INTEGRATION OF INDIRECT CO_2 EMISSIONS FROM THE FULL ENERGY CHAIN

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Abstract

The methodologies of life-cycle analysis are discussed. The system boundaries have to be adequately defined, which is illustrated with the example of coal-fired electricity generation. The input/output method of LCA is discussed, including the incorporation of material recycling in the analysis. Also discussed is the linkage of engineering and economic approaches together with the necessary improvements of MARKAL in order to integrate the indirect processes. Finally examples are given of the analysis of the direct and indirect CO_2 emission from a pressurized-water reactor and its fuel cycle. The analysis shows that the life-cycle CO_2 emission coefficient is 25.7 g CO_2/ kW.h in case of gas-diffusion enrichment, whereas in case of centrifuge enrichment this emission coefficient amounts to 7.9 g CO_2/kW.h only.

1. INTRODUCTION

From energy economy statistics one might infer that supply and demand of goods and services are increasing with socioeconomic development. The problems associated with energy and environment might, therefore, be increasingly complex. Among these problems global warming which arises from emissions of greenhouse gases like CO_2, becomes the most misgiven and worldwide recognized problem. Global warming has a worldwide impact, with impacts that would be irreversible. Moreover, several generations will experience its impacts. Therefore, taking the appropriate countermeasures is very difficult. The difficulty can be well understood if one considers that our daily lives, i.e. food, clothing, shelter, energy, infrastructures, etc., depend so much on carbon [1], as shown in Fig. 1. Especially for energy, the dependence on carbon is high.

We are apt to consider energy and environment problems from the viewpoint of only the direct utilization of goods and services. Of course, the impact of direct energy utilization to the environment is usually large. For example, the direct emissions of CO_2 from automobile use, have a share of 81% of the total CO_2 emissions, which includes the emissions from indirect energy use such as for the production process of goods and services and for the disposal of the car. However, in case of a house about 7% of CO_2 emissions comes from direct energy use, while 93% stems from indirect processes [1].

Analysis of the energy requirement for the production of goods and services can hardly be made if one focusses on these goods and services only. Indirectly, many other goods and services are involved, e.g. in the production process, which in turn can be divided into sub-processes such as material production, manufacturing of parts, assembling of equipments. More or less the same applies to operation and maintenance of the production process, and to dismantling.

Life Cycle Analysis (LCA) is a tool for the analysis of above kind of problems where all activities related to production, operation and disposal have to be taken into account. In such cases, mutual substitutability of materials is an important topic, especially for future supply and demand of energy. For attaining the sustainability of socio-economic activities, we must consider the nature of various kinds of goods and services from the viewpoint of LCA, and improve the associated weaknesses through technological and institutional measures. Since many goods and services have international distribution through world trade, the assessment must also take an international point of view.

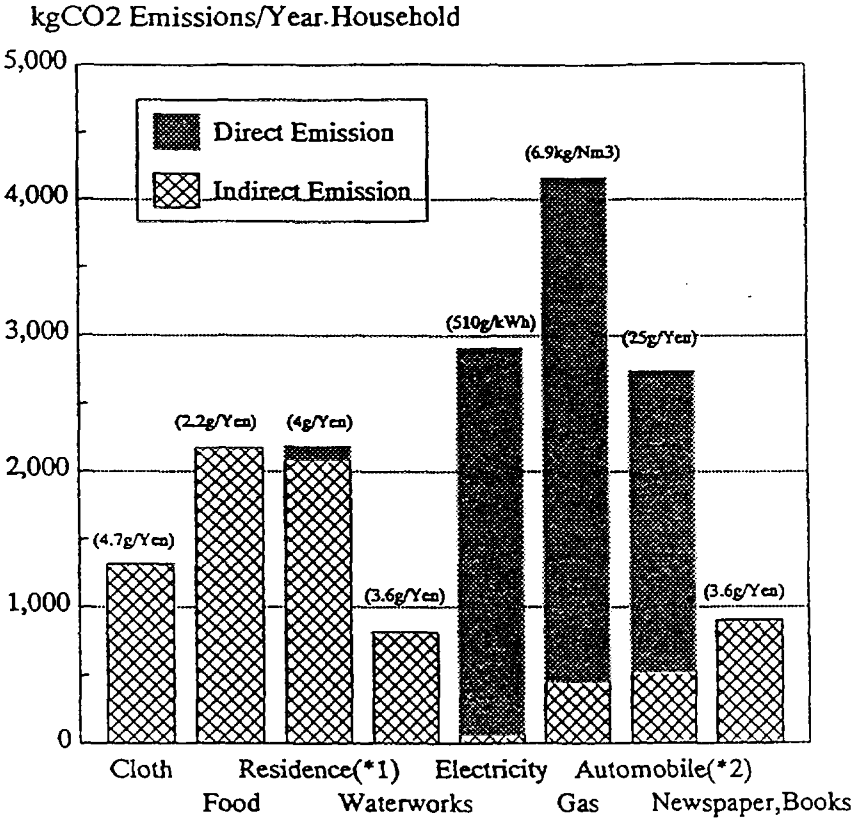

*Fig. 1. Annual CO_2 emissions from a household. (*1): Excludes contributions of maintenance and demolition; (*2): Assumed: 10 000 km/year travel and 11.9 l/km fuel use.*

In the following the way will be investigated to use LCA in integrating the direct and indirect effects of production, operation, disposal, etc. of coal-fired and nuclear power generation.

