FULL ENERGY CHAIN ANALYSIS OF GREENHOUSE GAS EMISSIONS FROM DIFFERENT ENERGY SOURCES

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Abstract

The field of work of the Advisory Group Meeting/Workshop, i.e. full-energy chain emissions of greenhouse gases, is defined, and its environment, i.e. the Earth Summit -the 1992 UN Conference on Environment and Development in Rio-, is discussed. It is inferred that countries that ratified the Earth Summit's Convention on Climate Change have committed themselves to lower the greenhouse gas emissions from their energy use, and that this can be done most effectively by accounting in energy planning for the full-energy chain emissions of all greenhouse gases. The scatter in literature values of greenhouse gas emission factors of the full energy chain of individual energy sources is discussed. The scatter among others is due to different analytical methods, data bases and system boundaries, and due to neglect of the non-CO_2 greenhouse gases and professional biases. Generic values for greenhouse gas emission factors of energy and materials use are proposed.

1. GENERAL

A period of onset of important developments in worldwide policy is following the 1992 UN Conference on Environment and Development in Rio. These developments might lead worldwide to a combination of development and better environment, usually summarized in the term sustainable development. There are indications that after the recent worldwide recession, many countries will experience a substantial economic growth. This could produce a more friendly climate for investments in environmentally benign activities and in development in less developed countries. It has become clear that with respect to the environment and the capital investment needs, the countries in economic transition are not in a much better position than the developing countries. One sincerely hopes that such investments will be in the spirit of the global partnership, as expressed by the Secretary General of the 1992 Rio Conference, Mr. Maurice F. Strong [1]:

> *"There must .... be a wholly new global partnership based on common interests, mutual needs and shared responsibilities, one in which developing countries will have the incentive and the means to co-operate fully in protecting the global environment while meeting their needs and aspirations for economic growth."*

Another important development are the feverish activities of the three Working Groups of the International Panel on Climate Change (IPCC). These activities focus on the preparation of the IPCC's Second Assessment Report which has to be presented to the Conference of the Parties that ratified the Framework Convention on Climate Change (FCCC) and that will be convened in spring 1995. The results of this workshop could have relevance for the Conference of the Parties, though maybe not on a short term.

The workshop deals with the worldwide dominating source of greenhouse gases, the use of energy. Energy has a double relevance in the FCCC. Firstly, energy consumption is the major source of greenhouse gases, which causes about 55% of the total perturbation of the Earth's greenhouse [2]. Secondly, and of almost equal importance for a Convention from the 1992 UN Conference on Environment and Development, the per capita and per GNP energy consumption of a country will grow concomitantly during its development to an economically healthier status. When reaching economic maturity the dependence on electricity becomes stronger whereas ultimately economic growth becomes much less dependent on energy consumption. In this context it is worthwhile to have a look at Article 2 of the FCCC, reading:

"The ultimate objective of this Convention and any legal instruments that the Conference of Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

This article of the Convention expresses the worldwide concerns about the threats of climate change to Nature, mankind and specifically about the sustainability of the economic development of the developing countries. It stresses that the structural changes in the developing countries, and also in countries in economic transition (especially the modernization of their national energy supply), should be sustainable. It is obvious that also the rest of the countries, which are the high-income countries and the major source of greenhouse gases, have to take mitigation measures to stabilize to a harmless level the atmospheric greenhouse gases. There is still uncertainty about what this critical load might be. However, the workshop might discuss in principle what could be the most comprehensive tool to lower the greenhouse gas emissions from energy supply.

According to Article 4c of the Convention the more than hundred ratifying countries committed themselves to:

"promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases not controlled by the Montreal Protocol in all relevant sectors, including energy, transport, industry, agriculture, forestry and waste management sectors."

This article of the FCCC could be considered to be the basis for the full energy chain approach to a climate benign energy strategy,which was the topic of the workshop: *all relevant sectors* should be considered, because all sectors mentioned in this article have their inherent contributions in the energy chain. Therefore, when comparing different energy sources, it would be incorrect to account for the greenhouse gas (GHG) emissions from the conversion step only, such as the combustion of fossil fuels. There are GHG emissions which are inherently associated with the rest of the energy chain such as the production of nuclear fuel, or the construction of a solar power plant. Moreover, according to FCCC Art. 4c, the emissions of all anthropogenic greenhouse gases (excluding the CFCs) have to be taken into account, which means that not only CO_2 is relevant, but also CH_4 and N_2O and probably a few more, e.g. CF_4 from aluminum manufacturing.

