial methanogenesis, and denitrification in reservoirs [Friedl 2002].

The flooding of the accumulation basin of a reservoir inhibits activities that depend on oxygen consumption, which leads to the death of the vegetation. Thus, carbon that was previously stored in biomass and soils is subject to decomposition by bacteria. Total emissions from reservoirs depend on the total carbon available and the rate of decomposition, which relates to the amount of standing organic carbon characteristic of the ecosystem before the filling of the reservoir [St Louis 2000].

Because the source of the emissions is the flooded biomas, the emissions of CO_2 and CH_4 are calculated based on the decay of the biomass in the reservoir. Usually, a percentage of the total available carbon is assumed to be emitted and 5 to 10% is assumed to be converted into CH_4 [Rudd 1993, Rosa 1995].

The characteristics of the flooded ecosystem affect not only the amount of carbon but also the duration of the decomposition process. Some reservoirs in temperate climates are installed over peatland, which is a soil type rich in carbon. Peat takes a long time to decompose; consequently, carbon emissions extend over long time periods if compared with emissions from other soils that are not so rich in carbon. Table 4 shows a list of emission factors for various reservoirs.

Table 4: Releases of CO_2 and CH_4 from Reservoirs.

author	year	location	climate	emissions (g m^{-2} yr^{-1})	
				CO_2	CH_4
Rudd	1993	Canada	temperate	450 to 1800	15 to 30
St. Louis	2000	Quebec, Canada: Laforge 1	temperate	73 to 3103	0.4 to 47
St. Louis	2000	Quebec, Canada: Robert Bourassa	temperate	58 to 4380	0.4 to 37
St. Louis	2000	Quebec, Canada: Eastmain-Opinica	temperate	803 to 1570	1.5 to 5
St. Louis	2000	Quebec, Canada: Cabonga	temperate	117 to 1752	0.7 to 95
St. Louis	2000	British Columbia, Canada: Revelstoke	temperate	569 to 1095	n.a.
St. Louis	2000	British Columbia, Canada: Kinsbasket	temperate	168 to 219	n.a.
St. Louis	2000	British Columbia, Canada: Arrow	temperate	208 to 646	n.a.
St. Louis	2000	British Columbia, Canada: Whatshan	temperate	197 to 288	n.a.
St. Louis	2000	Ontario, Canada: Experimental Reservoir	temperate	402 to 1351	18 to 33
St. Louis	2000	Finland: Lokka	temperate	281 to 1241	4 to 91
St. Louis	2000	Finland: Porttipahta	temperate	496 to 1205	4 to 5
St. Louis	2000	Ontario, Canada: Experimental Reservoir	temperate	402 to 1351	18 to 33
Chamberland	1996	Canada – La Grande	temperate	402 to 657	1 to 3
St. Louis	2000	Panama: Gatun Lake	tropical		22 to 478
St. Louis	2000	Brazil: Curua Una	tropical		1 to 248
St. Louis	2000	Brazil: Tucurui	tropical		7 to 51
St. Louis	2000	French Guyana	tropical	212 to 3833	1.8 to 1387
Rosa	2002	Miranda - cerrado - 18°55'S - 390 MW	tropical	4388	154.2
Rosa	2002	Samuel - amazonic - 8°45'S - 216 MW	tropical	7488	104

Rosa	2002	Serra da mesa - cerrado - 13º50'S - 1,275 MW	tropical	3973	51.1
Rosa	2002	Itaipu – Atlantic forest	tropical	171	20.8

4.1.1.2 Net Ecosystem Production Balance

The installation of a reservoir displaces a terrestrial ecosystem that was in equilibrium with the atmosphere by an aquatic ecosystem that tends also to reach equilibrium. If carbon uptake before the reservoir filling was a result of vegetation growth and transfers to the soil, after the formation of the reservoir, phytoplankton is responsible for carbon sequestration that may be buried in the sediments of the reservoir. Therefore, a comparative assessment between processes affecting carbon transfers between the two ecosystems and the atmosphere is key to understand the impact linked to reservoirs on climate change.

The computation of the net GHGs emission due to the installation of a reservoir reflects the difference between the previous emissions from the ecosystem before the reservoir's filling and the emissions after the reservoir is formed, which also changes over time as the flooded biomass decays and is released in the form of gas containing carbon.

In contrast, damming as many other human made modification on natural aquatic ecosystems affects the capacity of freshwater to mobilize and exchange carbon with the atmosphere. The aquatic ecosystem can be either a net source or a net sink of carbon. In order to understand changes in natural flow regimes, it is fundamental to realize how they affect both biotic and abiotic carbon pathways.

Similarly to what happens in terrestrial ecosystems, aquatic ecosystems such as lakes and reservoirs also exchange carbon with the atmosphere. Particulate organic carbon (POC) is the dominant source of organic carbon (OC) buried in the sediments. Although some of these particles are transported into the lake as a result of soil erosion, the majority is locally produced by phytoplankton [Dean 1998]. The carbon to nitrogen (C/N) ratio of organic matter that is transported to the reservoir (allochthonous) is in the range of 20 to 30 whereas the C/N ratio of locally produced (autochthonous) organic matter is less than 10. This difference allows researchers to identify the source of OC and has demonstrated that a significant amount of carbon is sequestered by aquatic primary productivity in lakes and reservoirs (Figure 11).

The OC mass accumulation rate may be estimated through the sedimentation rate, and usually values for lakes and reservoirs are different. For example, the average OC and carbonate carbon concentrations in surface sediments of 46 lakes in Minnesota are 12% and 2%, respectively, and the average OC mass accumulation rate for small (<100 km^2) lakes are 27 g m^{-2} yr^{-1} for oligotrophic lakes and 94 g m^{-2} yr^{-1} for meso-eutrophic lakes. The level of eutrophication seems to be directly correlated with the rate of accumulation of OC. In the case of reservoirs, the average sedimentation rate is about 2 cm yr^{-1}. Assuming an average bulk density of 1 g cm^{-3} and 2% of organic carbon the OC accumulation rate equates to 400 g m^{-2} year, which is much higher than the rates estimated for lakes in Minnesota [Dean 1998].

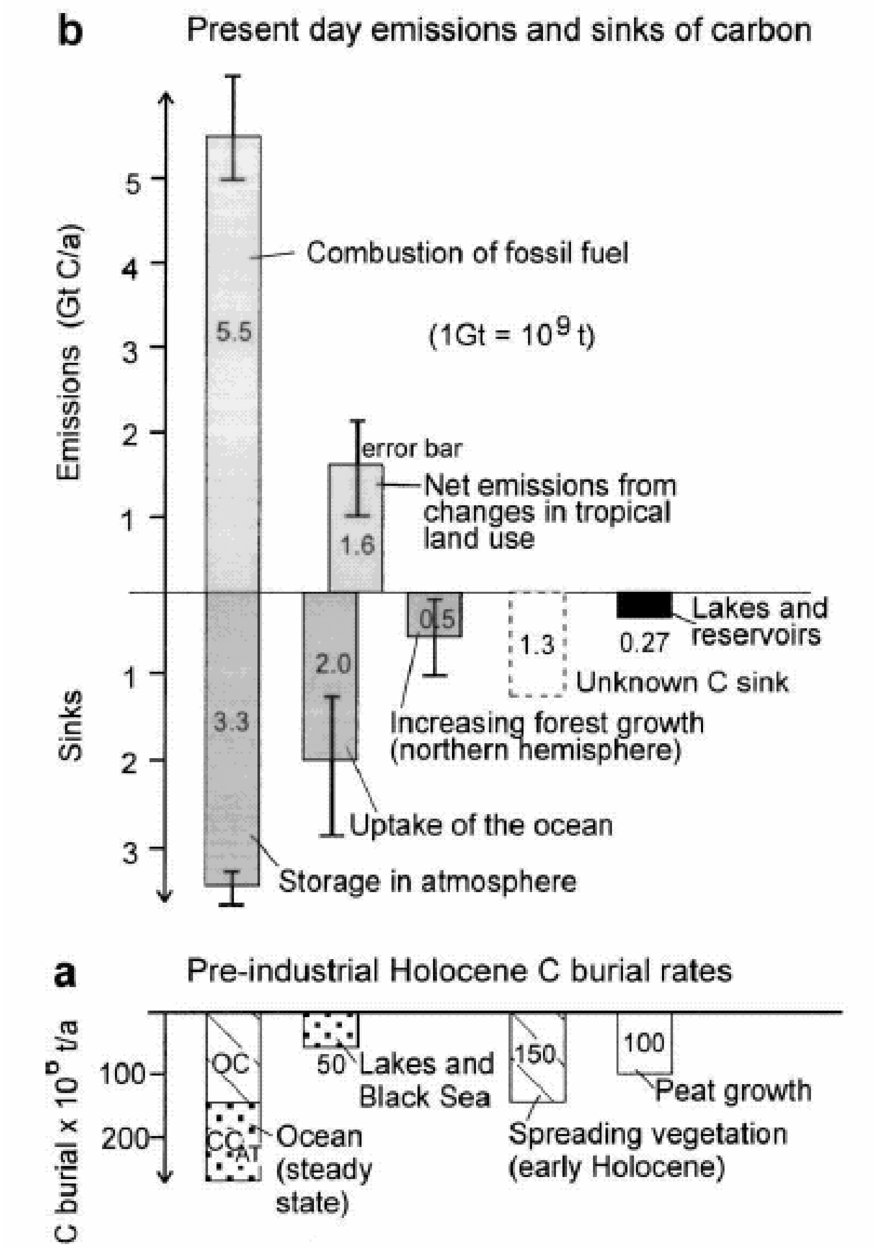


Figure 11: Present Day Emissions and Sinks of Carbon [Einsele 2001]

The dynamics of sedimentation and carbon accumulation in reservoirs is also peculiar because of the impact caused by the installation of a reservoir. Thus, high rates of carbon burial are characteristic of the first years of a reservoir due to soil erosion, and soil and biomass flooding [Einsele 2001]. Although external (allochtonous) sources of carbon contribute to the stock of carbon buried in the reservoir, this is not a sink for atmospheric carbon unless the original source is being restored somewhere by means of photosynthesis [Stallard 1998]. Thus, only the accumulation of carbon fixed through primary production of the aquatic organisms that also accumulates in the sediments (e.g., autochtonous carbon) is the phenomenon that should be compared to the forgone NEP of the flooded ecosystem.

The installation of dams disrupts natural biogeochemical cycles and affects the balance of carbon in ecosystems [Friedl 2002]. Damming implies a reduction in the flow, which allows particle settling and enhances the transparency of the water and light penetration. Thus, the primary productivity in reservoirs tends to be high, which contributes to the fixation of OC. The level of primary productivity in a reservoir also depends on the availability of nutrients such as nitrogen (N) and phosphorus (P), and dissolved organic carbon (DOC).

DOC, which supports life in aquatic ecosystems, can either be transported into the reservoir or produced within the reservoir through bacteria, algae, and macrophytes. Decomposition is also a source of DOC. The relative importance of allochthonous versus autochthonous production of DOC is accentuated in arid regions because of the poor contribution of terrestrial external sources [Nguyen 2002].

4.1.2 Hydroelectricity Case Studies

Arch and gravity dams are two basic designs for damming rivers that form accumulation reservoirs. When a river runs in a canyon an arch dam blocks the water passage through a high wall of steel-reinforced concrete, and the head of the project is an important factor for the final power capacity of the facility. In contrast, gravity dams rely on earth and rock filled structures to retain the water. The concrete structure in a gravity dam houses the power houses and the spillways to control the overflows in the reservoir. In the case of large gravity dams the flow of the river is an important component of the final installed capacity.

The two case studies selected in this research are the Glen Canyon Dam on the Colorado River in the U.S. with an installed capacity of 1,296 MW, and the Tucurui Dam on the Tocantins River in Brazil with an installed capacity of 8,670 MW. The Glen Canyon Dam is an arch dam in a desert while the Tucurui dam is a gravity dam in a tropical forest. The local characteristics not only affect the choice of the design but also the performance of the alternatives with respect to their life-cycle GHG emissions. Therefore, all other technologies assessed in this study are based on the context and characteristics of these two power plants. Figure 12 shows the alternatives considered as a replacement of the hydroelectric power plant and the impact categories considered.

In the case study of Glen Canyon Dam the upgrade of the power plant is also considered. This option associated with the continuous maintenance of the plant can extend the operation period of the facility and depending on the technology at the time of the upgrade, it is able to add some additional output. The advantage of upgrading is that much less environmental impacts are produced than building a new power plant to generate electricity [Pacca 2002].

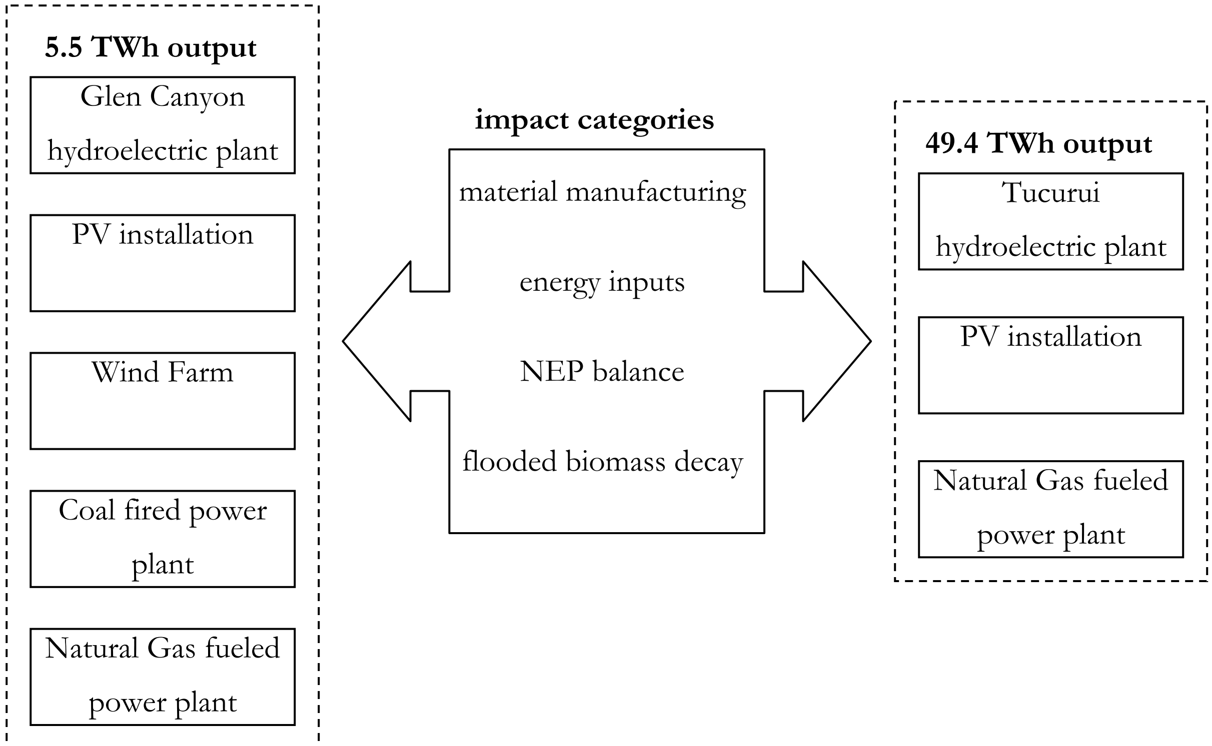


Figure 12: Electricity Generation Alternatives and Impact Categories Considered in This Assessment

The model used to assess emissions from hydroelectric plants assumes that carbon emissions are heavily influenced by decay of biomass in the reservoir. [Rosa 1995, Delmas 2001, Fearnside 2002]. Therefore, a sensitivity analysis is carried out based on two different case studies with two different dam designs on two different ecosystem types to see how emissions from each technology are affected.