2. EMISSION COEFFICIENT

2.1. Definition

Let us consider the emissions of SO_2, NOx, and CO_2 from fossil fuel combustion. As an energy source material, let us consider coal. The main constituents of coal are carbon and hydrogen, but it contains also small quantities of sulphur, nitrogen and other elements. During coal combustion heat is generated and most of the carbon and hydrogen is converted into carbon dioxide and water vapor. The sulphur and nitrogen compounds are released into the environment as sulphur dioxide and nitrogen oxides.

Environmental emissions do not always result from the fuels themselves. Some of the nitrogen in air is also oxidized during fossil fuel combustion and released as nitrogen oxides to the environment. As shown in Fig. 2, under some circumstances a part of the raw materials can be emitted as pollutants to the environment. E.g. in the cement production process more than two thirds of the total CO_2 emission comes from calcination of calcium carbonate is emitted as CO_2 emissions, and there are also sulphur dioxide emissions from aluminum refinering, etc. [2]. Accordingly, we must include the emissions not only from fuels but also from raw materials and auxiliary materials and impurities.

The emission coefficient of a pollutant is defined in several ways, per volume unit for emissions at normal temperature and pressure, emissions per unit of mass, emissions per unit of energy, etc. In the analysis of energy-environment systems, emissions are generally expressed in amounts per energy unit. In this definition, however, a clear distinction must be made between

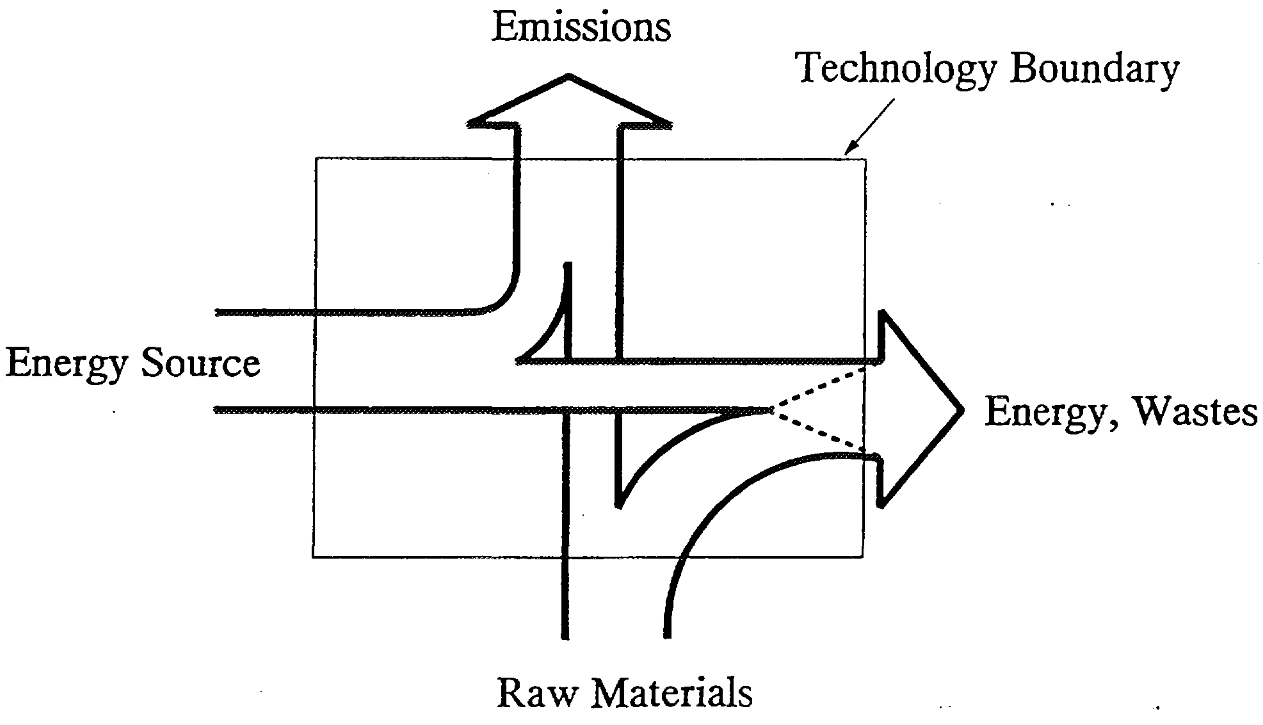

Fig. 2. Routes of environmental emissions and wastes.

gross energy and net energy. Additionally, we must indicate where this unit energy refers to, i.e. at inlet or at outlet. For example, the CO_2 emission from heavy distillate oil is 69.3 kg CO_2 per GJ of gross heating value, but per unit of net heating value it is 73.3 kg CO_2/GJ, i.e. 6% higher than the former value [2].

