OVERVIEW OF EXISTING STUDIES ON FULL-ENERGY-CHAIN (FENCH) EMISSIONS OF GREENHOUSE GASES

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Abstract

Literature on investigations into full-energy-chain emissions of greenhouse gases is scanty. Fourteen different studies are reviewed most of which deal with energy use only in parts of the fuel chain or with CO_2 only. The scatter in full-energy-chain emission factors of individual energy sources is not very large, except that in the emission factors of gas-fired power, biomass-fueled power and hydropower generation. The sources of this scatter are discussed. Fossil fuels have emission factors in the range of 500-1200 g CO_2 equiv./kW(e).h. Wind, nuclear and geothermal power generation are in the range of low emission factors: 10-70 g CO_2 equiv./kW(e).h. Emission factors of hydropower and sustainable biomass-fueled power generation range 10-400 and 40-180 g CO_2 equiv./kW(e).h, resp. The solar and ocean power generating sources are in the range of 100-300 g CO_2 equiv./kW(e).h.

1. GENERAL DISCUSSION

FENCH studies on GHG emission factors deal with emissions of all GHGs from all GHG intensive fluxes of energy and materials within and into the whole energy chain. There are only a few of such studies and they are difficult to access because they have been published either in conference proceedings or as an institute report, and often in a language which is not an UN language. This low accessibility could indicate that the relevance for policy-making is not yet large. One of this workshop's aims is to discuss and promote the use of FENCH-GHG emission factors in energy planning.

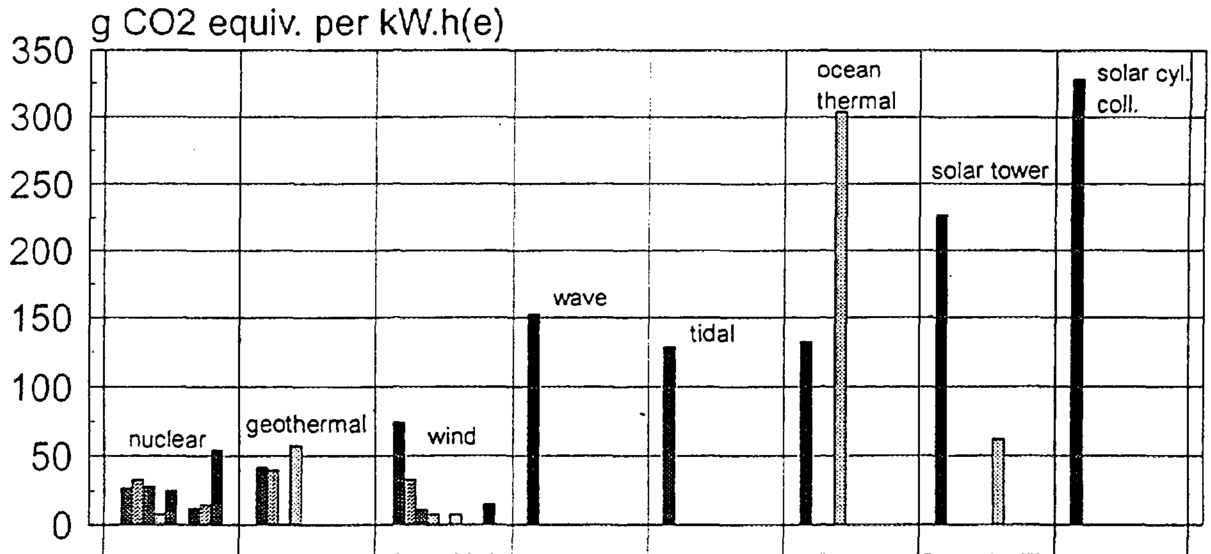
Some FENCH studies deal with the energy fluxes only, not accounting for the emissions associated with the materials fluxes. These "net energy" studies were popular in the 1970s. However, though incomplete from our point of view they could be made complete by adding the GHG emissions associated with the materials fluxes. Though some of these older investigations need some updating, but by completing such "net energy" studies they could add the existing small set of FENCH-GHG data. Unfortunately, with a few exceptions the net-energy analyses of the 1970s have evaluated only nuclear energy and the fossil fuels. They did not include the renewable energies. In general, the older analytical results on these energies should be considered with reserve in view of the important technological progress since the 1970s in the field of renewable energies. Similarly, present FENCH-GHG assessments of renewable energies, which are still in the stage of development (such as solar photo-voltaic), should also not be used as the ultimate indicator of the climate benignancy of the future mature energy technology.