4.1.2.1 Glen Canyon Dam

Glen Canyon dam on the Colorado River is the second highest concrete arch dam in the U.S. with 3,750,000 m^3 of embedded concrete. Lake Powell, which is formed by water retained by the 216 m high structure was completely flooded only in 1980 taking over 689 km^2 of land area [USBR 2001a]. The power plant, which began operation in 1964, is the second largest operated by the U.S. Bureau of Reclamation (USBR) according to the electric output for all facilities in 1999 [USBR 2001b].

Between 1984 and 1987, the generators were upgraded by 338 MW for a total of 1,296 MW. The facility upgrade consisted of rewinding the generators and reducing the size of each penstock (the tube transferring water into a turbine) from 15 to 14 inches in diameter [USBR 2001c]. The facility has 8 units; five generators are presently rated at 165 MW each, and three generators are rated at 157 MW each. The upgrade of the existing dam has resulted in 39% additional power [USBR 2001a]. Additional energy produced from the upgraded hydroelectric power plant was 1.48 TWh in 1999. The contract cost to upgrade units 1, 3, 5, and 6 was $7,044,724 ($26/kW), while it cost $5,026,724 ($30/kW) to upgrade units 2, 4, 7, and 8, for a total upgrade cost of $12,071,448 in 1987 dollars [USBR 2001a]. The cost calculations do not include the offset in upgrade cost by routine operation and maintenance costs. Namely, normal maintenance costs would have been incurred to replace a worn generator winding even if the upgrade had not occurred. This consideration makes upgrade costs comparably smaller.

Based on detailed technical records [USBR 1970], GWP calculations, the GWE formula, and the CO_2 response function, the estimated GWE of Glen Canyon's construction is 500,000

$MTCO_2Eq$ (after 20 years) of operation. The contribution of construction materials and processes, and power plant components is shown in Table 5. Emissions from excavation were calculated based on the fuel consumption of the construction equipment, assuming that all fuel was converted to CO_2.

The GHG emissions from the upgrade were estimated assuming that all replaced parts came from the sector that produces turbines and turbine generator sets. Since EIO-LCA in its current version [EIO-LCA 2003] uses 1997 dollars, we converted the upgrade costs from 1987 to 1997 dollars using the Consumer Price Index (CPI) [BLS 2002]. The upgrade, which increased power capacity by 39%, resulted in 10,000 metric tons of CO_2 emissions, 1.3% of the estimated CO_2 emissions of Glen Canyon's original construction (800,000 metric tons of CO_2).

While hydroelectric power plants do not use fossil fuels in operation, they emit GHGs from biomass decay in the dam's reservoir, a subject of debate lately [Rosa 1995, Gagnon 1997, WCD 2000]. Annual biomass emissions are reduced as the flooded vegetation decays over time. Colder climates have slower decay rates, thus lower annual emissions [Gagnon 1997]. For Glen Canyon, the assumptions were that (1) the area of the flooded land is similar to the surface area of the reservoir, Lake Powell (653,130,000 m^2), (2) originally the land was covered by desert scrub that has a carbon density of 0.3 kg C/m^2 [Harte 1988], (3) the e-folding time for the biomass decay is 7 years, and (4) 10-30% of the carbon was subject to anaerobic decomposition and released as CH_4 [Rosa 1995]. Accordingly, using the CO_2 response function, the GWE is estimated to be 2,000,000 – 5,000,000 $MTCO_2Eq$ (after 20 years).

Table 5: Glen Canyon Hydroelectric Plant Construction Inputs and GWE (after 20 yr of operation) [Pacca 2002]

		Unit cost	Total cost	GHG emissions (MT CO_2 equiv.)			
Inputs:	**Total MT**	**(1992 $/MT)**	**(1992 $)**	**CO_2 +**	**CH_4 +**	**N_2O =**	**GWE**
concrete	9,906,809	30[1]	296,752,257	400,792	751	7,898	**409,441**
excavation (m^3)	4,711,405	n.a.	114,839,000	3,812			**3,812**
turbines and turbine generator sets	n.a.	n.a.	65,193,084	41,725	45	249	**42,019**
power distribution and transformers	n.a.	n.a.	13,754,764	12,358	16	79	**12,453**
steel	32,183	385[2]	12,402,138	47,310	29	244	**47,583**
Copper	90	2,368[2]	214,167	186	0	2	**188**
aluminum	67	1,268[2]	84,804	157	0	2	**159**
total (rounded)			**503,240,216**	**500,000**	**1,000**	**9,000**	**500,000**

In addition, the formation of Lake Powell displaced an ecosystem and resulted in forgone carbon uptake measured by Net Ecosystem Production (NEP), which is the difference between Net Primary Productivity (NPP), which absorbs carbon from the atmosphere, and heterotrophic respiration in the absence of disturbances, which releases carbon to the atmosphere [Baldocchi 2001]. NEP is calculated as:

$$\mathrm{NEP} = \mathrm{NPP} - \frac{C}{\tau} \qquad (10)$$

where:

C is the amount of carbon stored in the terrestrial ecosystem

τ is the average turnover time, which is calculated as (27, 28):

$$\tau = 42.8 \times e^{-1921\left(\frac{1}{283.15\ -139.4} - \frac{1}{\mathrm{MAT}\ -139.4}\right)} \qquad (11)$$

Using 298 K for the local Mean Annual Temperature (MAT), τ was calculated as 15 years. Based on annual NPP of 0.032 kg C m^{-2} [Harte 1988], and carbon density in the desert scrub ecosystem (0.3 kg C m^{-2}; [Harte 1988]), the annual NEP was calculated as 21 g of C m^{-2}. Assuming constant carbon sequestration rates, the estimated GWE due to the forgone carbon uptake of the flooded area is 400,000 $MTCO_2Eq$ (after 20 years).

In a 1986 report from the USBR determined that the average sediment deposition rate over the 23.5 years of the operation of the reservoir was 45,603,741 m^3 yr^{-1}, corresponding to an annual average accumulation of 7 cm [USBR 1988]. The accumulation rate for Lake Powell is more than three times the average sedimentation rate for reservoirs worldwide (2 cm yr^{-1})

[Mulholland 1982]. Assuming an average bulk density of 1 MT m^{-3} and 2% of organic carbon [Dean 1998], the organic carbon accumulation rate equates to 912,075 MT per year, which corresponds to 3,344,274 $MTCO_2Eq$. This calculation assumes an average carbon percentage in sediments; however, the climate of the Upper Colorado watershed is classified as semiarid, and the lower part of the basin is sparsely vegetated because of inadequate rainfall and poor soil conditions [USBR 1988]. Thus, the carbon content in the sediments is likely to be much less. The burial of allochtonous carbon is not a sink for atmospheric carbon unless the original source is being restored somewhere by means of photosynthesis [Stallard 1998]. Consequently, sedimentation is not considered as a carbon sink in this case.

Summing the two GHG emission sources (construction of the dam and biomass decay from the reservoir) and the forgone NEP, the total GWE of the Glen Canyon Dam after 20 years (at the time of the upgrade) is estimated at 3,000,000 – 6,000,000 $MTCO_2Eq$.

Hydroelectric plants have been intensely criticized for changing and destroying the physical environment, such as destroying natural habitat (e.g., of Pacific Northwest salmon) and species, being unsightly (such as the flooding of Glen Canyon), siltation, dislodging indigenous populations, etc. While undoubtedly important, these issues are not the subject of this dissertation.

4.1.2.2 Tucurui Hydroelectric Plant

The importance of hydroelectricity in Brazil is demonstrated by the 93% (assuming 860 kcal of oil equivalent per 1 kWh of electricity) share of this source in the country's electricity matrix, which corresponded to 322 TWh in the year 2000. The Ministry of Energy of Brazil estimates that the full exploitation of domestic hydroelectric resources could add 143 GW of power to the existing 61 GW [BEN 2001].

When completed the Tucurui power plant on the Tocantins River will become the largest hydroelectric plant entirely on Brazilian territory (The world's largest power plant, Itaipu, is on the border of Brazil and Paraguay). The power plant is located in the northern region, in Pará state, at latitude 3° 45' S and longitude 49° 41' W. The Tocantins River is part of the north-south Tocantins/Araguaia watershed, and flows into the Amazon River estuary. The reservoir flooded 2,850 km^2 of rain forest, and only 140 km^2 of vegetation have been cleared in advance [La Rovere 2000].

The reservoir, which is owned by the public utility Eletronorte (ELN) was filled in 1985-1986, and the motorization of the power plant was divided in two phases. Phase I has been already completed and is composed of twelve Francis-type turbines (369 MW each) and generator sets plus two small auxiliary units (20 MW each). Phase II comprises of 11 Francis turbines with 382 MW each. The expected total installed capacity of the power plant is 8,670 MW (Table 6). Assuming a capacity factor of 65% the power plant yields an annual energy output of 49,367 TWh [ELN 2003].

The Tucurui dam is a concrete gravity dam with a total installed capacity of 8.67 GW. The major structures are an earth dam on the right bank, a riprap dam on the river bed, and a concrete spillway. Construction included 57,385,718 m^3 of excavation, 84,682,890 m^3 of earthfill and rockfill, and 17,900,070 m^3 of concrete. Initially, the cement was to be imported from Colombia but the government decided to buy domestically produced cement at a higher cost to support the local industry [La Rovere 2000]. Herein it is assumed that the cement comes from Recife, which is a major city in the northeast of Brazil, located 2,150 km away from Belem [CDP 2003].

Table 6: Characteristics of the Turbine Generator Sets in Tucurui [La Rovere 2000]

	Phase I		Phase II
	main	auxiliary	main
Number	12	2	11
Type	Francis	Francis	Francis
Capacity	369 MW	20 MW	382 MW
Head	60.80 m	60.80m	61.7 m
Speed	81.80 rpm	327.27 rpm	81.80 rpm
Rotor Diameter	8.10 m	n.a.	8.50 m
Flow Intake	575 m^3/s	39.50 m^3/s	679 m^3/s
Generator Output	350 MVA	250 MVA	395 MVA

n.a. not available

The Tocantins River is navigable and 254 km separate the estuary, which is close to Belem, the capital of Para State, from the dam. Tugboats are used for cargo transport in the Tocantins/Araguaia system; thus, commodities are easily transported to Belem Port on the Atlantic Ocean. This transportation mode was used to send materials and equipment used in the construction of the power plant because of its lower cost compared to road transportation. In fact, the improvement of the roads connecting Tucurui to the major cities in the region was not accomplished during the construction phase as initially expected [La Rovere 2000].

Based on the characteristics of the reservoir and the GWE method [Pacca 2002], the estimated GWE of Tucurui's construction is 1,600,000 $MTCO_2Eq$ after 20 years (Table 7). The contributions of construction materials and processes, transportation, and power plant components are shown in Table 7. Emissions from excavation were calculated based on the fuel consumption of the construction equipment, assuming that all fuel was converted to CO_2. Emissions from cement transportation were calculated assuming that 8% of the concrete mass is cement that was shipped from Recife, combined with a fuel efficiency of 104 metric tons km^{-1} $liter^{-1}$, and an emission factor of 2.8 kg of CO_2 per liter of fuel oil [Davis 2002, IPCC 1997].

While hydroelectric power plants do not use fossil fuels in operation, they emit GHGs from biomass decay in the dam's reservoir, a subject of debate lately [Rosa 1995, Gagnon 1997, WCD 2000]. Yearly biomass emissions are reduced as the carbon previously stored in the ecosystem decays over time. For Tucurui, the assumption was that the area of the flooded land is similar to the surface area of the reservoir (2,430 km^2) subtracting the old riverbed, the islands and deforested areas, which yields a flooded area of 1,180 km^2 [Rosa 2002]. Originally the land was covered by tropical forest that has a carbon density of 18.8 kg C m^{-2} [Harte 1988], the e-folding time (time required for an initial amount to decay to 1/e of its initial mass) for the biomass decay is 7 years, and 10-30% of the carbon was subject to anaerobic decomposition and released as CH_4 [Rosa 1995]. Accordingly, assuming a parameterized CO_2 pulse response function, the GWE is estimated to be 118,576,083 to 355,728,188 $MTCO_2Eq$ (after 20 years of operation).

After 15 years, the contribution of biomass decay only equates to 42 to 126 MT km^{-2} yr^{-1} of

CH_4, and 1,040 to 3,271 MT km^{-2} yr^{-1} of CO_2. In comparison, the gross GHG emissions measured in a previous study between 1998 and 1999 fluctuate from 5.33 to 76.36 MT km^{-2} yr^{-1} of CH_4 and from 2,378 to 3,808 MT km^{-2} yr^{-1} of CO_2 [La Rovere 2000]. In another study emissions from the reservoir in 1990 accounted for 278 to 466 MT km^{-2} yr^{-1} of CH_4, and 3,396 MT km^{-2} yr^{-1} of CO_2 [Fearnside 2002]. Therefore, emissions modeled in this research conform to previous published results in a conservative way.

The formation of the reservoir also displaced the tropical ecosystem and resulted in forgone carbon uptake measured by Net Ecosystem Production (NEP), which is the difference between Net Primary Productivity (NPP), which absorbs carbon from the atmosphere, and heterotrophic respiration in the absence of disturbances, which releases carbon to the atmosphere The NEP measured in pristine, seasonal tropical rain forests in Amazonia is 1.0 t C ha^{-1} yr^{-1}, whereas values for dense moist rain forest are up to 5.9 t C ha^{-1} yr^{-1} [Watson 2000]. Assuming constant carbon sequestration rates, the estimated GWE due to the forgone carbon uptake of the flooded area ranges from 14,316,148 to 84,465,274 $MTCO_2Eq$ (after 20 years).