2. PREPARATORY MEETINGS TO THE ADVISORY GROUP MEETING/WORKSHOP

The IAEA has convened in recent years two consultancies on the Full-Energy-Chain (FENCH) analysis of energy use associated GHG emissions. The first one, in 1993, supported the IAEA plans to convene a workshop on this subject, in a developing country if feasible. A second consultancy, in April 1993, focussed on renewable energies and critically reviewed also the methods in use for FENCH analysis.

3. FULL-ENERGY-CHAIN EMISSIONS OF GREENHOUSE GAS EMISSIONS

"FENCH" requires additional discussion. In case of nuclear energy it begins with its "cradle", uranium mining, and ends with its "grave", dismantling the nuclear power plant and storage of the nuclear waste. In between birth and death there is: ore handling; fuel fabrication (including enrichment in most cases) and transportation; power plant construction, operation and maintenance; possibly spent fuel reprocessing; and handling and storage of spent fuel or waste.

In principle all flows of GHG-intensive energies and materials into the individual links of the FENCH are important in accounting for the emissions of GHGs from the complete energy chain of any energy source. Each energy source has its own typical FENCH to be analyzed: the three fossil fuels (coal, oil, and natural gas), hydro and nuclear power, wind and solar power (PV and "solar tower"), geothermal energy, biomass energy, and the ocean energies (wave, tidal and ocean thermal). Each chain consists of at least three upstream links (manufacturing, transportation and construction) and one downstream link (waste handling and storage). For practical reasons one has to put boundaries to the system to be analyzed at this workshop. The following limitations were considered.

Firstly, one should focus on electricity generation, because many of the above mentioned energy sources, such as nuclear, hydro, solar, wind and tidal power, commonly generate only electricity (which as argued above is an essential commodity in development). The energy efficiency of such energy technologies is poorly defined in many cases, making it difficult to define for these technologies a functional unit of primary energy (e.g. joules or megatonnes of oil equivalent). Consequently, comparison can only be done on the basis of the unit of electrical energy, such as watt-hour(electric), W(e).h. Moreover, for fundamental reasons, technologies with dual output such as cogeneration of heat and power cannot be dealt with FENCH analysis. Secondly, one should limit to existing energy technologies and exclude for the time being technologies which are not yet commercial. In view of these two limitations our list might comprise: coal, oil, natural gas, hydropower, nuclear power, geothermal energy, wind and solar PV power, solar thermal tower, and biomass energy.

Thirdly, there are important time and space aspects to the emission factors of the energy and materials flows associated with FENCH. For example, the CO_2 emission factor of electricity is low in countries with a low share of fossil fuels such as Brazil, Norway and France. However, one might consider to use globally averaged emission factors for electricity and materials in FENCH analysis for the time being, especially where basic data are not available. The same applies to the future lower energy intensity of materials in case these would become recycled to a large extent, such as aluminum. However, for the time being one might use the present global without-recycling values. This seems plausible since most of the non-conversion FENCH GHG emissions come from the upstream steps and, hence, are short-term emissions. Fossil fuels and biomass are special cases because of their fuel associated emissions upstream of the combustion step. These are primary energy sources, requiring a conversion factor, the efficiency of power generation, in order to express in W(e).h. For worldwide use a conversion factor of 0.38 is recommended by the World Energy Council [3]. However, where advanced thermal power plants generate electricity this conversion factor might be significantly higher.

4. UNCERTAINTIES AND BIASES IN FENCH-GHG ASSESSMENT

There are many sources of uncertainty and some possible biases in assessing FENCH GHG emission factors. These error sources need discussion in order to reach international consensus about the use of FENCH-GHG assessment in energy planning. The most important sources of uncertainties and biases are the methods used, the input data bases, the assumed global warming potentials, and the assumed life-times of energy systems..