The present overview of existing FENCH-GHG assessments, will give an impression of what has been achieved until now. In view of the rather limited accessibility of these studies, an overview will probably not be exhaustive. Moreover, it consists of a mixture of FENCH-GHG data on energy sources of different methodological origin which have to be made comparable in a number of cases by modifying, or by combining, with information from different sources. The necessity to modify and the inherent subjectivity of such modifications indicate that international consensus is required about the methods and data bases for FENCH-GHG investigations. This is one of the main reasons for convening this workshop.

In a general discussion of the review, a few studies will be discussed in some detail, particularly the FENCH-GHG emission studies of nuclear energy, natural gas, hydropower and sustainable biomass. Sustainable biomass is defined as biomass which is grown by sequestering the CO_2 emitted from combustion of the same amount of biomass carbon. This is considered to be attractive in view of a neutral atmospheric CO_2 balance.

2. REVIEW OF FENCH-GHG EMISSION FACTORS

Figs. 1 and 2 illustrate the set of FENCH-GHG emission factors of 13 different energy sources. Fig. 1 represents the energy sources with higher emission factors, such as the fossil fuels; Fig. 2 shows those with the lower emission factors, such as the renewable energies. The set of energy sources displayed in this overview is almost identical to that of the extensive CRIEPI study by Uchiyama [1], because this CRIEPI study of 13 energies covers by far the most energy sources. Twenty years lifetime of installations has been assumed in all cases.



	nuclear	geothermal	wind	wave	tidal	ocean thermal	solar tower	solar cyl. coll.
Uchiyama	27.0	42.0	74.0	152.0	128.0	132.0	227.0	328.0
Yasukawa	33.0	40.0	33.0					
Lewin	28.0		11.0					
San Martin	7.8	57.0	7.4			304.0		
Science Conc.	25.0							
Van de Vate			7.4				62.0	
Weis	12.0							
Moraw	14.5							
Fritsche	54.0		15.0					