Table 7: Major Construction Inputs and GWE (after 20 yr of operation) for Tucurui Hydroelectric Plant[a]

Inputs	total MT	unit cost (1997 $/MT)	total cost (1997 $)	GHG emissions (MT of CO_2 equiv)			
				CO_2	+ CH_4	+ N_2O	= GWE
concrete	17,900,070	$29.70	$531,590,919	380,412	390,130	697	**771,239**
turbines and turbine generator sets	n.a.	n.a.	$1,119,386,000	245,546	250,295	459	**496,300**
Steel	203,440	$275.63	$56,074,916	60,853	52,782	66	**113,702**
power distribution and transformers	n.a.	n.a.	$99,245,000	31,435	30,336	55	**61,825**
excavation (m^3)	57,385,718	n.a.	n.a.	54,570			**54,570**
cement transportation (MT km^{-1})	3,805,916,004	n.a.	n.a.	55,671			**55,671**
earthfill and rockfill (m^3)	84,682,890	n.a.	n.a.	51,524			**51,524**
total				**880,000**	**720,000**	**1,300**	**1,600,000**

[a] Total emissions are rounded to two significant digits. MT, metric ton; GWE, global warming effect; na, not available.

If the productivity of the land ecosystem replaced is of concern, the productivity of the aquatic environment may also affect the balance of carbon. High rates of sediment deposition can bury organic sediments in anoxic strata slowing oxidation. Reservoirs can be a carbon sink if the organic carbon that is being buried represents an increase in the input into streams and rivers and if carbon in natural environments would have been oxidized instead of buried in reservoirs. Indeed, a large fraction of the carbon fixed in freshwater ecosystems is captured in the sediments because of shallower water columns, prevalence of anoxic strata, higher NPP, and sedimentation rates. Large lakes have an accumulation rate of 2 to 10 g C m^{-2} yr^{-1} [Mulholland 1982]. Based on this numbers the Tucurui reservoir would account for a carbon uptake of 286,323 to 143,615 $MTCO_2Eq$ (after 20 years).

Summing the two GHG emission sources (construction of the dam and biomass decay from the reservoir) with the forgone NEP, and subtracting the carbon uptake by the reservoir, the total GWE of the Tucurui Dam after 20 years (at the time of the upgrade) is estimated at 691,887,398 to 1,871,684,087 $MTCO_2Eq$.

4.2 Photovoltaic Electricity Generation Systems

PV modules convert solar energy directly into electricity. Although several LCAs in the literature show CO_2 emissions normalized by electricity output of PV installations, different assumptions used in each study make results difficult to compare; thus, the range of results published is quite large. Table 8 shows a compilation of studies that published CO_2 emissions associated with electricity generation using PV technology.

Table 8: Published Carbon Dioxide Emissions per Kilowatt-hour for PV Systems.

Author	year	Characteristics	gCO_2/kWh
Fritsche	1989	n.a.	32.0
Meridien Corp.	1989	central station PV plant	6.5
San Martin	1989	central station PV plant	5.4
Kreith	1990	central PV system 100 MW	24.0
Uchiyama	1992	PV	201.3
Nieuwlaar	1996	roof integrated system - 30 m^2 amorphous cells	47.0
Komiyama	1996	Japan – polycrystalline	522.0
Komiyama	1996	Indonesia – polycrystalline	1004.4
Dones	1998	PV p-Si (CH) - 100yr. GWP	189.0
Dones	1998	PV m-Si (CH) - 100yr. GWP	114.0
IEA	1998	mc-Si	87.0
Frankl	1998	monocrystalline silicon PV power plant	200.0
Kato	1998	single-crystalline silicon	83.0
Kato	1998	polycrystalline silicon (poly-Si) PV module - future technology	20.0
Kato	1998	amorphous silicon (a-Si) PV module - future technology	17.0
Alsema	2000	thin film (amorphous) grid connected roof top systems (1700 kWh m^{-2} yr^{-1}) 30yr. lifetime	50.0
Alsema	2000	monocrystalline grid connected roof top systems (1700 kWh m^{-2} yr^{-1}) 30yr. lifetime	60.0
Greijer	2000	dye sensitized solar cell (ncDSC) 20 yrs. Lifetime - 2190 kWh m^{-2} yr^{-1} - 500MW plant - amorphous - Efficiency=7% and process energy=100 kWh m^{-2}	19.0
Greijer	2000	dye sensitized solar cell (ncDSC) 20 yrs. Lifetime - 2190 kWh m^{-2} yr^{-1} - 500MW plant - amorphous	47.0

Greijer	2000	efficiency=12% and process energy=220 kWh m^{-2}	22.0
Greijer	2000	efficiency=9% and process energy=180 kWh m^{-2}	25.0
Oliver	2000	building integrated grid connected 12% module efficiency poly-crystalline	120.0
Oliver	2000	centralized Plant 12% module efficiency poly-crystalline	170.0
Nomura	2001	concentration design using a polycrystalline solar-cell - grid connected - near future technology	190.0
Nomura	2001	concentration design using a polycrystalline solar-cell - grid connected - short run technology	133.0
Nomura	2001	concentration design using a polycrystalline solar-cell - grid connected - long run technology	104.0
Ganon&Uchiyama	2002	n.a.	13.0
Meier	2002	building integrated PV system	39.0
Ito	2003	polycrystalline 12.8% efficiency	44.0

Indeed, a set of parameters is responsible for the variability in the performance of different installations. Besides the level of insolation (incoming solar radiation), which depends on the latitude and the characteristics of the local air mass, and reflects a natural characteristic of the site selected for the installation of the modules, other parameters are simple choices made by the user of the system, which sometimes are technology dependent, and other times are driven according to the purpose of the system. Some of these parameters are listed on Table 9 and discussed in the following paragraphs.

Currently, PV modules production follows three types of technologies: monocrystalline, polycrystalline, and amorphous. The manufacturing of crystalline PV modules requires a larger share of electricity input than the manufacturing of amorphous panels. The primary energy required for the fabrication of crystalline PV modules is 3.8 to 2.9 times the input for the same unit area of amorphous modules [Alsema 2000b]. Table 10 shows different phases in the manufacturing of crystalline and amorphous modules and their respective energy consumption. However, these estimations are contentious and the energy necessary for manufacturing of crystalline modules varies between 2,400 and 7,600 MJ/m^2 for polycrystalline (mc-Si) technology and between 5,300 and 16,500 MJ/m^2 for monocrystalline (sc-Si) technology. Manufacturing energy requirement for thin film (amorphous) modules ranges from 710 to 1,980 MJ m^{-2} [Alsema 2000b].

Table 9: Characteristic Parameters in a PV installation.

Technology	**System configuration**
Module's technology	Array area
Module's efficiency	Tilt angle and/or orientation
Tracking system	Mounting structure
Components' lifetime	Stand alone vs. grid connected
	Installation scale
	Other B.O.S. components

Although the energy required for manufacturing PV modules is more a function of the modules' area than its power [Alsema 2000], other studies report the manufacturing energy normalized to the power output. For example, the manufacturing of a 11.2% efficient monocrystalline module requires 9,683 kWh/kWp of electricity, whereas the manufacturing of a 10.3% efficiency polycrystalline module requires 12,723 kWh/kWp [Frankl 1998]. Assuming Standard Test Conditions (irradiance level of 1,000 W m^{-2}), these values equate to 3,904 MJ m^{-2} and 4,718 MJ m^{-2} respectively, which allows the comparison with the ones presented in Table 10.

The primary energy input in the manufacturing phase affects the energy pay back ratio of the modules, depending on which is the source of the energy mix used, the embedded emissions are remarkable. Most GHGs emissions associated with PV systems (80 to 90%) are linked to electricity requirements in the fabrication of modules. The energy mix that goes into the manufacturing of the module is crucial to its GHG emissions. Thus, the substitution of renewable electricity for fossil based electricity in the manufacturing of the modules would reduce its emissions [Dones 1998]. In addition, the energy consumed to produce the machinery used to make PV modules is not negligible (Alsema 2000].

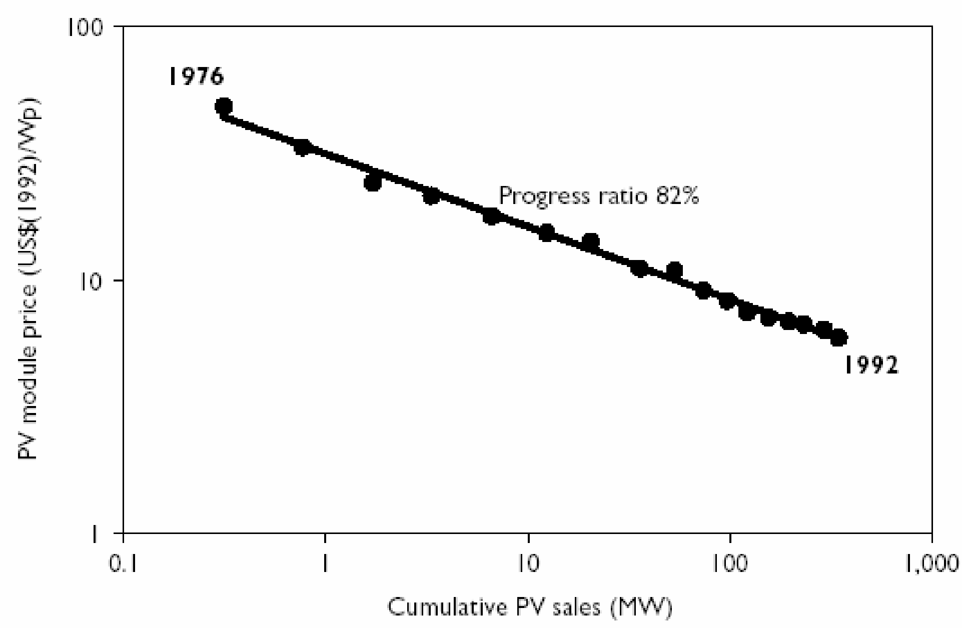
Table 10: Energy Requirements for Module Manufacturing (MJ/m^2) (Adapted from [Alsema 2000])

<table>
<tr><th colspan="2">Process</th><th>Crystalline</th><th>Amorphous</th></tr>
<tr><td rowspan="2">Cell material</td><td>Silicon mining and purification</td><td>2,200</td><td rowspan="2">50</td></tr>
<tr><td>Silicon wafer production</td><td>1,000*</td></tr>
<tr><td colspan="2">Cell module processing</td><td>300</td><td>400</td></tr>
<tr><td colspan="2">Module encapsulation materials</td><td>200</td><td>350</td></tr>
</table>

Overhead operation and equipment manufacturing	500	400
Total module (without frame)	4,200	1,200
Module frame (aluminum)	400	400
Total module (framed)	4,600	1,600

*monocrystalline wafers require an additional 1,500 MJ m^{-2}

Of course, the energy conversion efficiency of the modules also affects the energy pay back ratio of PV systems. The energy conversion efficiency measures the ratio between the electric output of the panel and the incoming solar radiation on the surface of the module, and is expressed as a percentage. The efficiency of a module is a function of the technology used; therefore, different brands, vintages, and types of modules will have different efficiencies. Improving both the energy conversion efficiency of the modules and their manufacturing efficiency, that is, reducing energy and materials inputs, affects the cost of the electricity produced out of PV installations. The continuous growth of the PV industry has benefited from both practices that ultimately reflect in the penetration of the technology in the market and affects the electricity cost. Such evolution in the industry is usually captured by a learning curve with the plot of the logarithm of the average electricity cost versus the cumulative sales of modules (Figure 13).



Experience curve for PV modules on the world market. The price for a module is given in constant 1992 US$ per peak watt,Wp. Peak watts are the power output from the module at optimum solar conditions as defined by certification agencies. Adopted from Williams and Terzian (1993).

Figure 13: Learning Curve for PV Modules [IEA 2000b]

The quality of the crystallization process is key to the final efficiency of the module. Depending on the technology, the efficiency of the modules also decreases with use. Technological changes are constantly improving the efficiency of the modules and reducing their costs. Monocrystalline ingots, which are harder to obtain, are used in the manufacturing of modules with the highest efficiencies whereas polycrystalline materials are cheaper and produce modules with efficiencies 1 to 2 % lower than monocrystalline modules. Between the production of electronic grade silicon and the wafers, 60% of the silicon is lost due to quality concerns [Alsema 2000]. Because the production of crystallized silicon demands a significant amount of energy, silicon losses affect negatively the energy payback ratio of the modules and their life-cycle emissions.

Because the electricity output of a module depends on how much solar radiation reaches the surface of the module, the position of the module with respect to the sun is important. The electricity produced by the module depends on the direction of the module's face and the angle with the horizontal plane. Some module's arrays are equipped with a frame that tracks the sun and increases the amount of incoming radiation. While some of the arrays move only along one axis based on a frame filled with refrigerating gas, other tracking systems move along four axes and are powered by a small electric motor. In this case some electricity generated by the system is consumed during its operation [Keoleian 1997].

The choice of the tilt angle depends not only on the maximization of the energy output of the modules, which varies with the seasons of the year, but also on the economic and environmental cost of the structures to hold the modules. The feasibility of such systems also depends on the balance between economic and environmental costs and benefits.

The Balance of the System (BOS) is the term used to refer to all the other components in the PV installation in addition to the modules. The BOS depends on the type of application and local conditions, and includes the structure to support the modules and hardware. Batteries to store and deliver energy during load periods, as well as inverters might be necessary if the system is connected to the grid that operates with alternate current. Cables to interconnect modules and arrays to batteries and inverters are also part of the BOS. Batteries have emission impacts throughout their life-cycle. The assessment of the energy, and carbon and other emissions associated with the BOS should also be part of a comprehensive LCA. The table below shows energy use estimations for components used in the BOS.

Table 11: Energy Inputs into System Components: [Alsema 2000b]

Aluminum module frame	MJ/m^2	500
Array support – central plant	MJ/m^2	1800
Array support – rooftop	MJ/m^2	700
inverter (3 kW)	MJ/W	1

Whenever energy is converted or stored to be further recovered, some losses occur; therefore, there are some efficiency losses associated with these practices that need to be included in the analysis. It is estimated that 25% of energy is lost in the system through BOS conversion efficiency losses [Alsema 2000].

A basic difference between systems is with respect to the purpose of the installation. While some PV systems are stand-alone systems that can only supply energy for small consumers, others are grid-connected. The scale of grid-connected systems is variable and this parameter affects the BOS of the system and its respective material requirements. Figure 14 shows a comparison of energy and material inputs in six different configuration for grid connected systems using monocrystalline (m-Si) and policrystalline PV modules (p-Si) [Dones 1998]. The assumed efficiency for the m-Si and p-Si modules is 16.5% and 14% respectively. Roof modules produce 860 kWh per year per kWp whereas the 100 kW plant produces 1000 kWh per year per kWp and the 500 kW plant produces 1200 kWh per year per kWp.