2.2. System boundary

In systems analysis the system boundaries need adequate definition. The emission coefficient is sensitive to the choice of the system boundaries, and in some cases even the definition of the emission coefficient depends on it. For example, let us consider again the CO_2 emissions from coal-fired power generation. The power plant consists of various facilities such as unloader, conveyer, storage yards, crushing machines, boilers, turbines, generators, transformer and switchyards, and also buildings and waste treatment facilities, etc. Part of the generated electricity is consumed by the unloader and the coal preprocessing facilities. Various oil products, e.g. light-distillate oil and gasoline, are used as fuels for driving transportation equipment. For each of these direct activities, one can define emission coefficients. By integration, one can also define an overall emission coefficient of the power plant, which includes the indirect processes, as shown in Table I.

One can also define a national average CO_2 emission coefficient for electricity generation. In this case, there must be included the contributions not only from coal-fired plants but also from the whole fuel mix for power generation from the other fossil fuels, and for the generation of nuclear power, hydro power, and others. This shows that the emission coefficient depends on the choice of the system boundaries.

TABLE I. CO_2 EMISSION COEFFICIENT DEPENDENCE ON THE CHOICE OF THE SYSTEM BOUNDARY[a]

Emission category	Coal ($g\ CO_2$/kcal)	Coal-fired electricity ($g\ CO_2$/kW.h)	Total electricity ($g\ CO_2$/kW.h)
Direct emission	0.387	955	396
Indirect emission	-	7	9
Total	0.387	962	405

[a] The "Indirect emission" from "Total electricity" generation is the average of the indirect emission coefficient of generation by oil-fired power (4.22 g CO_2/kW.h), LNG-fired power (2.16 g CO_2/kW.h), coal-fired power (6.94 g CO_2/kW.h), nuclear power (22.8 g CO_2/kW.h), and hydropower (12.8 g CO_2/kW.h), averaged for the 1990 Japanese electricity generation of 29.6%; 23.6%; 10.4%; 23.5%; and 12.9%, resp. Uranium enrichment by gas diffusion was assumed.

3. INTEGRATION OF INDIRECT EFFECT

3.1. Direct and indirect processes

A clear distinction between direct and indirect processes is required for LCA. Here, "direct processes" means direct utilization of various kinds of goods and services, direct operation of equipments and facilities, etc., while "indirect processes" means the activities of producing goods and services or disposing them.

The production process can be subdivided into sub-processes, i.e. of material production, manufacturing of parts and equipment, construction of facilities, etc. The operation process requires some auxiliary materials, e.g. gypsum for coal ash treatment, spare parts for repair. At the dismantling stage of the plant, some auxiliary equipment and materials are also used. Evidently, each stage of production, operation and disposal has its demands for goods and services and the production of these goods and services require materials, energy, goods, etc. Such a chain of demands extends into the upper stream of production process. The input-output (I/O) method can be used for evaluation of these propagation chains. As shown in Fig. 3, the total energy requirement e of this process is given by $e = f + H(I-A)^{-1}y$, where y is a demand vector of goods and services for the final demand sector, A is a matrix of I/O coefficients, H is a matrix of energy intensity, and f is an energy demand vector at final demand sector.

Total environmental emissions are expressed in an emission vector b, which is given by $b = B_f + B_m H(I-A)^{-1}y$, where B_f and B_m are matrices composed of emission coefficients of the final demand sector and the intermediate sector, resp. After normalization of e and b by the absolute value of the vector y, one obtains the sum of the direct and indirect components of the energy use and environmental emissions normalized to vector y. Matrix $(I-A)^{-1}$ shows the propagation of intermediate demand, and is called the induce coefficient. To evaluate this matrix, one has to know how many stages of propagation must be included. According to Saito's study, 10 stages are enough to obtain a stable value, as shown in Fig. 4 [3].

In the traditional I/O tables, both by-products and scraps are treated by a transfer method and/or a negative input method. However, with a negative input method the value-added process cannot be expressed correctly. Therefore, I/O tables must be improved, if one wishes to apply this method to the evaluation of recycle use of various kinds of wastes, by-product material and scraps. This difficulty can be circumvented by the introduction of additional columns and additional rows corresponding to the recycling activities, accounting for these activities as intermediate transactions. Such modelling has the additional advantage that it also evaluates the value-adding process of recycled materials.