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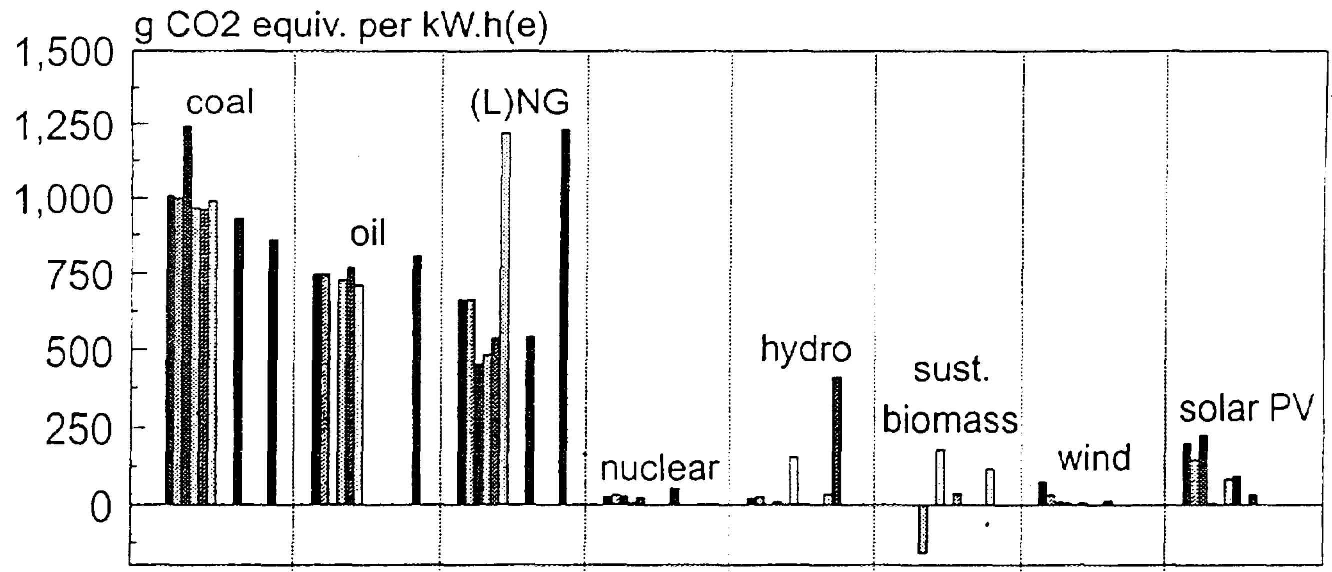
Fig. 1. Full-energy-chain emission factors of greenhouse gases of the fossil fuels, nuclear power and some renewable energy sources (see also the list of literature references).

The fossil fuels have the highest emission factors: 500 - 1000 g CO_2 equiv./kW(e).h. This is due to the combustion step associated GHG emissions which should not be levelized over the installation life-time. The coal values range from ca. 900 - ca. 1000 g CO_2 equiv./kW(e).h with one exception: Levin's value of more than 1200 g CO_2 equiv./ kW(e).h for which there is not yet an explanation. Oil has a relatively narrow range of 700 - 800 g CO_2 equiv./kW(e).h. Apart from two very high emission factors of ca. 1200 g CO_2 equiv./kW(e).h, natural gas could be the most climate benign fossil fuel with its 450 - 650 g CO_2 equiv./kW(e).h. The two high values are recent data from Sullivan [2], Australia, and from Van de Vate [3], IAEA, Austria. The increased emission factors are due to the accounting for methane emissions from losses of natural gas during



Uchiyama	1,008.0	748.0	660.0	27.0	21.0		74.0	201.0
Yasukawa	1,001.0	748.0	660.0	33.0	26.0		33.0	147.0
Lewin	1,244.0		453.0	28.0			11.0	228.0
San Martin	964.0	725.0	484.0	7.8	10.0	(160.0)	7.4	5.4
Science Conc.	960.0	770.0	538.0	25.0				
Van de Vate	990.0	711.0	1,220.0		156.0	180.0	7.4	83.0
Haene								93.0
Born						37.0		
Fritsche	929.0		542.0	54.0			15.0	32.0
Rudd-1					35.0			
Rudd-2					410.0			
Turhollow						116.0		
Sullivan	860.0	809.0	1,234.0					

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Fig. 2. Full-energy-chain emission factors of greenhouse gases of nuclear power and some renewable energy sources (see also the list of literature references).

its production, transmissions, and distribution to the end-user. The lack of reliable internationally accepted values of the GWP of methane is an important factor in the large scatter in emission factors of natural gas (see also the contribution "Climate Change and Global Warming Potentials").