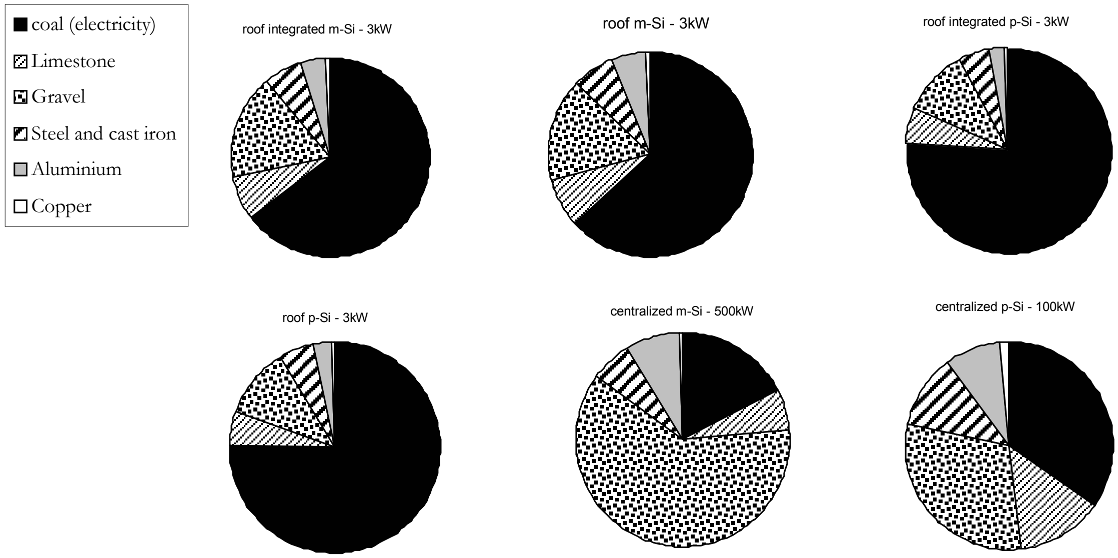


Figure 14: Materials and Energy inputs in Different Grid Connected Systems (kg/kWp) [Dones 1998]

The share of coal is greater in the systems installed on roofs because the manufacturing of PV modules requires a significant amount of energy and such systems use less material for the installation of the modules compared with the centralized plants that in addition to coal also have significant shares of other materials. Likely, different conversion efficiencies are responsible for higher electricity consumption by the roof integrated system with a poly-crystalline module in comparison with roof integrated system with mono-crystalline modules.

Different mounting options are reflected in the amount of energy input into the system; thus, the energy pay back time for a rooftop system is 2.5 to 3 years, and the pay back time for a ground mounted system is 4 years [Alsema 2000]. This shows that even with the optimization of the conversion efficiency of ground-mounted modules the energy used in the structures to support the modules drains a considerable amount of energy. Indeed, concrete and steel used in the construction of the structures to support the modules are responsible for the high energy content of the PV plants [Frankl 1998]. The use of an existing structure to support the modules also reduces the footprint of this electricity generation alternative since the structure stands in that place for other reasons than just to support the modules.

In urbanized settings grid connected modules are placed on existing building structures. Such installation is known as building-integrated PV (BIPV) [Keoleian 2003]. While rooftop modules are placed on an existing structure through the use of simple frames to hold a set of modules, stand-alone systems demand the manufacturing and installation of special frames on the ground to hold an array, which includes a set of modules.

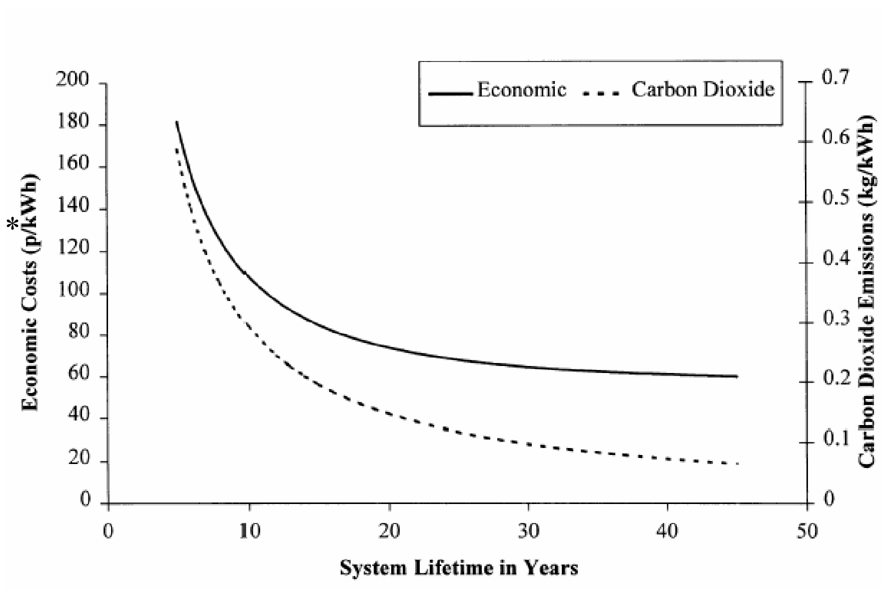
Although small producers may own grid-connected systems, the aggregation of several small suppliers in a network may result in a significant energy source, which could be comparable to centralized power plants. Actually, when a large number of individual modules are connected to the grid the scale of the system can be compared with the capacity of a PV power plant where all modules are located side by side in the same place. Advantages of a network system include its resilience to massive power outages that are characteristic in large-scale centralized systems, and the elimination of power transmission losses when modules are installed close to consumers. [Pearce 2002]. In a recent study distribution losses where calculated as 7.03% of the power delivered to the grid [Spath 1999].

The scale of grid-connected systems varies, and although a collection of small modules may match the energy produced in a larger installation there are some advantages due to economies of scale in the construction of large-scale centralized systems. One advantage of a centralized system is that the materials used in the facility can be reused, recovered, and recycled more easily than if they were in dispersed installations [Fthenakis 2000]. Changing the position of the panels to maximize the amount of incoming radiation in their surfaces may also be easier in a centralized plant. In Japan large-scale centralized plants (100 MW) are expected to be constructed over the next couple of years [Pearce 2002].

A comparison between crystalline and amorphous technologies shows that more efficient crystalline modules consume more energy during manufacturing than less efficient amorphous modules. However, the efficiency of amorphous modules diminishes over time whereas the efficiency of crystalline modules lasts longer. Therefore the decreasing efficiency of amorphous modules over time needs to be factored into the analysis. The efficiency of amorphous modules typically declines about 25% over the first few months of exposure to the sun due to the Staebler-Wronski effect [Staebler 1977], but then the efficiency stabilizes and the quality of the modules do not continue to degrade after this point for the life-cycle of the PV.

In a LCA all emissions, including emissions during manufacturing, are compared to the energy produced over a certain period. Usually this period is the lifetime of a major component of the system. In the case of PV systems 25 to 30 years is used as the lifetime of the modules. However, for some types of amorphous modules a lifetime between 10 to 20 years is more realistic even if some higher performance brands such as the triple junction Unisolar modules may reach 25 to 30 years of life time [Jacobson 2003]. While some parameters are choices made by the investor others are circumstantial, that is, they depend on local characteristics or natural conditions. The lifetime of the modules is an important parameter that affects both the electricity costs and the abatement of CO_2 emissions (Figure 15).

The PV industry follows a proactive LCA approach to reduce GHG emissions of the electricity generation systems and improve manufacturing, design and end of life of the facilities [Fthenakis 2000]. The reduction of GHG emissions over the life-cycle of the system depends both on improving conversion efficiency of solar radiation to electricity and using efficient and low emission energy sources. Beyond that, energy and material amounts in the PV system should be minimized [Greijer 2000]. Retrofitting PV installations seems also beneficial since part of the old structure could be reused and new modules could be more efficient and embed less carbon emissions over their life-cycle.



* assumes 8% annual discount rate.

Figure 15: Electricity Costs and CO_2 Emissions Versus System Lifetime [Oliver 2000]

4.2.1 Global Warming Effect of a PV System

In this section the GWE method is applied to two case studies that consider the installation of massive and centralized PV plants as a replacement of large hydroelectric plants. The first one in the desert takes into account the replacement of the energy generated at Glen Canyon hydroelectric plant and the second one in a tropical forest assumes the replacement of energy generated at the Tucurui hydroelectric plant.

4.2.1.1 PV System in a Dry Ecosystem

Medium-sized PV plants of 1 MW capacity are considered the functional unit [Tahara 1997]. Ordinarily, large capacity solar plants are designed as thermal systems instead of incorporating PVs. These plants use reflective surfaces to focus sunlight on a collector that contains a working fluid (e.g., an oil-filled tube). The heat from the working fluid is transferred to water, and the resulting steam powers a turbine-generator set to produce electricity [Johanson 1993]. This setup would be more appropriate at the scale under consideration here; however, solar industry trends point toward PV module production.

Manufacturing and constructing a PV plant to match the annual electricity output of Glen Canyon power plant (5.55 TWh) would result in a GWE of 10,000,000 $MTCO_2Eq$ after 20 years of operation (Table 12). The total cost of materials and construction was $3,578,458,000 (in 1997 dollars), excluding land purchases, labor/installation and maintenance costs.

About 35 million 100 W modules of dimensions 1.316x0.66 m^2 [Shellsolar 2003] could be used in a non-concentrating array composed of array units of 3x10 panels, each having its own concrete foundation, for a surface area of 3.9x6.6 m^2, sited at 30 degrees latitude, at a 30-degree tilt (approximately 1.2 m of additional width is needed to account for shading by the array due to the sun's angle). There is 0.9 m between each of these array units for personnel access. Each adjacent unit covers a land area of 37.44 m^2, and has a capacity rating of 3 kW. Some 1,372,52400 of these 3 kW units are required [NREL 1991]. The upgraded Glen Canyon plant yields 5.55 TWh of energy each year from a capacity of 1,296 MW. Since the PV plant will have a smaller capacity factor (due to solar resource availability), the necessary installed capacity to achieve the same delivered energy is 4,118 MW, more than three times the hydroelectric plant's capacity. By comparison, the world production of PV modules was 260 MW in 2000 [Pearce 2002], thus meeting the capacity with PV is unreachable without major investments in production capacity or new technological breakthroughs.

The PV array required in this analysis would demand approximately 51,386,400 m^2 of land area. Land costs will vary depending on location. A PV plant of this magnitude must be constructed in a remote area such as a desert where land prices are low and solar resource is high. Given a range of prices between $250 and $1,200 per ha, the required land would add an additional $1,269,234000 to $6,346,171000 to the cost of the PV plant, an insignificant amount given the total life-cycle cost of $3.6 billion. The cost of land is reduced when the PV system is distributed, i.e., the generating capacity required is spread over a larger number of small systems (e.g., existing rooftops).

It was assumed that after 30 years of operation [Stronberg 1998] all PV panels had to be replaced (but not the concrete and steel base), and that the required construction energy was 100% of the original due to an energy-intensive PV manufacturing process. The electricity output of the facility remained constant. The refurbishment resulted in 4,000,000 metric tons of CO_2 emissions, a quarter of the original emissions from manufacturing and construction (20,000,000 metric tons of CO_2).

The solar plant would displace an ecosystem similar to what Glen Canyon Dam's reservoir flooded. The NEP loss is estimated at 30,000 $MTCO_2Eq$, and the decay of the biomass removed from the site during construction amounts to 40,000 $MTCO_2Eq$ (assuming the same ecosystem conditions as for the Glen Canyon site, measured after 20 years). Therefore, the total GWE of the PV plant (accounting for the manufacturing, construction, and NEP loss) would amount to 10,000,000 $MTCO_2Eq$ 20 years after construction.

Table 12: Major Construction Inputs and GWE (after 20 yr) for a PV Plant

Inputs:	Total MT	Unit cost (1992 $/MT)	Total cost (1992 $)	GHG emissions (MT CO_2 equiv.)			
				CO_2	+ CH_4	+ N_2O	= GWE
steel	4,600,276	385[1]	1,772,797,382	6,957,724	4,216	35,924	6,997,865
copper	480,029	2,368[1]	1,136,805,659	984,580	1,617	10,504	996,701
electricity (MWh)	7,556,010	36[2]	268,780,863	2,152,447	1,077	20,407	2,173,931
aluminum	177,788	1,268[1]	225,374,699	428,610	405	6,558	435,573
cement	2,222,356	55[1]	121,362,849	410,263	394	15,497	426,153
glass	1,066,731	50[1]	53,336,538	56,951	67	759	57,777
total (rounded)			**3,578,457,990**	**10,000,000**	**8,000**	**90,000**	10,000,000

[1]USGS 2002

[2] IEA 2000

4.2.1.2 PV System in a Tropical Forest

Because the solar industry is currently based on the production of PV modules, which convert solar energy directly into electricity, medium-sized PV plants of 1 MW capacity are considered the functional unit in this analysis [Tahara 1997]. Manufacturing and constructing a PV plant for the required annual electricity output of Tucurui (49,367 GWh) would result in a GWE of 30,000,000 $MTCO_2Eq$ after 20 years of operation (Table 13).

The installation would use 110 W (1.32 x 0.66 m) monocrystalline modules with a rated efficiency of 12.66% [Shell 2003]. They would be mounted in a non-concentrating array consisting of 3 x 10 panels positioned at an angle corresponding to the local latitude to maximize the average daily output. Each array is anchored in a 2 m^3 concrete foundation, and covers a 37.8 m^2 area. The arrays are arranged on sets that are serviced by 2 m wide asphalt paved roads. Each unit has 2 rows of 10 arrays with 1.2 m between the 2 rows to account for shading by the array due to the sun's angle, and 0.9 m between each of these array units for personnel access.

Some 8,541,603 of these 3.3 kW units are required to meet the output of Tucurui, based on the available insolation [Sundata 2003]. Since the PV plant will have a smaller capacity factor (due to solar resource availability) than Tucurui, the necessary installed capacity to achieve the same delivered energy is 25,600 MW, three times the hydroelectric plant's capacity. By comparison, the world production of PV modules in 2000 was 260 MW [Pearce 2002]. Thus meeting the capacity with PV is unreachable without major investments in production capacity or new technological breakthroughs.

Because there is no PV manufacturer in Brazil it was assumed that the modules would be shipped from Europe. Each module weighs 11 kg and the distance between the supplier and the construction site is 6,760 km, which includes a round trip between the Port of Belem and Tucurui besides the distance between the two continents. Marine transportation is used for the modules' shipment.

The PV array required in this analysis would demand approximately 331 km^2 of land area, which corresponds to 12% of the reservoir's area. It was assumed that after 30 years of operation [Stronberg 1998] all PV panels had to be replaced (but not the concrete foundation and the steel support), and that the required construction energy at that time was 100% of the original due to an energy-intensive PV manufacturing process. The electricity output of the facility remained constant. The refurbishment resulted in emissions of 12,000,000 $MTCO_2Eq$, over a third of the original emissions from manufacturing and construction (30,000,000 metric tons of CO_2).