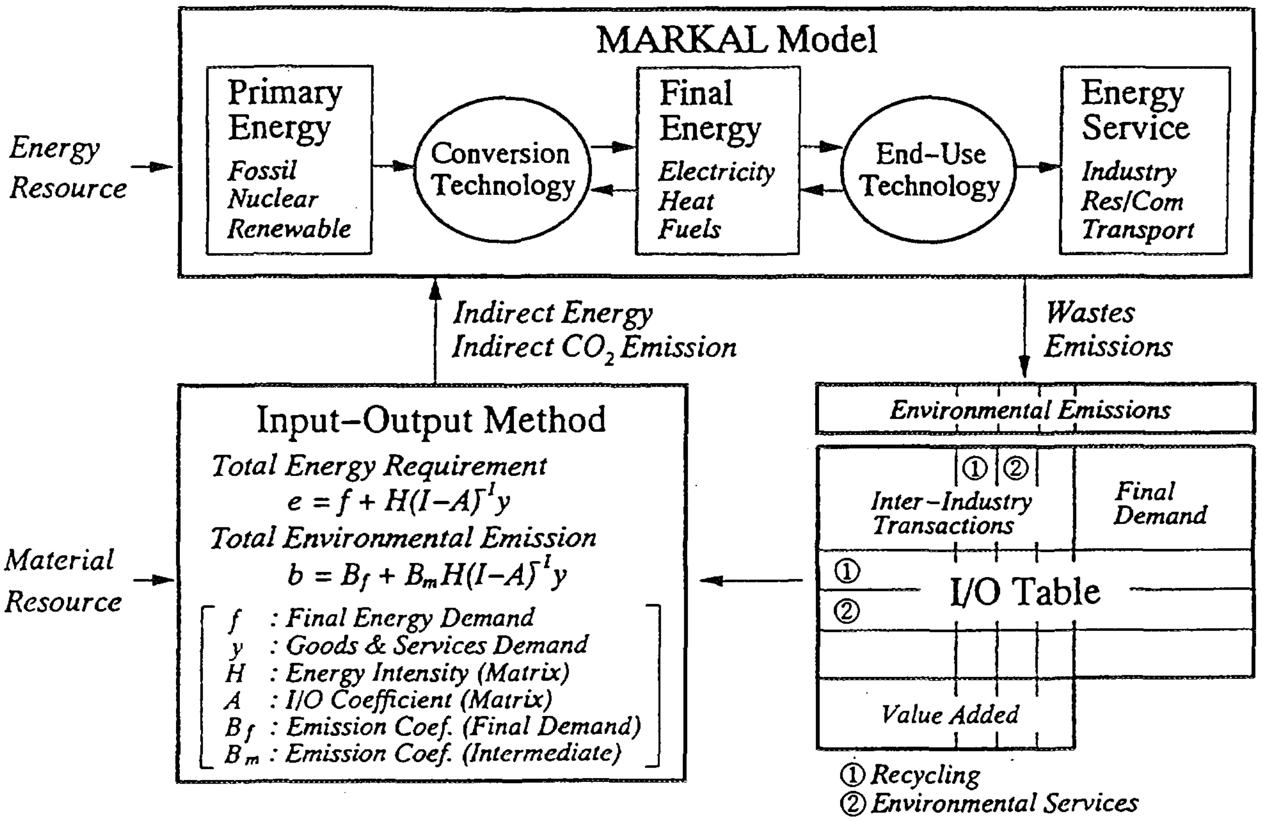

Fig. 3. Application of the Input/Output method for integration of indirect processes.

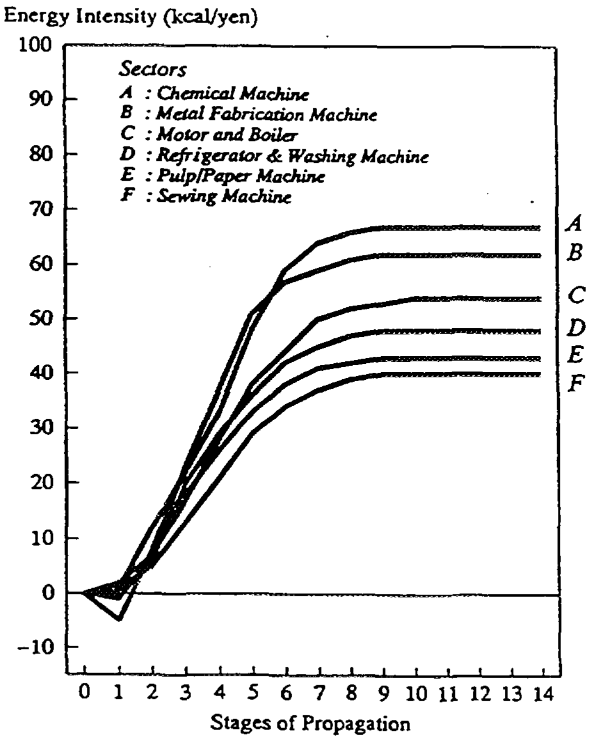

Fig. 4. Changes of energy intensity in various stages of propagation.