Hydropower, sustainable biomass and solar PV all show substantial scatter. Fig. 1 displays large error bars in the emission factors for these renewable energies, even a negative value. The reasons for this scatter are different for each of these energies. The reason for the scatter in the solar PV data is most unclear; it could be related to different chain assessments. San Martin's extremely low, even negative, emission factor for biomass energy [4] is caused by incomplete chain assessment. San Martin assumes permanent sequestering of CO_2 in in-soil biomass such as roots. This is not realistic: the in-soil biomass biodegrades within 5-10 years after above-ground harvest, returning the carbon to the atmosphere as CO_2 and possibly CH_4. The studies of Turhollow [5] and Van de Vate [3] are based on net-energy analyses of biomass energy, accounting for the energy used for the agricultural activities associated with biomass energy production. Van de Vate uses the net-energy data of Born [6]. In this study also the fate of carbon sequestered in in-soil biomass is discussed and he assumes that, after harvesting the above-ground biomass, 1% (a few days per year) of the in-soil biomass to CH_4 degrades anaerobically. Moreover, N_2O emission from fertilizer use was accounted for.

Hydropower, generally, shows low emission factors in the range of 10 - 35 g CO_2 equiv./kW(e).h. However, Rudd *et al* (Ontario Hydro) [7] and Van de Vate took into consideration also the emissions of CH_4 from anaerobic degradation of the organic material inundated at the bottom of the hydropower plant's water reservoir. Accounting for this CH_4 source leads to emission factors for hydropower which are 5 -10 times higher. Rudd has used methane measurements of CH_4 above Canadian water reservoirs.

Fig. 2 shows that the three mature non-fossil energy sources (wind, nuclear and geothermal energy) have low emission factors all in the range of 10 - 70 g CO_2 equiv./kW(e).h Nuclear energy is a special case because it has a very complicated energy chain due to its fuel manufacturing step and its waste management activities. This may lead to different emphasis on parts of the fuel chain. Therefore, reported assessments of CO_2 equiv. emission factors of the nuclear energy chain are rather global. However, there are good reasons of analyzing this chain in much more detail, in view of not so obvious emission sources such as the emissions of N_2O from the dissolution of spent fuel in nitric acid. That this source can be neglected (ca. 5 g CO_2 equiv./kW(e).h), can be established only by doing the calculation. One might expect a large scatter in the emission factors of nuclear energy, which (neglecting the probably obsolete low figure of 5.4 mg CO_2 equiv./kW(e).h of San Martin [4]) surprisingly is not the case. Only Fritsche's estimate is relatively high [8]; lack of detailed information on this study makes explanation speculative.

The wind energy data scatter substantially: 7-70 g CO_2 equiv./kW(e).h. The high figure of Uchiyama [1] (74 g CO_2 equiv./kW(e).h) cannot be interpreted because of low accessibility of the publication (in Japanese). Obviously, both Japanese studies, [1] and [9], are on the high side, which could have to do with a low capacity factor of wind turbines in Japan.

The emission factors of geothermal energy are within the small range of 40 - 60 g CO_2 equiv./kW(e).h.

The remaining ocean and solar energies, including solar PV, show relatively high GHG emission factors in the range 100 - 300 g CO_2 equiv./kW(e).h, probably because of being in an early stage of technological development. With the exception of solar PV, the review given of these energy sources had to rely almost exclusively on the Japanese CRIEPI study [1].

3. SOURCES OF SCATTER IN FENCH-GHG EMISSION FACTORS

3.1. The example of biomass energy

Biomass is a good illustration of substantial uncertainty in its emission factor due to the many variables with limited reliability of the system. The definition of its energy chain in terms of its system boundaries and the fluxes of materials and energies, creates a large scatter in its emission factor. San Martin [4] only accounts for the CO_2 sequestering in the roots, whereas Turhollow [5], Born [6] and Van de Vate [3] also account for the fluxes of energy and materials (fertilizer) associated with all activities in the FENCH of sustainable biomass. Born and Turhollow do not account for emissions of GHGs other CO_2. Van de Vate also accounts for the emissions of CH_4 and N_2O. Table I provides an analysis of the sensitivity of this study. Remarkably, accounting for the release of CH_4 from biodegradation of the in-soil biomass, the root system, substantially increases the emission factor more than three-fourth. Increasing the GWP of CH_4 by a factor of almost five[1], doubles the emission factor. Increasing the GWP of N_2O 2.5 times (H.1 *versus* H.4) changes the emission factor by +50%.