Similarly to Tucurui, the solar plant would displace a tropical forest. After 20 years, the NEP loss is estimated at 1,662,081 to 9,806,280 $MTCO_2Eq$, and the decay of the biomass removed from the site during construction amounts to 12,400,000 $MTCO_2Eq$ (assuming that all carbon is emitted as CO_2). Therefore, the total GWE of the PV plant (accounting for the manufacturing, construction, and NEP loss) would amount to 47,060,000 $MTCO_2Eq$ 20 years after construction. A sensitivity analysis was carried out assuming that a different module technology is used in the installation. If amorphous modules with a 8.49% efficiency replace the monocrystalline modules, the land required would amount to 582 km^2 and emissions reach 129,699,433 $MTCO_2Eq$ 20 years after construction.

Table 13: Major Construction Inputs and GWE (after 20 yr of operation) for a PV Plant in Brazil[a]

Inputs	total MT	unit cost (1997 $/MT)	total cost (1997 $)	GHG emissions (MT of CO_2 equiv)			
				CO_2	+ CH_4	+ N_2O	= GWE
steel	26,521,675	$275.63	7,310,274,207	7,933,148	6,881,048	8,658	**14,822,855**
copper	2,767,479	$2,352.24	6,509,775,067	4,183,481	4,244,985	5,129	**8,433,595**
aluminum	1,024,992	$1,696.20	1,738,591,878	1,331,417	1,398,471	1,496	**2,731,384**
concrete	39,633,038	$29.70	1,177,010,091	842,282	863,798	1,542	**1,707,622**
asphalt	4,927,972	$30.00	147,839,167	577,830	645,092	312	**1,223,233**
glass	6,149,954	$50.00	307,497,679	197,840	193,568	251	**391,660**
PV shipment	2,923,557			289,042			**289,042**
oil	2,487,912	$105.71	262,997,974	176,447	104,474	218	**281,140**
coal	743,888	$31.49	23,425,201	9,910	8,844	13	**18,767**
electricity (MWh)	43,562	$35.57	1,549,585	7,670	8,760	4	**16,433**
sand and gravel	1,734,646	$5.55	9,627,287	5,716	5,446	6	**11,168**
total				**16,000,000**	**14,000,000**	**18,000**	**30,000,000**

[a] Total emissions are rounded to two significant digits. MT, metric ton; GWE, global warming effect; na, not available.

4.3 Wind

The installation of new wind turbines in Europe is ramping up; in the year 2002 over 23 MW of new capacity have been added, which corresponds to a 33% increase [Johnson 2003]. In the U.S. the numbers are still modest but thanks to dropping costs, more reliable systems, tax credits, and regulatory requirements demanding a share of renewable energy in the utilities electricity mix, EIA expects a 300% increase in the installed capacity over the next 25 years. Sizes and shapes of new projects in the U.S. span from a couple of turbines in a school in Iowa to hundreds of MWs in a Californian desert or at off shore installation in the northeastern region.

Although the technology of most modern wind turbines is equivalent, results from LCAs of their energy and CO_2 emissions vary [Lenzen 2002]. One basic difference is the location of wind turbines, which can be on land or offshore. Recently, the installation of offshore turbines, such as the proposed 170 MW project on Cape Cod, has attracted the attention of investors [Angelo 2002]. The foundation requirements for offshore wind turbines are different from the requirements for land based turbines. The energy intensity of turbine's tower is associated with the materials used in its construction. A concrete tower requires half the energy of a steel tower [Lenzen 2002]. Offshore support structures require more material and are more energy intensive to install.

A recent literature review shows that CO_2 emission factors for wind power plants range is 7.9-123.7 g of CO_2/kWh, capacity factors are 7.6-50.4%, and lifetime of the facilities is 15-30 years [Lenzen 2002]. Table 14 presents results from various emission assessment studies, which indicates that the reported values are between 7 and 74 g of CO_2/kWh.

Table 14: Published Carbon Dioxide Emissions per Kilowatt-hour for Wind Farms

Author	year	Characteristics	gCO_2/kWh
Fritsche	1989		15
San Martin	1989	wind energy conversion system	7
Uchiyama	1992	Wind 100 kW turbine	74
Kuemmel	1997	Danish average system	16
Dones	1998	wind mix (CH) - 100yr. GWP	36
IEA	1998		8
Schleisner	2000	Offshore 5 MW – 500 kW turbine	17
Schleisner	2000	Land based 9 MW – 500 kW turbine	10
Voorspools	2000	coast	9
Voorspools	2000	Inland	25
Nomura&Inaba	2001	100 kW turbine	38
Ganon&Uchiyama	2002		9

Combining the GWE with a list of inputs provided by recent LCAs of wind farms minimizes problems arising from the use of different assumptions related to the impacts of basic inputs in the power plant life-cycle. However, such information is not readily available in the literature, and moreover, it is inconsistent. The technology of wind turbines is changing rapidly. In the beginning the most efficient turbines were in the 50 to 200 kW range but currently they are in the 1 to 3 MW range. Both their weight and cost per installed capacity is lower than the previous technology [Johnson 2003]. Table 15 presents a list of material inputs to wind farms based on different turbine sizes.

Table 15: Material Inputs in Wind Farms as a Percentage of the Total Mass

Reference	Schleisner 2000		Lenzen 2002	McCulloch 2000	Kuemmel 1997		
Turbine size	500 kW		average values	600 kW	400 kW	1 MW	3 MW
	offshore	land					
Steel	12.2%	18.2%	32.0%	54.7%	43.5%	37.2%	11.0%
Aluminum	0.2%	0.4%		1.6%			
Copper	0.4%	0.1%	4.7%	0.9%	0.7%	0.4%	0.1%
Sand	0.3%	0.6%					
Fiberglass	0.2%	0.3%		5.6%	5.3%	3.0%	1.1%
Plastics	0.4%	0.6%	3.0%	0.0%			
Oil products	0.0%	0.0%					
Others	0.1%	0.2%		0.2%			
Concrete	85.6%	79.6%	60.3%	37.0%	50.5%	59.5%	87.8%
Lead	0.5%						

The weight of a 1.65 MW turbine per installed power is similar to the weight of a 600 kW turbine per installed power, which means that new technologies make the turbine lighter than its predecessors. However, the percentage of materials by weight depends on the size of the turbines (Table 15).

The lifetime of wind turbines is usually assumed to be 20 years; however, they can operate for longer [Krohn 1997], and the expected life of larger turbines is on the order of 25 years [Kuemmel 1997].

4.3.1 Global Warming Effect of a Wind Farm in the U.S.

In this assessment the feasibility of a wind farm is investigated as replacement for the energy generated by Glen Canyon hydroelectric plant. A wind farm producing 5.55 TWh of electricity per year was assumed to be in southern Utah, the same geographic area as Glen Canyon, at an elevation of 2,134 m (7,000 ft), close to the Escalante Desert where the average wind speed is 6.5 m/s [PNNL 1986]. A turbine of 600 kW [Schleisner 2000] was used as the unit for the farm's total of 4,480 turbines that would occupy an area of 48,9580,000 m^2. The total cost of materials and construction of the facility would amount to $206,881,000 (in 1992 dollars) without labor/installation and maintenance costs. Given a range of prices between $250 and $1,200 per ha, the required land would add an additional $12,098,162000 to $60,490,811000 to the cost. Given the large area, land between the turbines could be used for other activities such as agriculture. No NEP loss was anticipated. It was assumed that after 20 years of operation all turbines had to be replaced (but not the concrete foundations), and that the required construction energy was 30% of the original electricity and 100% of the petroleum used. The electricity output of the facility remained constant. The refurbishment resulted in 900,000 metric tons of CO_2 emissions, two-thirds of the original emissions from manufacturing and constructing the plant (1,300,000 metric tons of CO_2). The contribution of construction materials and energy to the GWE of the wind farm after 20 years of operation (800,000 $MTCO_2Eq$) is shown in Table 16. Therefore, the total GWE of the wind farm (accounting for the manufacturing, construction, and refurbishment) would amount to 2,000,000 $MTCO_2Eq$ 20 years after construction.

Table 16: Major Construction Inputs and GWE (after 20 yr of operation) for a Wind Farm in the U.S.

Inputs:	**Total MT**	**Unit cost (1992 $/MT)**	**Total cost (1992 $)**	**GHG emissions (MT CO_2 equiv.)**			
				CO_2 +	**CH_4 +**	**N_2O =**	**GWE**
steel	289,987	385[1]	111,751,615	426,296	258	2201	**428,755**
electricity (MWh)*	1,691,678	36[2]	40,756,138	317,231	158	3008	**320,397**
concrete	1,266,172	30[3]	37,927,398	51,225	96	1009	**52,330**
aluminum	6,275	1,268[1]	7,954,337	14,703	13	225	**14,941**
plastics	20,169	220[4]	4,445,273	5,090	7	53	**5,150**
copper	1,569	2,368[1]	3,715,021	3,127	4	33	**3,164**
glass	4,930	50[1]	246,511	256	0	3	**259**
oil	448	106[2]	47,380	204	0	1	**205**
sand	9,412	4[1]	37,743	55	0	0	**55**
total (rounded)			**206,881,416**	**800,000**	**500**	**7,000**	**800,000**

4.4 Coal

Approximately 56% of all utility-produced electricity in the U.S. is generated by coal-fired power plants. Electricity production from coal typically involves a sequence of phases (Figure 16). However, the majority of the environmental impacts are associated with the operation of the power plant and the disposal of by-products generated during combustion.

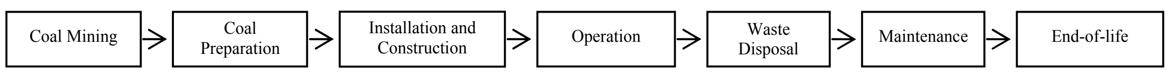


Figure 16: Coal Power Generation Life-cycle Phases

Results from published LCAs show that over 93% of the GHGs emissions from electricity generated by coal power plants are released during fuel combustion (Table 17). Indeed, the extraction of the chemical energy from coal, which in the U.S. averages 21.072 million Btu per short ton [U.S. EIA 2003], is directly proportional to the amount of fuel combusted. Table 17 also shows that recent LCAs report very small emissions associated with coal power plants; however, the technology considered in these schemes that usually involves a coal gasification phase has not been demonstrated yet. Actually, only three integrated gasification combined cycle (IGCC) power plants completed in the U.S. have their performance scrutinized by the National Energy Technology Laboratory (NETL) indicating that the maximum CO_2 emissions attained is 20% less than conventional technology [NETL 2003].

Conventional coal-fired power plants consist of a boiler that produces steam that is injected in a turbine that is coupled to an electric generator. More advanced designs, such as IGCC plants are based on the gasification of coal and the utilization of a combined cycle scheme to maximize the conversion efficiency of the power plant. A combined cycle scheme involves the use of two turbines in series and the reuse of the heat in the exhaust of the first turbine to power the second turbine. Nowadays, it is possible to reach 60% energy conversion efficiency through IGCC technology [Lombardi 2003]. Alternatively, the fuel obtained from coal gasification could be used in a fuel cell that also attains high efficiencies.

Table 17: Published Carbon Dioxide Emissions per Kilowatt-hour for Coal-fired Power Plants.

Author	Year	Characteristics	Capacity (MW)	combustion share	g/kWh
Fritsche	1989				929
Meridien Corp.	1989	Conventional coal plant with a scrubber	500	99.90%	1166
Meridien Corp.	1989	Atmospheric fluidized bed combustion plant (AFBC)	500	99.90%	1163
Meridien Corp.	1989	Integrated gasification combined cycle plant (IGCC)	1,000		908
San Martin	1989	Integrated gasification combined cycle plant (IGCC)			751
San Martin	1989	Conventional pulverized coal plant	500	99.79%	964
San Martin	1989	Atmospheric fluidized bed combustion plant (AFBC)	500	99.79%	962
Kreith	1990	Fluidized bed combustion	747		1041
Uchiyama	1992	Coal	1000		989
ORNL	1994	Pulverized Fuel - Southeast	500	99.91%	1230
ORNL	1994	Pulverized Fuel - Southwest	500	99.91%	1279
Nieuwlaar	1996	Integrated Coal Gasification Combined Cycle	600		800
Audus	1997	Steam cycle - no carbon capture - 43% efficient			775
Audus	1997	IGCC - 32% efficiency			135

Tahara	1997	Commercially available 75% CF 39% efficiency	1000		915
Dones - GaBE	1998	Lignite - 100yr. GWP			1340
Dones - GaBE	1998	Hard coal PC - 100yr. GWP			1071
IEA	1998	Hard coal			1000
Spath	1999	Average System - 60% CF – 32% efficiency	360	93.30%	1022
Spath	1999	New Source Performance Standards (NSPS) 60% CF– 35% efficiency	425	92.70%	941
Spath	1999	Low Emission Boiler System (LEBS) 60% CF– 42% efficiency	404	95.60%	741
Nomura	2001	IGCC - oxygen-blowing - 70% CF	6000		810
Ganon&Uchiyama	2002	Existing plant without SO_2 scrubbing			1050
Ganon&Uchiyama	2002	Modern plant with SO_2 scrubbing			960
Lombardi	2003	Semi closed gas turbine combined cycle (SCGT/CC) 46 % efficiency	243		65
Lombardi	2003	(IGCC/CC) 39% efficiency	288		130

Molten-carbonate fuel cells (MCFC) reach high electricity generating efficiencies. When the fuel cell is coupled to a turbine in a combined cycle scheme the 65% efficiency is superior to IGCC [Srinivasan 1999]. The operation of MCFC involves a cathodic reaction that consumes oxygen and CO_2 and produces carbonate ions. These ions are transferred through an electrolyte to the anode where hydrogen reacts with carbonate to produce water and CO_2, which is fed back into the cathodic reaction.

In the case of more traditional technology, the boiler is a central device in any thermal power plant. The boiler is where the heat produced from the fuel combustion is transferred to a fluid that is further used to run the turbine. The technology used in boilers is continuously evolving. Flue bed and pulverized fuel (PF) boilers are the most common designs, which also refer to the lay-out of the combustion chambers. In the future, pulverized coal boilers known as new source performance standards (NSPS) with 35% conversion efficiency and low emission boiler systems (LEBS) with 42% conversion efficiency are expected to produce less emissions than the currently installed power plants with 32% conversion efficiency [Spath 1999].

Besides the effect of the technology installed in the power plant the amount of CO_2 produced from coal combustion is also a function of the type of coal burned and its carbon content. Carbon dioxide emission factors for coal depend on its ranking and geographical source. There are four different classifications for coal in the U.S.: anthracite, bituminous, subbituminous, and lignite. The carbon content of lignite on a mass dry basis is 60% whereas the carbon content for anthracite is 80% [Hong 1994]. The U.S. EIA keeps a database with results from coal sample analyses (Figure 17). However, the coal supplied for a power plant or region is not homogeneous, which complicates the development of CO_2 emission inventories.