Again, for the evaluation of various kinds of waste independent columns and independent rows can be introduced for environment related industry sectors. With the use of such an improved I/O frame, not only the recycling of by-products, scraps and waste materials but also the regeneration process of waste materials can be handled. The matrix A, previously introduced, should be of this type.

3.2. Linkage of engineering and economic approach

Substitutability and/or complementarity of economic resources, i.e. capital, labor, materials, energy, etc., are very important analytical subjects in production and consumption. Therefore, many economy models take the substitution of goods and services into account. However, these models usually are not sufficiently technologically detailed, contrary to process models in which each economic activity is described as an activity of technologies responding to the system.

The dynamics of technology can be expressed by a set of variables, and the fundamental mathematical relations contain many such variables and parameters. Most macro-economic models do not encompass the method of process model, because some of the variables and parameters are constrained, even if they are treated at all. If we cannot quantify parameters, the model cannot work. Furthermore, there are errors associated with aggregation, and an aggregated result of variables does not always coincide with the macro result, especially if the system has non-linear characteristics.

In the process approach, however, the normative side of a problem is emphasized and a fundamental nature is sought, omitting actual behavioral details. For example, one could imagine the following model framework: investment, stock, and activity are selected as a set of variables which describe technology behavior, by setting balance relations of capacity utilization, of energy supply and demand, of energy resource utilization, by accounting for costs associated with the installation, operation and decommissioning of a technology, by assessing environmental emissions, by considering system operational principles (e.g. minimize discounted system costs), and by keeping operation standards and other constraints (e.g. installed capacity bound from upper and lower side).

The economic model, mentioned first in the above, is sometimes called a "top-down" model, and is used for analyzing the macro behavior of the system. The model output is used for a ceiling purpose which determines again the macro-nature of the system. On the other hand, the process model, which aims for analyzing system behavior from a structural side, is called "bottom-up" model. The MARKAL model developed at OECD/IEA/ETSAP is an example of the latter model.

Also combined top-down and bottom-up models are being developed. Examples are the MARKAL-MACRO model developed at BNL for OECD/IEA/ETSAP, and the JAERI model MARKAL-MACROEM [4], [5]. In the former model, the industrial sector is represented by a single production function, while in the latter model several sectors are introduced to express inter-industry transactions. With the models MARKAL-MACRO and MARKAL-MACROEM, one can obtain an optimal view of a technology installation. In addition, the balance between supply and demand, substitution of factor inputs, and technological progress are taken into account in the technology set. However, optimization is carried out considering the direct process only. Accordingly, the energy embodied in facilities and equipment, and the associated environmental emissions, cannot be handled in the above two models. Materials substitution is one of the most interesting analytical subjects, especially for capital goods, and it is worthwhile to integrate these indirect processes into the MARKAL model, using an endogenous approach as shown in Fig. 3 [6].

The analysis of energy and material flows has been made simultaneously with the extension of MARKAL [7], [8]. Compared with these studies, the approach proposed here is much more comprehensive. Firstly, the effects from the indirect processes, covering all activities from material production to the disposal stage, are included. Secondly, in order to make a realistic evaluation of value adding processes of the goods and services, the costs associated with material processes are divided according to the stage of the life-cycle. Conservation of the value in these processes is assured by using a salvage equation in the terminal condition of the model.

3.3. Material substitution

In order to integrate the indirect processes, the MARKAL model requires three improvements: 1) the integration of indirect energy utilization and environmental emissions into the direct processes, 2) the economic valuation of the indirect parts of processes compared to the direct parts, 3) avoiding double accounting of various activities associated with indirect processes. To accomplish this, one has to investigate the following possibilities. Firstly, an data base has to be developed covering material use for energy facilities and equipments and auxiliary material demand for operation and maintenance of these facilities and equipment. And secondly: 1) one has to formulate the relationship between supply and demand of those materials; 2) one has to estimate the energy intensities and environmental emission coefficients for material production, discriminating between the direct parts and the indirect parts by means of the I/O table; 3) for the rest of the activities, i.e. manufacturing of equipments, construction of facilities, etc., one uses the sectoral approach, i.e. assigning energy intensity and emission coefficient sectorially as shown in Fig. 3.

One has to add a new set of endogenously defined constraint relations, which represent material supply and demand to the usual constraint relations, e.g. energy carrier balance, electricity and heat balance, and environment emissions, etc. Concerning material uses, one has to include the materials embodied in facilities and equipments and the auxiliary materials used for construction, operation, and dismantling of facilities as illustrated in Fig. 5. Waste materials must also be accounted for. To such endogenously constrained relations, one must add energy input and environmental emissions from indirect processes. However, in order to avoid double accounting, one should account for the direct and indirect components separately. Instead of simply adding them, a function is introduced which takes care of the trade-offs between these two parts.