4.1. FENCH methods

Two basically different methodological approaches are in use: process analysis and input/output (i/o) analysis. Sometimes a hybrid of these two methods is applied.

Process analysis considers all individual emission points of GHGs, and therefore requires careful analysis of all flows of energy and materials associated with the various FENCH links. It is very time-consuming. The system boundaries are arbitrarily defined and depend largely on subjective judgements and on the availability and quality of data. Inventiveness of the systems analyst plays an essential role in the identification of all GHG sources, which could lead to a bias in the result of process analysis.

The i/o analysis essentially uses a national economic data matrix on sectorial consumption and production of energy and materials. Combination with sectorial energy statistics yields the energy consumption per unit of material produced. Generally, the economic statistics required for i/o analysis is inadequate and limited to one country (import/export flows cannot be assessed). It is basically not up-to-date, which makes i/o analysis less applicable for planning purposes. Of course i/o analysis does not yield information on GHG-intensive material flows which are not energy intensive; these require additional assessment using process analyses.

4.2. Global warming potentials (GWPs)

In order to express in common units FENCH GHG emission factors which apply also to non-CO_2 GHGs, it is generally accepted to convert the emission rates of these gases into CO_2 equivalents. The conversion factors for this conversion are the so-called GWPs. IPCC has recommended GWPs in its 1992 Supplementary Report, see Table I. These GWPs do not

TABLE I. DIRECT GLOBAL WARMING POTENTIALS (MASS BASIS) OF ENERGY RELEVANT GREENHOUSE GASES FOR DIFFERENT TIME HORIZONS.
Source: IPCC 1992 Supplementary Report; the last column shows the GWPs of Van de Vate

compound	residence time (yrs)	GWP_{20}	GWP_{100}	GWP_{500}	indirect effect	GWP (Van de Vate)
CO_2 (carbon dioxide)	100-200	1	1	1	0	1
CH_4 (methane)	10	35	11	4	++	50
N_2O (nitrous dioxide)	130	260	270	170	0	270
CF_4 (carbon tetrafluoride)	$5x10^3$-10^4	-	10^4	-	0?	10^4
CO (carbon monoxide)	0.3	-	-	-	+	-
C_xH_y (hydrocarbons)	<0.1	-	-	-	+	-
NO_x (nitrogen oxides)	1-7 days	-	-	-	0	-

account for the indirect climate effects of the gases. In particular CH_4 has important indirect effects on the climate which, if accounted for, increases its total GWP substantially. GWP values of CH_4 in literature range from 11 to 90. IAEA preferred a GWP of 50 for CH_4 which could be high in view of very recent estimates. This is discussed extensively in the workshop paper entitled Climate Change and Global Warming Potentials.

4.3. Databases

A large variety of data is required for FENCH-GHG analysis. In particular, the emission factors of the energies (heat and electricity) and materials flowing into the energy system as well as the energy and material intensities of various FENCH activities are of concern. Table II gives the materials and energy associated emission factors which IAEA has been using for the calculation of the emission factors of the different energy sources. Most of emission factors of the materials are taken from Uchiyama's study [8]. It is interesting to note that without exception substantial use of energy, concrete, and steel, is made in any energy chain. Silicon and glass use are typical for solar energy, and fertilizer use is relevant for biomass energy. There is nitric acid use in the nuclear energy chain, upstream and particularly downstream of the power generation step. The emission factor of energy use is discussed briefly in footnote 1 to Table II.

TABLE II. GREENHOUSE GAS EMISSION FACTORS OF GREENHOUSE GAS INTENSIVE MATERIALS RELEVANT TO FULL ENERGY CHAIN ASSESSMENT

	Releases from manufacturing processes			Energy intensity[1] (kW(e).h/kg)	Emission factor (g CO_2 equiv. per g)
	CO_2 (g/g)	CF_4[2] (g/kg)	N_2O[3] (g/kg)		
Cement	0.5[4]	irrelevant	irrelevant	0.36 [4]	0.76
Concrete[4,5]	0.14	irrelevant	irrelevant	0.093 [4]	1.95
Steel	0.3[5]	irrelevant	irrelevant	2.7 [4]	2.2
Aluminum	2[6]	1.6	irrelevant	22.5[2]	34.2
Copper	irrelevant	irrelevant	irrelevant	4.8 [4]	3.5
Silicon	irrelevant	irrelevant	irrelevant	251 [4]	181
Glass	irrelevant	irrelevant	irrelevant	1.7 [4]	1.2
Plastics	irrelevant	irrelevant	irrelevant	11 [5]	7.9
Nitric Acid	irrelevant	irrelevant	2.9 [6]	0.81 [7]	1.4
Fertilizer	irrelevant	irrelevant	20 [8]	8.6 [9]	11.5