[1] The high GWP value of 50 for CH_4 is double the GWP of CH_4 recently adopted by IPCC.

TABLE I. SENSITIVITY OF THE CO_2 EMISSION FACTOR OF BIOMASS ENERGY (in g CO_2 equiv./kW(e).h of biomass energy) TO VARIOUS FACTORS OF SEQUESTERING OF CO_2 IN BIOMASS IN THE SOIL

	Sequestering fractions				GWP		Emission factors	
	F1[1]	F2[2]	F3[3]	F4[4]	F5[5]	F6[6]	In-soil biomass[7]	Total biomass[8]
Uncertainty ranges	0.33-0.50	0-0.01	0-0.1	0-0.01	11-50	100-270		
L.1	0.33	0.01	0.1	0.01	11	100	24	52-71
L.2	0.33	0.01	0	0.01	11	100	25	53-72
L.3	0.33	0.01	0	0	11	100	10	48-58
H.1	0.50	0.01	0.1	0.01	11	100	29	58-77
H.2	0.50	0	0	0.01	11	270	62	90-109
H.3	0.50	0	0	0.01	50	270	145	173-192
H.4	0.50	0	0	0	11	270	39	67-86

[1] F1 = in-soil fraction of biomass.

[2] F2 = "permanent" fraction of in-soil carbon.

[3] F3 = fraction of in-soil biomass used for energy production.

[4] F4 = fraction of in-soil biomass degraded to CH_4.

[5] F5 = global warming potential of CH_4.

[6] F6 = global warming potential of N_2O.

[7] Total emission factor of biomass including the upstream emissions of greenhouse gases; Born estimates this to be ca. 37 g CO_2 equiv./kW(e).h of biomass energy.

[8] Biomass emission factor associated with the in-soil carbon.

3.2. Sources of scatter in FENCH-GHG emission factors

The use of different methods and data bases can be the reason for large scatter in emission factors of individual energy sources and limits the comparability of the emission factors of different energy sources. Table II gives an overview of the different FENCH-GHG studies in terms of their comprehensiveness and the methods used. The study by Van de Vate [3] deals with all GHGs, viz. CO_2, CH_4, N_2O, and CF_4. Apart from investigations by Uchiyama [1], who considered natural gas releases, all other studies focus on CO_2 almost exclusively.

Firstly, comprehensive assessment of FENCH-GHG emission factors requires expressing emissions of different GHGs in a common unit. As shown in Table II, only a few studies account for emission sources of non-CO_2 GHGs such as CH_4 and N_2O. The exceptionally high emission factors in our review of natural gas, hydropower and biomass, are from those studies which account for the non-CO_2 GHGs, in particular CH_4. This has two aspects. The conversion factor to be used is the GWP which is needed for the conversion of amounts of non-CO_2 GHGs into CO_2 equivalents. There is uncertainty about the so-called indirect effects of non-CO_2 GHGs. Also the uncertain effective atmospheric residence time of CO_2 adds to the uncertainty in the GWPs to be used. In its First Assessment Report [10] of August 1990, IPCC has recommended GWPs for non-CO_2 GHGs including the indirect effects. However, in 1992 in its Supplementary Report [11] IPCC recommends GWPs which are based only on the direct effect of trapping IR radiation. IPCC leaves open future changes in GWPs. This has become an important source of uncertainty. Rudd and Van de Vate have been using GWPs for CH_4 of 60 and 50, resp. The studies using the present IPCC values of the GWP of CH_4 assume this GHG to be only 30 times more effective as a GHG than CO_2.