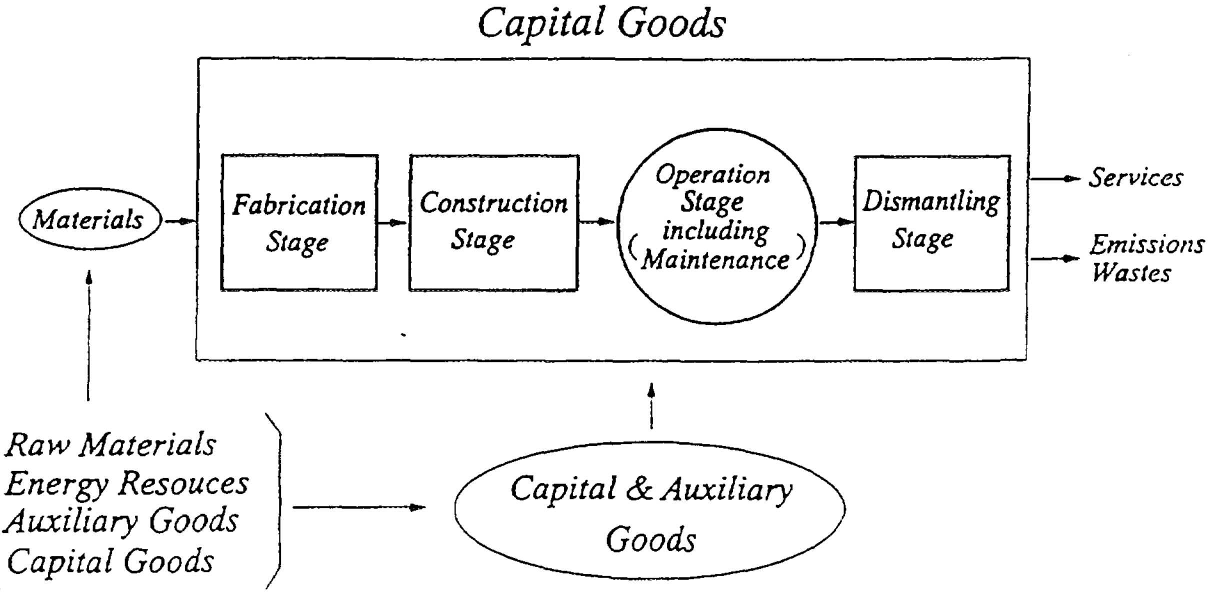

Fig. 5. Direct and indirect processes in production of capital goods and their uses.

Regarding discounted system costs, one of the objective functions, namely the material costs, also must be treated separately. Such an approach is required for economical assessment of material substitution on the one hand; on the other hand one needs an assessment of the time evolution of impacts and effects of the material recycling as well as a re-valuation of waste materials. Therefore, one should separate material costs from capital costs, operation and maintenance costs, transportation and storage costs, disposal cost, etc.

3.4. Indicator and phase diagram

Life cycle analysis deals with very long chains of goods and services, and these chains contain many different technologies. Accordingly, LCA results depend on many variables and parameters. Among the characteristics concerning energy and environment both the energy intensities and emission coefficients are the most frequently used indicators for understanding the characteristics of goods and services from the viewpoint of LCA. Energy saving can be assessed from energy intensity analysis, if the energy utilization is considered separately for the direct and indirect processes for each good and service. The same applies to environmental emissions, e.g. what goods and services and which part of them must be improved for reducing CO_2 emissions. This requires for example area maps, phase diagrams, and correlation matrices. The use of area maps has advantages: it visualizes quantitatively, while phase diagrams show trade-off relationships and/or the time evolution. One specific example of such representations is the Hill's diagram as shown in Fig. 6, where results of Kaya's decomposition of CO_2 emission are given on a logarithmic scale.