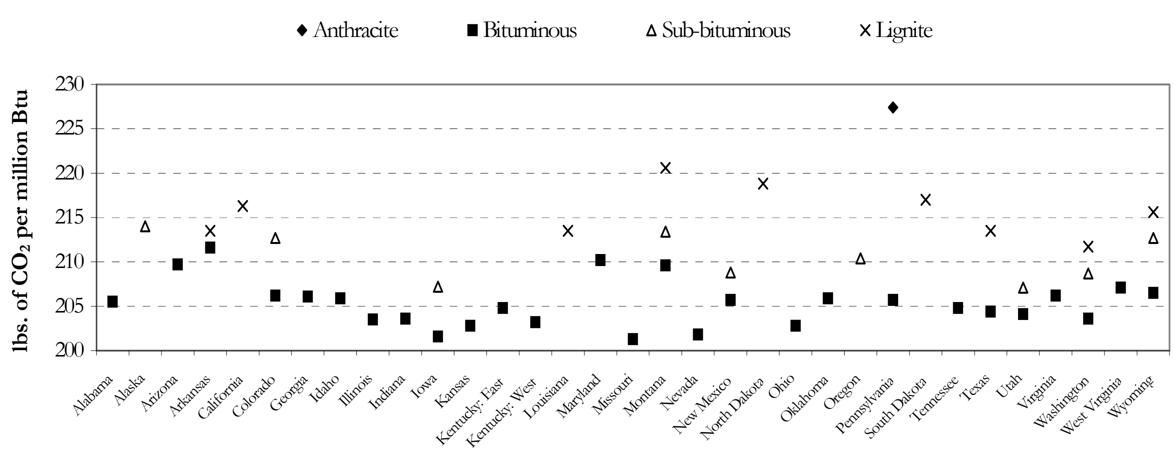
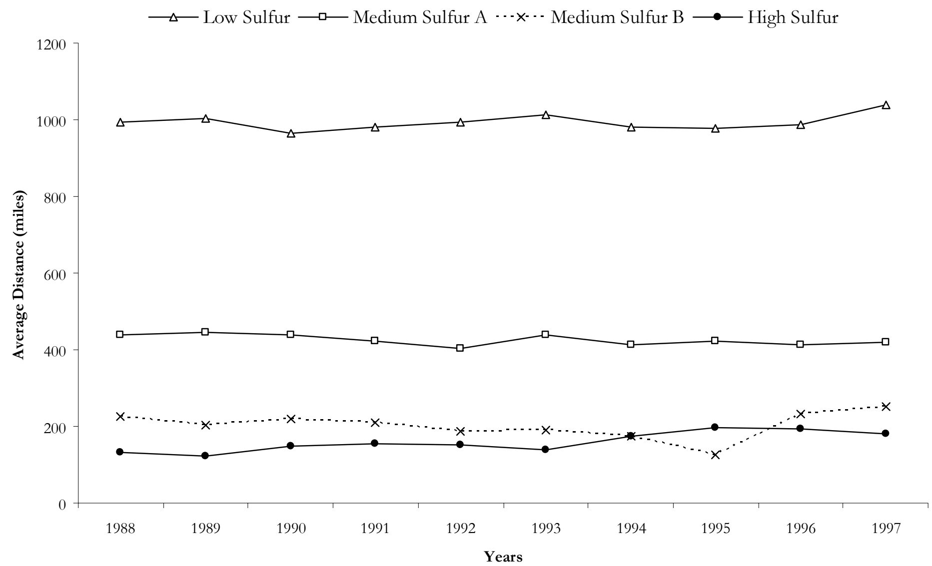


Figure 17: Carbon Dioxide Emissions by Coal Ranking and Geographical Location

Despite the dramatic contribution of combustion to the life-cycle emissions of coal power plants, other phases such as coal mining, transportation, materials manufacturing, construction, maintenance, and end-of-life should also be considered in a LCA.

In the case of mining, there are two variants: surface mining also known as strip mining, and underground mining. It is estimated that every year 3.6 million metric tons of CH_4 are released from coal mining activities in the U.S., most of which come from underground mining [Longwell 1995]. About 2.29 million metric tons per year are released through ventilation air, 1 million metric tons are produced at the coal seam degasification process, and 0.24 metric tons are post-mining emissions. About 30% of the concentrated CH_4 from wells in the coal seam is collected.

The transportation of coal is usually done by ships, barges or rail, which are the most fuel efficient options to transport bulk material [Davis 2002]. The contribution of coal transportation to the total life-cycle emissions of a power plant is more a function of the distances than the mode selected. Usually, the contribution of emissions from transportation is only a small fraction of the emissions from coal combustion; however, the demand for low sulfur coal leads to longer shipment distances. Figure 18 shows the average distance of contract coal shipments by rail between 1988 and 1997 in the U.S. [EIA 2000].



Notes: Low Sulfur = less than or equal to 0.6 pounds of sulfur per million Btu; Medium Sulfur A = 0.61 to 1.25 pounds per million Btu; Medium Sulfur B = 1.26 to 1.67 pounds per million Btu; High Sulfur = greater than 1.67 pounds per million Btu.

Figure 18: Average Distance of Coal Shipments by Rail in the U.S., 1988-1997 [U.S. EIA 2000]

In the case of technologies that demand lime or limestone for flue gas desulfurization, total emissions produced during the transportation of such materials could be higher than total emissions produced during coal transportation. In addition limestone production requires considerable amounts of energy, and therefore its production is also responsible for CO_2 emissions [Spath 1999]. The coal versus limestone ratio varies according to the power plant's technology. A Pulverized Fuel (PF) plant, for instance, has a 8:1 ratio of coal to limestone.

Some environmental regulations affecting coal power plants are significant in terms of their CO_2 emissions. For example, flue gas clean-up, which is used to remove sulfur emissions, produces more CO_2 emissions than other upstream processes [Spath 1999]. The process requires considerable loads of limestone, which are responsible for 59 to 62% of the non-coal CO_2 emissions of the average and NSPS systems respectively. Such emissions amount to twice as much the emissions released from the transportation of the coal consumed by these technologies. Alternatively the use of coal with lower sulfur content may incur in additional emissions from coal transportation from longer distances compared to the range of distances to obtain a higher sulfur content fuel.

The production and use of natural gas to regenerate the CuO absorber during the life-cycle of the LEBS system releases 35% of the non-coal CO_2 emissions [Spath 1999]. Coal transportation to operate a LEBS power plant amounts to 40% of the non-coal CO_2.

The contribution of the coal power plant construction phase to the life-cycle emissions is minimal. Usually the LCAs report only the major construction materials, which are concrete and steel. In addition, some sources also report the consumption of inputs used in the operation of the power plant such as lime, limestone, natural gas, etc. (Table 18).

The capacity factor of a coal power plant affects the life-cycle emissions of the plant. However, a higher capacity factor may lead to shorter life-time of some structures of the power plant, and moreover, the importance of the fixed factors such as the construction of the power plant is minimal regarding its contribution to GHGs emissions [Pacca 2002]

One concern in a LCA of coal power plants is the fugitive CH_4 emissions from coal mining and handling, which contain significant amounts of CH_4. Emissions during mining depend on the ranking of coal, depth of the mine, technology used, and other environmental conditions [Hayhoe 2002]. Underground mines in the U.S. release 11.0 to 15.3 m^3 CH_4 per metric ton of coal (0.67 Gg CH_4/106 m^3 CH_4, assuming 20º C and a pressure of 1 atm

[Houghton 1996]. These values are already part of the emission factors reported for coal mining [EIO-LCA 2002].

Table 18: Life-cycle Material Inputs by Technology and Information Source (kg/GWh)

	Spath 1999			Tahara 1997	ORNL 1994			
	Average	NSPS	LEBS		PF	AFBC	PFBC	IGCC
Concrete	1,007	1,007	1,007	977	796	803	776	797
Steel	322	322	322	341	202	204	198	203
Aluminum	3	3	3					
Iron	4	4	4					
coal	448,171	409,756	333,081	383,958	416,330	410,985	366,751	376,684
Lime	6,769	7,207						
Limestone	90,704	96,576			52,041			
Copper oxide			268					
Ammonia			136					
natural gas			3,810					

Because of resource availability this technology is only considered as a replacement for energy supplied by the Glen Canyon hydroelectric plant.

Future technologies are expected to reduce life-cycle emissions from power plants. Amine solution chemical absorption processes can be used either to remove CO_2 from the exhaust of power plants or from the coal gasification process [Lombardi 2003]. Another process involves the use of CO_2 as the hot fluid injected in the turbines. The idea is that after going through the turbines the CO_2 is extracted at high pressure in liquid phase. The CO_2

emissions from this technology are argued to be zero. This technology has not been empirically demonstrated and the feasibility of the system needs to be proven considering emissions from construction, maintenance, end-of-life, transportation, and storage of CO_2 produced.

Coal combustion also releases black carbon (BC) and sulfur dioxide (SO_2), which are precursors to aerosol formation. The radiative forcing of such substances is not yet precisely defined, but it is believed that they produce a cooling effect in the atmosphere [Hayhoe 2002].

4.4.1 Global Warming Effect of a Coal Fired Power Plant

A 1,000 MW coal-fired power plant with 6.08 TWh/year output [Tahara 1997] was scaled down to 5.55 TWh to match Glen Canyon power plant output. The technology and design of coal-fired power plants are not site-specific. Their environmental performance depends on coal quality, firing configuration and technology type. Its location depends on the availability of coal and cooling water. Since this alternative could replace energy from hydropower, it could be installed close to the load center or the current power transmission lines, and be accessible by railroad to deliver the coal.

It was assumed that after 30 years of operation all boilers had to be replaced (but not the structure of the building), and that the required construction energy was 50% of the original. The electricity output of the facility remained constant. The refurbishment resulted in 70,000 metric tons of CO_2 emissions, one-third of the original emissions from manufacturing and constructing the plant (200,000 metric tons of CO_2). As shown in Table 19, the GWE for this power plant after 20 years of operation was estimated at 90,000,000 $MTCO_2Eq$.

Table 19: Major Construction Inputs and GWE (after 20 yr of operation) for a Coal Power Plant

		Unit cost	Total cost	GHG emissions (MT CO_2 equiv.)			
Operational inputs:*	**Total MT**	**(1992 $/MT)**	**(1992 $)**	**CO_2 +**	**CH_4 +**	**N_2O =**	**GWE**
coal combustion	2,336,000	28.76[1]	61,180,849	75,825,360	322,383	1,886,309	**78,034,052**
coal extraction	2,336,000	18.05[1]	38,396,257	7,203,494	25,271	44,197	**7,272,962**
transportation by railroad	2,336,000	10.71	22,784,592	503,325	5,054	254,597	**762,976**
construction inputs:							
steel	62,200	385.37[2]	21,826,601	83,261	51	430	**83,742**
concrete	178,320	29.95[3]	4,863,858	6,569	13	130	**6,712**
aluminium	624	1,267.66[2]	720,289	1,331	2	21	**1,354**
total* (rounded)				**90,000,000**	**400,000**	**2,000,000**	**90,000,000**

*includes fuel consumption over an assumed service life of 20 years

[1] EIA/U.S.DOE 2002

[2] USGS 2002

[3] Means 1995

4.5 Natural Gas

Natural gas accounts for 22% of all energy consumed in the U.S., and its role in energy production is becoming increasingly important due to environmental concerns. In comparison with a coal-fired power plant a natural gas fueled power plant does not have the problem of SO_2 emissions and because the conversion to electricity is more efficient less CO_2 is emitted per unit of electricity output [Spath 2000]. In contrast to coal, natural gas is a much more homogeneous fuel which is formed by 90% to 98% of pure methane and contains 15 kg of carbon per GJ [Hayhoe 2002]. However, different natural gas turbine technologies entail different efficiencies, heat rate, and consequentially different CO_2 emissions. (Table 20).

Table 20: Performance of Natural Gas Generation Technologies [CEC 1997]

Natural Gas Generation Technology	**Fuel Efficiency**	**Heat Rate (Btu/kWh)**	**CO_2 Reduction Compared to Baseline**
Baseline: Steam Turbine	32%	10,666	
Conventional Gas Turbine (simple cycle)	36%	9,508	11%
Conventional Gas Turbine (combined cycle)	51%	6,692	37%
ATS Gas Turbine (simple cycle)	43%	7,937	26%
ATS Gas Turbine (combined cycle)	60%	5,688	47%
Fuel Cell/Gas Turbine Hybrid	70%	4,876	54%

Direct emission of particles is also minimal in a natural gas power plant compared to a coal-fired power plant. However, some of the releases from natural gas handling and combustion are also precursors for secondary particle formation in the atmosphere and some air emissions contribute to the build up of GHGs in the atmosphere.

An assessment of the aggregated performance of the global electric system has shown that a substitution of coal by natural gas initially leads to higher global temperatures compared to the status quo. However, in the long run the world's temperature is expected to decrease due to lower CO_2 and black carbon (BC) emissions. The time lag results from the continuous production of aerosol precursors by coal power plants in contrast to the negligible production of such precursors by natural gas-fueled power plants [Hayhoe 2002].

One concern in a LCA of natural gas power plants is the leaking of natural gas during production and transportation, and the high rates of CH_4 associated with such leaks. During natural gas production 39,590 to 104,220 kg CH_4/PJ natural gas may be released [Houghton 1996]. During natural gas processing, transport, and distribution 59,660 to 116,610 kg CH_4/PJ natural gas may be released. In the GWE method these emissions are taken into account as they are already part of the emission factors reported in EIO-LCA for the sectors "natural gas transportation" and "natural gas distribution" under the "transportation and utility sector" [EIO-LCA 2002].

Table 21 shows published CO_2 emissions for natural gas-fueled power plants. The range of results is significant but most of the results converge to 400 to 600 g/kWh.

Table 21: Published Carbon Dioxide Emissions per Kilowatt-hour for Natural Gas fueled Plants.

Author	Year	Characteristics	Capacity (MW)	g/kWh
Fritsche	1989	Gas turbine		542
Fritsche	1989	Gas Cogeneration		33
San Martin	1989	Gas fired steam electric plant		484
Uchiyama	1992	LNG	1,000	652
Nieuwlaar	1996	Gas engine - CHP	500	480
Audus	1997	No carbon capture - 53% efficient		410
Audus	1997	Gas field - 44% efficient		75
Kuemmel	1997	Europe		401
Tahara	1997		1,000	563
Dones - GaBE	1998	Gas mix – 100 yr. GWP		915
IEA	1998	Combined cycle gas		400
Spath	2000	Natural Gas Combined Cycle	505	499
Nomura	2001	GTCC - 70% CF	6,000	445
Ganon&Uchiyama	2002	Combined cycle		443
Meier	2002	Combined cycle natural gas plant	620	469

Two case studies for natural gas fueled thermoelectric power plants are considered in a relative comparison to hydroelectric plants.