[1] Energy production associated CO_2 emission factors amount to 78 and 82 Tg CO_2 per EJ, or 701 and 737 g CO_2 per kW.h, for both developed and developing countries, resp. A reasonable global average of the emission factor is 720 g CO_2 per kW.h.

[2] The Global Warming Potential of CF_4 is ca. 10^4. Abrahamson D., Aluminum and Global Warming, Nature **356** (1992), 484.

[3] The Global Warming Potential of N_2O is ca. 270. Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment (Eds. J.T. Houghton, B.A. Callander, and S.K. Varney), Cambridge University Press, Cambridge (UK), 1992.

[4] 0.50 tonne of CO_2 are stoichiometrically released during $CaCO_3$ manufacturing for each tonne of cement produced. World Resources 1990-91, A Report by The World Resources Institute, Oxford University Press, Oxford, UK, 1990.

[5] Correcting for the use of CO (product of iron ore reduction) for energy purposes, it is assumed that 3/8 of the stoichiometric amount of CO_2 is generated from reduced iron. Reinforced concrete has been assumed to contain 7 w% of steel and to use 18 w% of cement for the concrete production.

[6] 2 g CO_2 are stoichiometrically released per kg of aluminum during the reduction process of aluminum oxide, Ref. [5].

4.4. Life-times of energy systems

The life-times of energy systems vary widely among advocates of energy technologies. The correct values of these life-times are of utmost importance for the non-CO_2 (non-fossil fuel) energy technologies since the upstream and downstream emissions have to be levelized over the installation lifetime. In IAEA studies a standard lifetime of 20 years has been assumed. Likely, this is too short for mature technologies, such as nuclear and hydropower, which have technical installation lifetimes of 40 years or more, and probably too long for some renewable energy systems.

5. CONCLUSIONS

Any country that ratified the Framework Convention on Climate Change has committed itself to make the greenhouse gas emissions from its national energy use an important factor in its national energy planning. For energy planning this implies comparison of full energy-chain emissions from different energy sources. Of course, the other factors in present energy planning, such as economic and secure supply of energy and the mitigation of environmental emissions other than greenhouse gases, will remain of importance.

Literature shows relatively large differences in the greenhouse gas emission factors of the full energy chains of energy sources. These differences could be the result from uncertainties due to:

- the use of different methods of full-energy-chain evaluation,
- neglect of the non-CO_2 greenhouse gases, or different views on the Global Warming Potentials of these gases,
- the use of different data bases, which all need updating and made adequate for mid-term projections,
- different views on the life-time of energy installations, especially of the new energy technologies.

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[8] "Meer energiekengetallen in relatie tot preventie en hergebruik van afvalstromen", Castro Consulting Engineer, Amersfoort, Netherlands (December 1992), for Novem BV and RIVM, Netherlands.

[9] YBEMA, Y.R., OKKEN, P..A, Full Fuel Chains and the Basket of Greenhouse Gases (draft), ECN Report, ECN-C-93-050, Petten, The Netherlands (September 1993): 4% to 3.2 % of nitrogen fertilizer is released as nitrous oxide with a medium estimate of 1%. For a fertilizer application of ca. 100 kg N/ha/y and an emission rate of 1.3-2.5 kg N_2O/ha/y, one derives 20 g N_2O/ kg N fertilizer.

[10] MUDAHAR, M.S., HIGNETTt, T.P. , Energy and Fertilizer; Policy Implications and Options for Developing Countries (International Fertilizer Development Center, Muscle Shoals, AL, USA, 1982), p. 42.

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