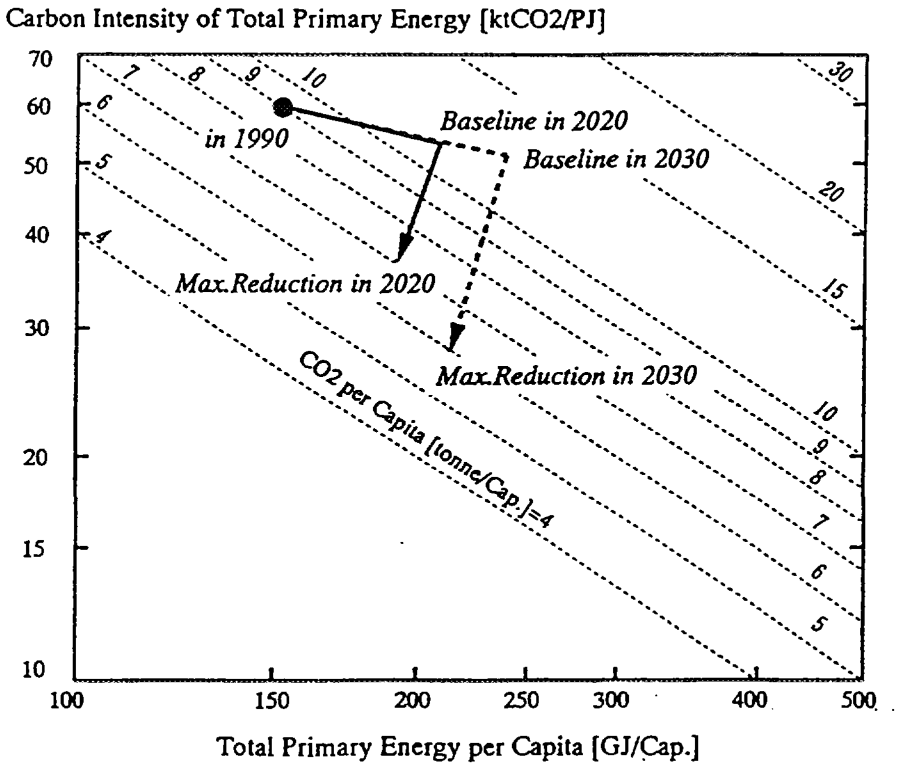

Fig. 6. CO_2 emission per unit of total primary energy as a function of the per capita energy use, according to Kaya's decomposition.

4. ANALYTICAL EXAMPLES

4.1. Assumptions

Nuclear power is one of the most promising energy sources for reducing CO_2 emissions.However, the market share of this energy is only about 6% of the world primary energy supply. This share is so low due to the fact that many of the major industrial countries presently are not adding nuclear capacity, because of safety problems and public acceptance, and the developing countries are still in a learning process.

The direct emissions of CO_2 from nuclear power are very low. However, nuclear power releases some CO_2 if indirect processes are taken into account. The indirect CO_2 emissions from nuclear power generation have been calculated taking into account the materials used and the costs of nuclear power plant and fuel cycle facilities.

The amounts of materials used in a typical large scale pressurized water reactor (PWR) power plant are listed in Table II. Table III gives the percentage share of each cost component in the total construction cost. The corresponding databases have been developed also for the facilities of the whole fuel cycle. In addition, inducement coefficients of final demand for goods and services have been derived from the I/O table modified as described above [9].

TABLE II. MATERIALS USED FOR A 1100 PWR

Material	kg/kWe	Material	kg/kWe
Stainless steel	2.34	Copper	0.71
Ordinary steel	52.59	Titanium	0.29
Special steel	0.62	Cement	70.27
Composite material	0.64	Insulation materials	0.43
Aluminum	0.08		
Total	127.97		

TABLE III. CONSTRUCTION COSTS OF A 1100 MWe PWR

Component	Share in total construction costs (%)	Component	Share in total construction costs (%)
Land and land rights	10	Engineering and services	14
Structures and site facilities - site facilities - reactor containment structures - other buildings	15 3 2 10	Reactor plant equipment - reactor equipment - accessory equipment - waste treatment & disposal - fuel handling & storage - other plant equipment - control & safety systems	28 2 10 1 1 9 5
Turbine plant equipment	15	Interest during construction	15
Electric plant equipment	3		
Total	100		

4.2. Results

Using the above databases, the direct and indirect CO_2 emissions from nuclear power generation have been calculated. Fig. 7 gives these emissions for the nuclear power plant itself, and for the front-end and for the back-end processes of the nuclear fuel cycle. The total CO_2 emissions associated with the construction of the PWR power plant is given in Fig. 8 for the major components of the plant.