A solid oxide fuel cell (SOFC) is a natural gas fuelled technology that converts chemical energy in natural gas to electricity with a 45% efficiency [Veyo 2002]. The fuel cell exhaust temperature reaches 850ºC, and therefore, it can be coupled to a gas turbine. The overall efficiency of the system reaches 60%.

4.5.1 Natural Gas Power Plant in the U.S.

Fuel switching such as the substitution of natural gas for coal is one of the most effective ways currently available to reduce CO_2 emissions [Hayhoe 2002].

The capacity of the facility used as a model for a natural gas power plant is 1,000 MW (6.34 TWh/year output scaled to Glen Canyon's 5.55 TWh/year). The technology and design of combined cycle gas turbines are not site specific. Its location depends on the availability of natural gas and cooling water. If this alternative is to replace energy from hydropower, it should be installed close to the load center or to the current power transmission lines.

It was assumed that after 30 years of operation all boilers had to be replaced (but not the structure of the building), and that the required construction energy was 50% of the original. The electricity output of the facility remained constant. The refurbishment resulted in 60,000 metric tons of CO_2 emissions, about 60% of the original emissions from manufacturing and constructing the plant (100,000 metric tons of CO_2). As shown in Table 22, after 20 years of operation, the GWE was estimated at 50,000,000 $MTCO_2Eq$.

Table 22: Major Construction Inputs and GWE (after 20 yr) for a Natural Gas Power Plant

Inputs:*	Total amount	Unit cost (1992 $/amount)	Total cost (1992 $)	GHG emissions (MT CO_2 equiv.)			
				CO_2 +	CH_4 +	N_2O =	GWE
natural gas combustion	1,560,300,000 m^3	0.130[1]	177,347,844	38,800,368	380,506	1886309	**41,067,183**
natural gas transportation	1,560,300,000 m^3	0.068	93,821,050	3,630,894	50,542	44197	**3,725,633**
natural gas extraction	1,560,300,000 m^3	0.061[1]	83,526,794	8,552,990	73,285	254597	**8,880,872**
construction inputs:							
steel	51,130	385[2]	17,217,555	65,679	40	430	**66,149**
concrete	71,270	30[3]	1,865,467	2,520	4	130	**2,654**
aluminum	230	1,268[2]	254,771	471	0	21	**492**
total* (rounded)				**50,000,000**	**500,000**	**2,000,000**	**50,000,000**

*includes fuel consumption over an assumed service life of 20 years

[1] EIA/U.S.DOE 2002

[2] USGS 2002

[3] Means 1995

4.5.2 Natural Gas Power Plant in Brazil

The capacity of the facility used as a model for a natural gas power plant is 1,000 MW (6.34 TWh/year output scaled to 49.4 TWh/year) [Tahara 1997]. In this idealized power plant we assume that a conventional gas turbine with a simple cycle and a 36% efficiency is used. A sensitivity analysis assuming the use of an Advanced Technology System (ATS) Gas Turbine with a combined cycle and 60% of efficiency [CEC 1997].

It was assumed that after 30 years of operation all boilers had to be replaced (but not the structure of the building), and that the required construction energy was 50% of the original. The electricity output of the facility remained constant. The refurbishment resulted in 148,431 metric tons of CO_2 emissions, about 55% of the original emissions from manufacturing and constructing the plant (270,553 metric tons of CO_2). As shown in Table 23, assuming 36% of efficiency after 20 years, the GWE was estimated at 420,000,000 MTCO2Eq. The use of the more efficient ATS would reduce the emissions to 250,000,000 $MTCO_2Eq$ (after 20 years).

Table 23: Major Construction Inputs and GWE (after 20 yr) for a Natural Gas Power Plant

inputs	total MT	unit cost (1997 $/MT)	total cost (1997 $)	GHG emissions (MT of CO_2 equiv)			
				CO_2	+ CH_4	+ N_2O	= GWE
natural gas combustion*	12,658,200,000	3,684	$1,646,528,495	332,953,108	1,206,478	2,828,526	**336,988,112**
natural gas extraction**	446,961	1,735	$775,477,408	54,460,716	232,108	294,684	**54,987,508**
natural gas transportation	n.a.	n.a.	$871,051,087	23,119,552	160,029	1,803,152	**25,082,732**
steel	398,128	276	$109,737,691	119,088	103,294	623	**223,005**
electricity (MWh)	69,301	36	$2,465,149	12,201	13,936	28	**26,165**
concrete	554,950	30	$16,480,747	11,794	12,095	104	**23,992**
aluminium	1,791	1,696	$3,037,751	2,326	2,443	13	**4,782**
coal	93,314	31	$2,938,494	1,243	1,109	8	**2,360**
oil	2,196	106	$232,121	156	92	1	**249**
total				**410,000,000**	**1,700,000**	**4,900,000**	**420,000,000**

Total emissions are rounded to two significant digits. MT, metric ton; GWE, global warming effect; na, not available.

4.6 Problems from Dimensioning and Characterization of Power Plants

Besides the two problems described (LCA and GWP) earlier, there is also a third source of problems which is how each of the electricity generation alternatives in a comparative analysis is assembled and represented. There is a range of technologies and design options for each alternative, which also need to be highlighted. Sometimes local conditions dictate a given choice, especially in the case of renewable energy that relies on natural resources such as insolation, wind distribution, water flows, topography, etc. In contrast, sometimes the alternatives in a comparative analysis are selected and characterized based on objectives of political considerations.

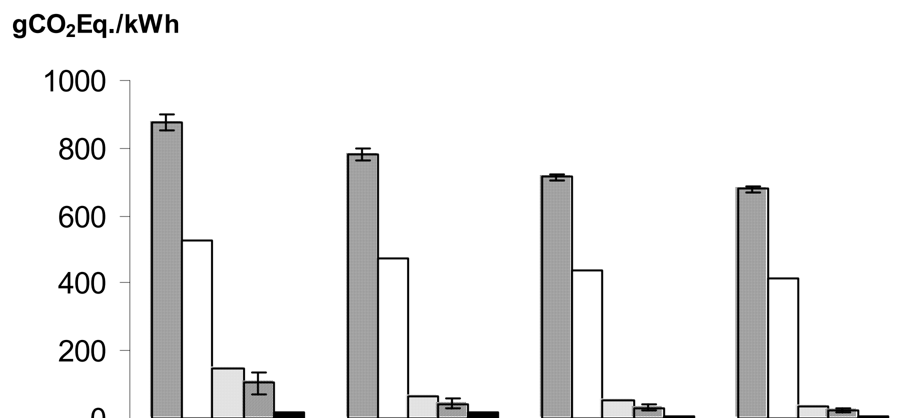
The selection of technologies within a given technology is also a key aspect. For example, there are different types of PV modules with different energy conversion efficiencies, lifetimes, and that require different material and energy inputs for its fabrication. Therefore, it is important to keep in mind that a technology is not homogeneous. Along the same lines, there are arch and gravity dams and the two designs also affect the performance of hydroelectric plants.

Economies of scale also affect the performance of the alternatives. The size of a wind turbine or a solar power plant affects the carbon emission intensity of the alternatives. The load curve assumed to be met by electricity produced by a power plant also influences the final result because sometimes some storage capacity could be necessary to match supply and demand.

Finally, the lifetime assumed for a specific technology and the level of replacement that some of the parts are subject to also affects the outcome of the assessment. The end-of-life of power plants suggests the recycling of part of the construction materials, which could be a benefit in terms of GHGs emissions depending on the emissions from the recycling process [Lombardi 2003].

Chapter 5: Discussion and Interpretation of Results

The point of the comparison proposed through the two case studies, Glen Canyon and Tucurui is to reinforce the idea that local characteristics are important in the modeling of power sources. The recognition and the incorporation of these conditions affect the final result of the comparison and the ranking of the alternatives. The GWE as a comprehensive method intends to facilitate the assessment of case studies that take into account local characteristics. Results based on the Glen Canyon case study show that the thermal options are associated with the higher GHG emissions in gCO_2Eq per kWh (Figure 19).



	10 years	20 years	30 years	40 years
Coal	877	781	714	678
Natural Gas	529	474	440	416
Photovoltaics	148	63	51	34
Hydroelectric	104	44	31	24
Wind Farm	17	15	8	6

Figure 19: Comparison of GWE for GCD with Four Other Alternatives and Four Time Periods After Construction (g of CO_2 equiv./kWh).

Electricity produced out of wind turbines is the alternative with the lowest emissions. PV and hydro have higher emissions, which are reduced (along with wind emissions) as the analytical period is extended. This outcome is not so perceptible for thermal power plants that have in the combustion of fossil fuels a large share of the final values.

Emission factors for the technologies considered in the Tucurui case study show that the hydroelectric plant is the alternative with the highest emission factors. The hydroelectric plant starts to be competitive only when the longest analytical period (40 years) is considered. The variability associated with the emission factors for the hydroelectric plant are high because of the uncertainties associated with assessing the role of the reservoir.

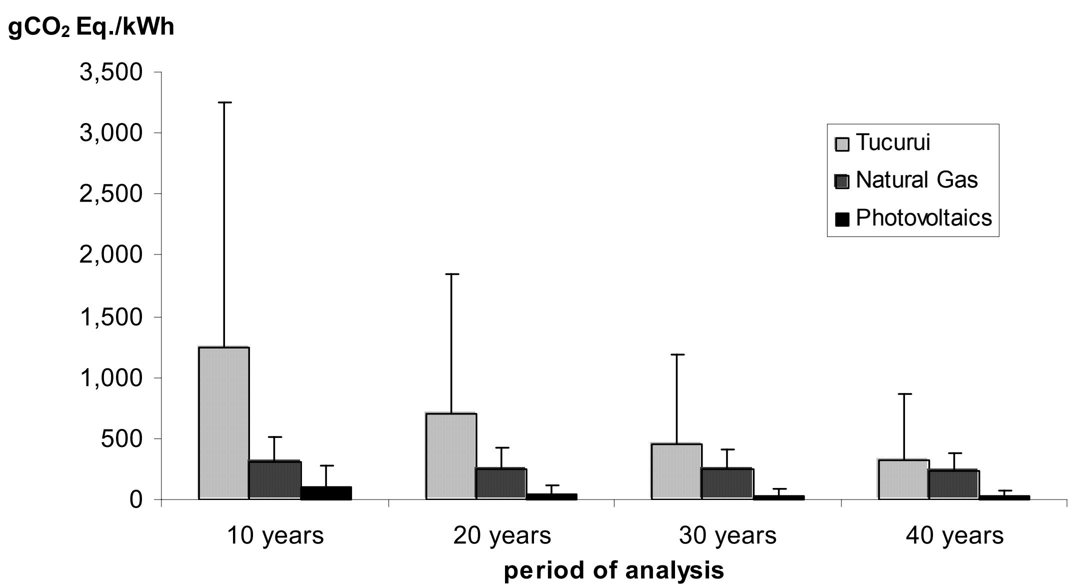


Figure 20: Estimation and Sensitivity Analysis of GWE for Electricity Generation Options Over Four Different Periods of Analysis

Because wind resources are not available in the Tucurui region this kind of technology has not been taken into consideration. Wind energy, which was the best alternative in the Glen

Canyon case study, is not possible in this setting unless it is installed off site and the energy is transmitted to the load area.

Most of the CO_2 emissions from fossil fueled power plants account for annual emissions from fuel combustion. Usually, this value depends on the annual electricity output of each power plant and is assumed to be constant; therefore, it is possible to make a parallel between the amount emitted by a fossil fuel plant and the amount corresponding to the forgone NEP due to the footprint of a land-use intensive alternative such as a hydroelectric plant or a massive PV installation. In this case, the NEP is also assumed to be constant over a year even if in reality it depends on the exact ecosystem type, which varies over small areas, and climatic conditions in a specific year.

Figure 21 shows such a comparison based on the three alternatives discussed, and the range of assumptions considered for each one. In the case of the fossil fueled technology the difference results from various technologies with different efficiencies. In the case of the PV installation the difference arises from different technologies for module fabrication, which also affect the efficiency of the devices. The lower CO_2emissions estimation from the fossil fueled power plant (133,000,000 $MTCO_2$/yr) is twice as much as the foregone carbon dioxide uptake due to the footprint of the hydroelectric plant (84,000,000 MTCO2/yr). The worst case for PV (17,000,000 $MTCO_2$/yr) is slightly over the best scenario for the hydroelectric plant (14,000,000 $MTCO_2$/yr).

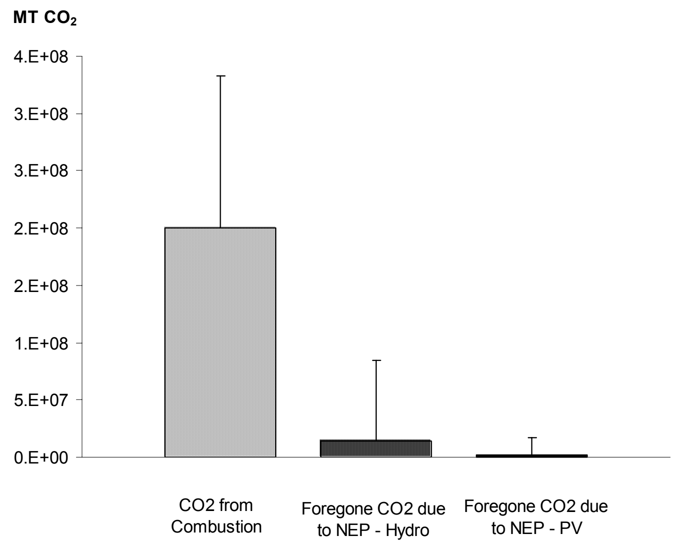


Figure 21: Carbon Dioxide Emissions from Combustion and Foregone Carbon Dioxide Uptake due to NEP.

The Tucurui power plant is penalized because it is located in an area with high ecosystem productivity. By changing the ecosystem type but preserving the design of Tucurui dam the GWE would be reduced. For example, in a boreal type ecosystem with a 9 kg C/m^2 density in the standing biomass, and NEP ranging from neutral up to 2.5 t C ha-1 yr-1, the GWE after 20 years would correspond to 325,000,000 – 900,000,000 MTCO2Eq. In a temperate forest ecosystem with a 14.6 kg C m^{-2} density in the standing biomass, and NEP ranging from 2.5 up to 7 t C ha^{-1} yr^{-1}, the GWE after 20 years would correspond to 530,000,000 – 1,500,000,000 MTCO2Eq. Figure 22 shows these values normalized by the 49.4 TWh total annual output.