Secondly, as Table II shows, the reviewed FENCH studies use different analytical methods, viz. input/output (i/o) analysis and process analysis, which can lead to different results. Process analysis can lead to GHG emission factors with a large bias. Process analysis is a tedious method and requires inventiveness, which can easily lead to unintentional overlook of important emission sources or to giving excessive weight to minor emission sources. One of the aims of this workshop is to make experts and policy-makers aware of such subjective elements in FENCH-GHG studies. I/o analysis has also its inherent uncertainties. The economic data bases needed for i/o analysis are often outdated and incomplete, and the commodity sectors usually are inadequately aggregated. Born [13] in his study on biomass energy has discovered some important pitfalls in this method and had to make tailor-made corrections.

TABLE II. ASPECTS AND GREENHOUSE GASES INVESTIGATED AND METHODOLOGIES USED IN VARIOUS FULL-ENERGY-CHAIN STUDIES OF GREENHOUSE GAS EMISSION FACTORS (for numbering of energy sources see Table III)

	input/output analysis	process analysis	energy flux related emissions	materials fluxes related emissions	CO_2	all GHGs
Uchiyama (1-13) [1]	+		+	+	+	(CH_4)
Yasukawa (1-7; 13) [9]	+		+	+	+	
San Martin (1-7; 10;13;14) [4]		+	+	+	+	
Lewin (1; 3-4; 7; 10; 13) [12]	+		+	+	+	
Fritsche (1; 3-4; 7; 13) [8]		+	+	+	+	
Science Concepts (1-4) [13]		+	+		+	
Rudd (5) [7]		+				CH_4
Van de Vate (1-3; 5; 7; 11; 13-14) [3]	(+)	+	+	+		+
Haene (13) [14]		+	+	+	+	
Born (14) [6]	+		+	+	+	
Turhollow (14) [5]		+	+	+	+	
Sullivan (1) [2]		+			+	CH_4

TABLE III. LIST OF ENERGY SOURCES INVESTIGATED CONCERNING THEIR FULL-ENERGY-CHAIN GREENHOUSE EMISSIONS AND THE NUMBERING USED IN THIS REPORT

coal	oil	(L)NG	nuclear	hydro	geother-mal	wind
1	2	3	4	5	6	7
wave	tidal	ocean therm	solar tower	solar cyl. coll.	solar PV	sustain. biomass
8	9	10	11	12	13	14

4. SUMMARY

Literature on Full-Energy-Chain Greenhouse Gas emission factors is limited and of low accessibility. The above overview of the emission factors gives a plausible impression of the climate benignancy of almost any energy source: the fossil fuels, nuclear and hydropower, biomass energy, and solar and ocean energies.

The fossil fuels with their combustion associated CO_2 emissions, and inherent CH_4 emissions associated with its production and transport are a separate category of high GHG emission factors, ranging from 500 - 1200 g CO_2 equiv./kW(e).h. Future energy efficiency improvements could lower these emission factors considerably but it is unlikely that the large gap between fossil fuels and the other energy sources can be bridged. A major factor of uncertainty of natural gas is the release of gas during production and transportation.

The emission factors of non-fossil fuel energies which are mature, viz. wind, geothermal and nuclear energy, are very low. They are in the range of 10 - 70 g CO_2 equiv./kW(e).h.

The emission factors of hydropower and sustainable biomass are uncertain due to difficulties in accounting for the emissions of CH_4 from anaerobic biodegradation from the hydropower water reservoir and in-soil biomass, (mainly roots), resp. Hydropower and sustainable biomass energy have emission factors in the range of 10 - 400 and 40 - 180 g CO_2 equiv./kW(e).h, resp.

The renewable energy sources, which are still under development, viz. solar and ocean energies, show emission factors of 100 - 300 g CO_2 equiv./kW(e).h.

Generally, accounting for methane sources in the complete fuel chain increases GHG emission factors substantially.

Scatter within the emission factors from different studies of an individual energy source can be attributed to different methods and data bases. Input/output analysis suffers from methodological weaknesses whereas process analysis suffers from the incomplete identification of GHG sources. Data bases often are not up to date. Uncertainties in the global warming potential of CH_4 also add to the scatter in the emission factors.

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