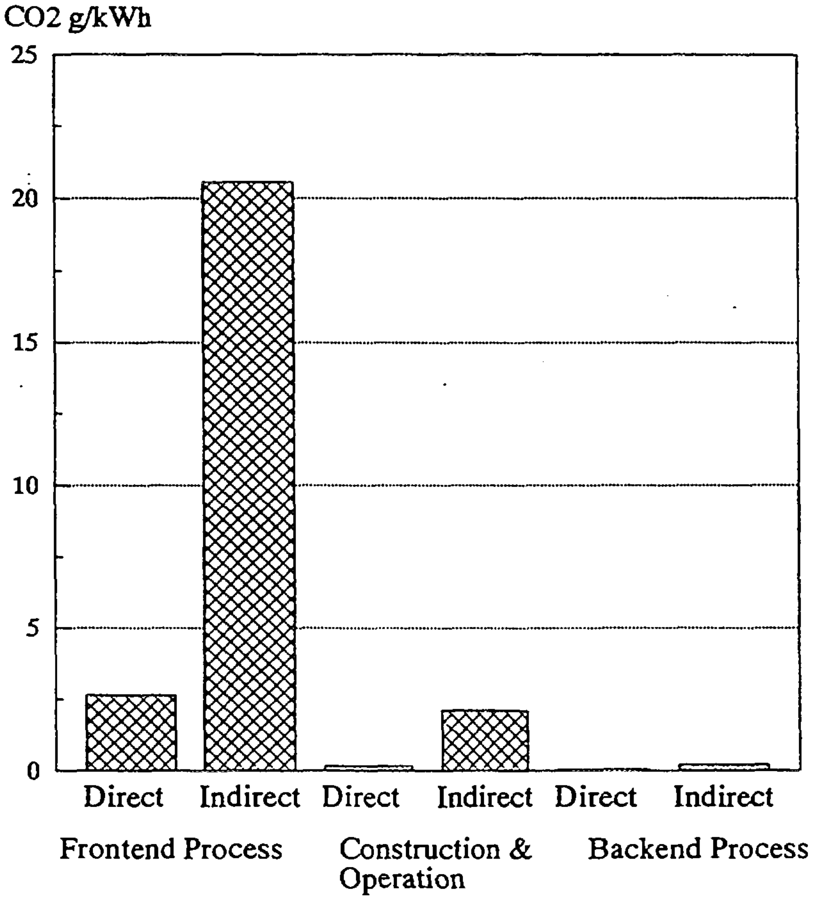

Fig. 7. CO_2 emission from nuclear (PWR) generation (for details of the indirect emissions from construction & operation, see Fig. 8).

The life-cycle CO_2 emission coefficient, the sum of the direct and indirect components, is about 25.7 g CO_2/kW.h when the gas-diffusion process is utilized for uranium enrichment. The indirect component is about 89% of the total CO_2 emission coefficient. The emissions associated with material production are 8% of the total.

The life-cycle CO_2 emission coefficient for nuclear power is 2.7% of that of coal-fired power generation. The enrichment process is a major contributor to the total CO_2 emissions from the nuclear fuel cycle, amounting to 72% of the total emission. However, if the centrifuge process is utilized instead of the gas-diffusion process, the life-cycle CO_2 emission coefficient reduces to 7.9 g CO_2/kW.h and the share of enrichment process becomes only 6.7%.

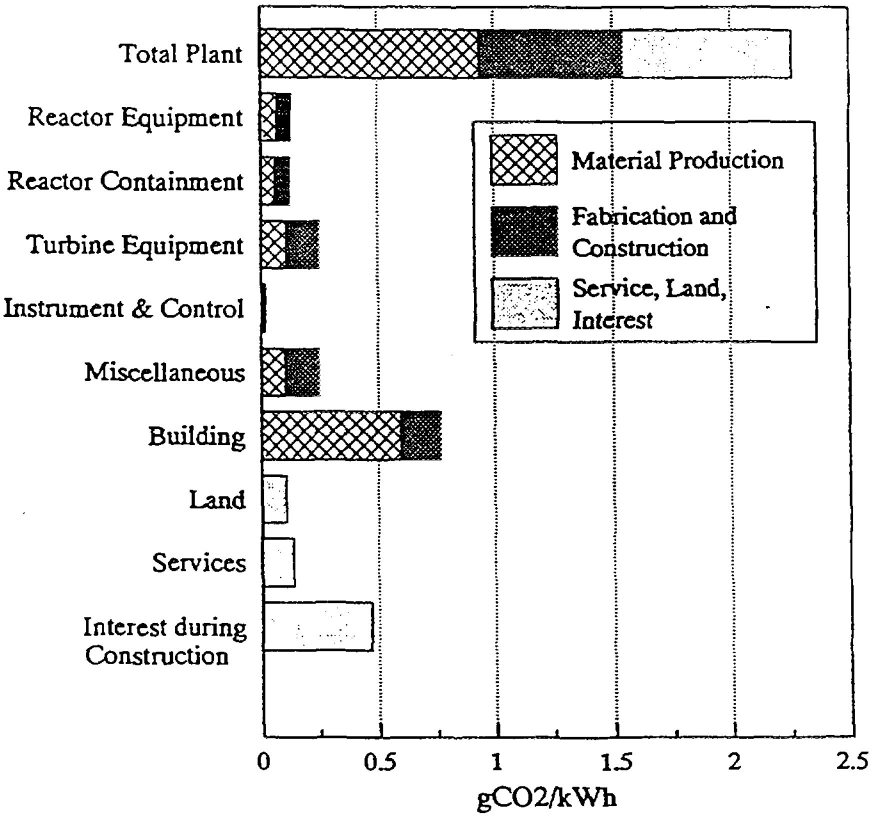

Fig.8. Indirect CO_2 emissions per component of a 1100 MWe PWR nuclear power plant.

5. CONCLUSIONS

The integration of the indirect processes into the direct processes has been explained by using the engineering model MARKAL as an example. However, indirect processes involve various kinds of engineering processes such as production of materials, fabrication, distribution, and waste disposal of goods. Using I/O data bases for deriving the effects associated with indirect processes allows to integrate indirect processes which are not part of the actual engineering processes.

In order to investigate the impacts from material substitution as well as from technology progress in the life cycle analysis, an appropriate method must be developed, which should be an engineering-economy linkage model. Such a model should handle material production, equipment fabrication, waste disposal, etc., through technology responses associated with demand and supply of capital goods and consumer goods. The MARKAL-MACRO and MARKAL-MACROEM models could be improved for the integration of the direct and indirect processes.

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