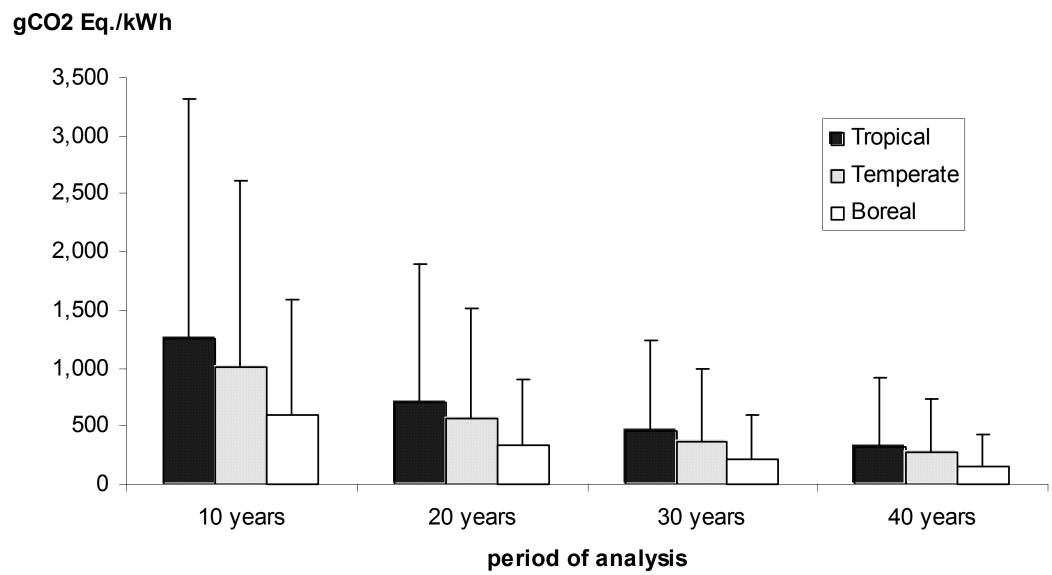


Figure 22: Sensitivity Analysis of the Tucurui Hydroelectric Power Plant Design Assuming Different Ecosystem Types.

The displacement of a terrestrial ecosystem and the consequent GHG emissions and imbalances should be factored in a comparative analysis of technologies responsible for large footprints such as large hydroelectric plants and massive PV installations. In the case of hydroelectricity the assessment of impacts from the aquatic ecosystem should also be considered. The new equilibrium between the aquatic ecosystem and the air may also contribute to the uptake of carbon and other GHGs from the air.

Within a specific generation technology such as PV, for example, there are different subtypes that affect the overall performance of the system with respect to GHG emissions. Conversion efficiency and manufacturing characteristics are some examples that should be carefully described in the analysis but not confounded with uncertainties. Instead they should be characterized as simple choices made by the proponent of the alternative.

A methodological distinction when doing a LCA is the difference between choices and uncertainty. While some criteria applied to the analysis are to the discretion of the analyst, others reflect the incomplete knowledge about the true value of a parameter. An imprecise measurement aggregates uncertainty in the analysis just as the estimations of parameters that are difficult to assess with precision are also a source of uncertainties. Although sometimes the analyst is forced to assume some values for parameters that are not precisely defined, this practice is completely different than ignoring something that is known or selecting alternatives among a set of available possibilities.

When assessing and comparing electricity generation technologies it is difficult to make generalizations: each technology and each power plant has particular characteristics that make them unique. For example, it is difficult to pick a number in the literature or analyze particular case studies for hydroelectricity and generalize to all the hydroelectric plants in the world. Depending on the ecosystem displaced the reservoir of a hydroelectric plant may produce more or less emissions, as a function of the local climate, nutrient availability, sediments, turbidity, water residence time, etc the productivity and consequent carbon burial can be significant and offset part of the uptake associated with the dry land that existed before the filling of the reservoir.

Accordingly, it is interesting to identify for each technology some characteristics that stand out because of their effects on the final results.

Chapter 6: Use of GWE in Environmental Policy and Management

Generally speaking the GWE method is offered to analysts who recognize that the selection of electricity generation technologies for reduced climate change impacts is a fundamental and necessary endeavor. Nonetheless, such action involves a set of assumptions, choices, and uncertainties that affect the result of the assessment and are well portrayed by the GWE framework.

Analysts carry out environmental assessments either to ratify a previously selected choice that needs justification or because they are interested in the formulation of a new assessment process and in achieving its refining to get the best outcome given an initial characterization of the problem. The former practice is defined as position-focused whereas the latter is known as the process-focused approach [Morgan 1990].

The GWE is a method that supports a process-focused analysis in the sense that the method attempts to portray with transparency the problems associated with the analysis. However, it would be naïve to neglect the existence of circularity between the definition and the identification of problems. That is, depending on the definition used some problems could be better identified than others, and depending on the identification of certain problems the definitions could change. In any case, definition and identification of problems often vary considerably depending on the circumstances of the analysis.

Accordingly, the GWE method is also designed for analysts that have a good knowledge about the major components of the framework (LCA, GWP, electricity technologies/power plants) and want to introduce modifications in the framework without losing the ability to interconnect these areas and tackle a specific problem. The GWE framework is flexible with respect to the identification and definition of problems because we rarely know enough to provide a definite answer to a problem, and the result from the analysis may be different depending how a problem is perceived. The structure presented in section 3.2. to classify and organize the problems arising from the use of each of the components of the GWE method intends to motivate and guide the action of researchers that want to refine the framework and obtain the best possible outcome.

Besides the flexibility arising from the transparency and the systematization of the sources of problems in each of the components of the framework that invite the work of experts and analysts willing to modify the assumptions, the GWE offers flexibility with respect to the analytical period selected for each analysis. This feature is fundamental to support decision-makers that usually demand answers in the short run (a couple of decades). In addition, due to unexpected outcomes shorter analytical periods may be necessary to avoid an even greater problem arising from global climate. Consequently, decision-makers interested in the mitigation of climate change could benefit from the GWE framework to initiate programs supporting technologies that reduce the burden of climate change over a time frame tailored to their needs.

The choice of analytical periods transcending the "life-time" of a power plant is interesting because it calls for the consideration of retrofits to extend the operation of the facilities. The method is appropriate for analysis that span across individual life-time horizons because it aggregates and weighs emissions over time.

Another use of the method is in the identification of a service or product's life-cycle phase that most contribute to the GWE given a chosen analytical time. Therefore, the method can be used as a management tool to improve the performance of each technology. Examples of energy technologies that benefit from such protocols are the use of renewable energy in the manufacturing of PV modules and the life extension of hydroelectric plants, provided that impacts from decommissioning of hydroelectric plants are constant after some time.

The GWE framework allows decision-makers to adopt a proactive approach towards the mitigation of climate change. Although the framework is applied for electricity generation options it could be used to compare alternatives within different sectors. The use of the GWE decoupled from ultimate damages associated with climate change enhances the method's applicability since less assumptions and uncertainties are incorporated in the assessment. Consequently, results can be more clearly presented to a broad audience.

1. relative comparison – ranking of alternatives

2. intermediate indicator avoid uncertainty to bridge emissions to changes in temperature, and finally to actual impacts.

It was already discussed that transparency in the framework allows the communication of uncertainties and problems that can be unbounded by the analyst. In addition the representation of uncertainty and problems in the framework enhance the acceptability of the framework as a decision-making tool. Representations of uncertainty in decision making facilitate interaction between scientists and policy worlds and help to sustain the authority of science [Shackley 1996]. Therefore, the quest for reduction of uncertainties does not necessarily means the construction of more complex or powerful models representing the real world but the use of simple interactive models that show clearly all uncertainties and assumptions involved in their formulation. If analysts communicate uncertainty well, people has a clearer idea about what experts know and how experts disagree on the formulations of uncertainties and problems.

The field of policy analysis needs to be concerned with the characterization and analysis of uncertainty to an extent that far exceeds the need in the physical sciences audience because a democratic decision process involves the input of various stakeholders who need to get their views about the problem represented in the analytical process. Moreover, details in a problem may change but the basic problem is the same it is important to be able to adapt, use, policy analysis that have been done in the past. This task is easier when uncertainties and problem are explicitly treated.

Chapter 7: Dissertation Contribution

This dissertation describes means to achieve sensible climate change mitigation based on current available energy technologies and at the same time it provides guidelines for perfecting the performance of such technologies with respect to their impacts on global climate change. That is, the method identifies the phases of a generation technology and the GHG releases that produce the most significant GWE given a chosen analytical period. The method intends to be an effective tool to assess and compare the potential impacts of energy generation technologies over flexible analytical periods, which can be determined by the user of the tool. Flexibility in the period of analysis strengthens the utility of the framework.

The choice of analytical periods transcending the "life-cycle" of a power plant is interesting because it calls for the consideration of retrofits and upgrades to extend the operation of the facilities. The method is appropriate for such analysis because it aggregates and weighs emissions over time. Therefore, the method can be used as a management tool to improve the performance of each technology. Examples of energy technologies that benefit from the use of such protocol are the use of renewable energy in the manufacturing of PV modules and the life-cycle extension of hydroelectric plants provided that impacts from decommissioning of hydroelectric plants are constant after some time.

Flexibility is also fundamental to support decision-makers that usually demand answers in the short run (a couple of decades). Moreover, due to unexpected outcomes shorter analytical periods than the 100 year time horizon associated with GWP usually applied to energy analyses may be necessary to avoid an even greater problem arising from global climate change.

The use of the framework presented herein can be extended to other services and goods. The use of GWE decoupled from ultimate damages associated with climate change enhances the method's applicability since fewer assumptions and uncertainties are incorporated in the assessment. Consequently, the framework allows for a more clear presentation to a broad audience. Even if the GWE method is not directly used to establish a global emissions level, its grand purpose is aligned with climate change mitigation. Three different approaches to define environmental protection levels are usually proposed: the zero risk approach, the balancing approach, and the technology based approach [Portney 2000]. The goal of the zero risk approach is to avoid the occurrence of any adverse health effect. On the one hand such approach seems sensible, on the other hand science and economics defy its actual application. It may be difficult to specify a threshold based on scientific evidence, and it may be impossible to keep an economic activity without producing environmental harm. The balancing approach weighs competing outcomes and recommends regulatory action based on the results. This approach has been presented in the discussion on BCA in this dissertation. The problem is that economic analysis is ill prU.S. EPAred to convert a myriad of non-market values into dollars. Finally, the technology-based approach characterizes the maximum attainable pollution level based on the adoption by all sources of the best available technology (BAT). A problem with this approach is that it is difficult to define the "best technology" because emissions can always be further reduced at higher costs.

The GWE framework fits the class of technology-based approaches; however, it is more flexible and powerful because despite being focused on a single service there are various technologies that can be considered for electricity generation. Moreover, the selection of one technology over another is a function of a nexus of a variety of factors, which are accommodated by the proposed framework. The framework also recognizes the variability within a class of energy technologies. For example, different hydroelectric dam designs, different PV system designs, as well as different scales, natural settings, etc, are accounted for.

The framework intends to be flexible in order to house and transparently represent variability. Because GWE is also useful to perfect each power generation technology regarding their overall contribution to climate change, the definition of technology in the framework is dynamic since it intends to transform current technologies into less polluting options. The continuous utilization of the framework as a management tool could feed a perpetual quest for sustainable energy technologies.

There is a considerable number of energy LCAs in the literature dealing with impacts on climate change. They draw on different methods and assumptions to assess carbon dioxide emissions from electricity generation projects. Some of these studies present the primary information used to characterize a given power plant but rely on different assumptions and methods to finally calculate the contribution of the power plants. Most studies that run assessment of various GHGs use a fixed GWP to convert other GHGs to carbon dioxide equivalents; and therefore, are locked to fixed time horizons. Such strategy may constrain the use of the results and the comparison of different case studies. The use of the GWE framework to process data available from other published sources is useful to normalize and compare results without having to collect basic information about each project. This could be useful to set up a database with various projects with different characteristics for a given power generation technology class and establish benchmarks for various alternatives. Because the GWE method relies partly on EIO-LCA, which provides average emission factors for the U.S. economy, it is a good tool to carry out comparisons of alternatives in the U.S.. Nonetheless, the use of average values to characterize emissions from materials used in the power plant should be contrasted with the use of specific information to portray accurately the design and operation of a power plant.

Notwithstanding the power of the GWE method, the framework highlights the assessment process as an active part of the results. The process is intended to be carefully explained in this dissertation in order to enhance its replicability. As is presented there are three main sources of problems associated with the GWE framework: (1) problems that arise from the life-cycle assessment methods, (2) problems related to carbon cycle models and ways to represent climate forcing of GHGs, (3) the diversity of various competing technologies, settings, scales, life-times, maintenance options, available for a given power generation technology.

To respond to such problems inherently associated with the framework but which are not necessarily outcomes of uncertain knowledge about different components, the framework attempts to be transparent. Consequently, the framework is implemented in a spreadsheet tool that allows modification of different parameters in the analysis. Sensitivity analyses can be performed parameter by parameter and values are subject to change at the discretion of the user.

Since the establishment of the Intergovernmental Panel on Climate Change in 1988, climate change science has attempted to investigate different areas of anthropogenic activities such as the ones represented in the IPCC special reports [Metz 2000, Nakicenovic 2000, Watson, 2000 Penner, 1999 Watson, 1997]. As a concept the GWE method attempts to bridge new scientific understanding between GHGs in the atmosphere and terrestrial ecosystems that are impacted by the footprint of large scale power plants such as a hydroelectric plant that occupies a large parcel of land due to its reservoir. GWE incorporates land use change information in the assessment of global climate change originating from the footprint of energy generation technologies.

Chapter 8: Future Work and Research Needs

A number of areas have been left unaddressed in this dissertation, and are available for future work. For example:

1. perfecting the LCA model incorporating more specific process modeling

2. finding more specific information and data especially from the industrial sources that manufacture the power generation equipment.

3. carrying out analysis of hybrid systems that involve the coupling of at least two electricity generation technologies (e.g. hybrid systems)

4. comparing using more recent climate models (carbon cycle models) would be useful to perfect the tool and update it with the latest scientific models.

5. adopting emission factors from other countries and add them to the model that currently includes emission factors of the U.S. economy.

6. extending the GWE concept to incorporate land use change information that could be related to a more precise assessment of the interactions between ecosystems change and life-cycle impacts of energy technologies, especially models involving the balancing of nitrous oxide.

7. assessing life-cycle emissions and climate forcing of other substances besides GHGs such as aerosols.

8. using a Monte Carlo Simulation with the various parameters in the assessment.

Only when the range of uncertainty is know or at least a given distribution can be associated with this range it is possible to use some computational frameworks to analyze the consequence of such variability in the final results of the assessment. Monte Carlo simulation is an alternative to cope with uncertainties that propagates known parameter fluctuations into an uncertainty distribution of the output variable.

Monte Carlo simulation is used to reveal the effects of uncertainties in the final results, which requires the selection of specific statistical distribution functions for the uncertain parameters. The logical association of the parameters is also selected by the analyst and the output of the simulation produces a range of possible scenarios.

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