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CO_2 EMISSIONS OF NUCLEAR ELECTRICITY GENERATION

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ABSTRACT

A survey of LCA studies on nuclear electricity generation revealed life cycle CO_2 emissions ranging between 3 g/kWh$_e$ to 60 g/kWh$_e$ and above. Firstly, this paper points out the discrepancies in studies by estimating the CO_2 emissions of nuclear power generation. Secondly, the paper sets out to provide critical review of future developments of the fuel cycle for light water reactors and illustrates the impact of uncertainties on the specific CO_2 emissions of nuclear electricity generation. Each step in the fuel cycle will be considered and with regard to the CO_2 emissions analysed. Thereby different assumptions and uncertainty levels are determined for the nuclear fuel cycle. With the impacts of low uranium ore grades for mining and milling as well as higher burn-up rates future fuel characteristics are considered. Sensitivity analyses are performed for all fuel processing steps, for different technical specifications of light water reactors as well as for further external frame conditions.

1 INTRODUCTION

Due to growing concerns over anthropogenic climate change, which are strengthened by the latest report of the IPCC (Intergovernmental Panel on Climate Change), political, social and scientific institutions postulate an increasing deployment of nuclear power in order to minimize the release of greenhouse gas emissions. Therefore, an appropriate understanding of the life cycle carbon dioxide (CO_2) emissions of nuclear power is required.

Despite relatively high capital and disposal costs nuclear energy is, at many places, competitive to fossil fuels for electricity generation, [1], [2]. Concerning CO_2 emissions several life cycle assessment (LCA) studies have been carried out worldwide, which revealed CO_2 emissions of nuclear power generation to be in a range of 3 to 15 g CO_2/kWh$_e$. This constitutes about one per cent of the CO_2 life cycle emissions of coal-fired power plants [3], [4], [5].

In recently published studies [6], [7], [8] authors argument that by a global extension of nuclear power capacity, the life cycle CO_2 emissions of this technology will increase significantly. In their opinion, this effect will considerably decrease the potential of reducing global greenhouse gas emissions by using nuclear power. Their results are based on the assumption that CO_2 emissions from nuclear power will steadily rise, e.g. due to growing energy expenditures for both uranium preparation and extraction of uranium from very low-grade ores in new mines.

Starting from previous LCA studies of the Institute of Energy Economics and the Rationale Use of Energy (IER), University Stuttgart, on different electricity generation technologies [9], [10], [11] this paper examines the impact of future developments within the nuclear fuel cycle on life cycle CO_2 emissions of the electricity generation in Light Water Reactors (LWR`s).

In this study the approach of Process Chain Analysis (PCA) is applied and the latest available data are used. Objective of the paper is to reveal the sensitive steps of the nuclear process chain in regard to their CO_2 emissions and to display the results in a high disaggregated form.

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2 METHODOLOGY

In LCA, the objective is to investigate the environmental impacts of all life cycle phases, which are involved with the manufacturing or generation of a product (i. e. from cradle to grave). LCA constitutes a tool which allows to assess the environmental performance of a product and to pin-point sources of environmental pollution arising from upstream and downstream processes.

An LCA on greenhouse gas (GHG) emissions provides information on the origin of these emissions and the contribution of individual processes along the life cycle. Such information is intended to provide support for strategic decisions of policy makers and stakeholders. Since this study has its focus on GHG emissions it has to be mentioned that the analysis of the contributing emissions into air illustrate only part of the environmental performance of nuclear electricity generation. Other aspects, which are usually covered by an LCA, namely acidification, eutrophication, stratospheric ozone depletion, land use, resource depletion of the investigated product system, are not analysed in this study.

In LCA studies all results on material and resource demand as well as on emissions are referred to the functional unit of the investigated product system, which in case of electricity generation commonly is one kilowatt hour (1 kWh_{el}) of busbar electricity. In this study solely carbon dioxide emissions are analysed, which are expressed in g CO_2/kWh_{el} for all life cycle phases of the electricity generation process listed below (in brackets the reference to the typical stages of the nuclear fuel cycle is given) [12]. According to the LCA approach, CO_2 emissions arising from the use of infrastructure and operating supplies are accounted for along all life cycle phases:

- Exploration and extraction of natural energy resources (uranium mining)
- Processing of the extracted raw materials (preparation and conversion of uranium)
- Further production steps (uranium enrichment and fuel fabrication)
- Construction of the nuclear power plant
- Power plant operation (nuclear electricity generation)
- Waste management during operation (once through versus reprocessing of used fuel elements)
- Dismantling of the nuclear power plant
- Transport processes during and between the individual life cycle phases

In general two different LCA approaches can be distinguished, which is the process chain analysis (PCA) according to ISO 14040 ff on the one hand and the input/output (I/O) analysis on the other hand. A combination of both methodologies constitutes the so called hybrid LCA [13]. This hybrid LCA has been applied within several studies of the IER Stuttgart. The methodology used in this study, however, is the process chain analysis (PCA).

The process chain analysis is a vertical bottom-up approach [14]. This technique aims at picturing the investigated production system by a chain of single, successively conducted processes. For these processes the involved material and energy demand as well as the release of these processes are surveyed. Since such a survey comprises huge amounts of data to be collected and analysed, commonly cut off-critera are defined, which exclude these processes or flows from the survey that are expected to only negligibly contribute to the overall results. As result of this cutting of some small material and energy flows as well as emissions PCA studies always underestimate the real conditions of the investigated product system.

The input/output LCA constitutes a top-down approach, which obtains central information from input/output tables. Input/output tables represent statistical surveys within the national economy, which provide data on the economic performance as well as on the energy and material demand within different economic sectors. When these tables are coupled to tables from environmental accounting that list sectoral release of emissions into air, the environmental performance of average products from individual sectors can be derived. The input/output approach distributes the processes of the investigated product system to the different economic sectors and derives the average environmental performance from the mentioned statistical information. This approach covers the entire economy and

avoids cut-off criteria, however, it goes in line with some inaccuracy due to the use of statistical information and a very rough categorization of processes.

The hybrid LCA approach combines the PCA and input/output methodology. In a hybrid LCA statistical information is used to firstly complement processes lacking data and secondly derive data for processes, which have been excluded from the product system due to cut-off criteria. This methodology promises further improvement of the LCA results to fully comprise an investigated product system, but at the same time causes new inaccuracy. The derivation of statistical information from input/output tables requires the considered processes to be monetarised. In order to achieve this monetarisation all balanced energy and material flows are valued by market prices and subsequently subtracted from the price of the belonging processes. This monetarisation is involved with some uncertainty and comes along with possible double-counting. Some material flows will be accounted for by both the PCA approach and within the statistical information from input/output tables. The application of the hybrid methodology thus is adequate for sectoral studies with clear correspondence of the processes to the economic sectors in the input/output tables.

The most exact, but also most laborious LCA approach constitutes the PCA approach. Since this study aims at a detailed analysis of the individual life cycle phases of especially the nuclear fuel cycle, the PCA approach has been chosen. At this approach, the inaccuracy by cut-off criteria becomes more and more reduced by the continuous development and improvement of LCI background databases, as for instance the EcoInvent database [15], which is used in this study.

3 CHARACTERISATION OF THE REFERENCE PROCESS CHAIN

The nuclear fuel cycle represents a complex system with different components and activities. A typical nuclear fuel chain consists of uranium mining (open pit and underground), milling, uranium preparation, conversion, enrichment (diffusion and centrifuge), fuel fabrication, power plant, (reprocessing), conditioning of spent fuel, interim storage of radioactive waste and final disposal. For each of the process steps, the material and energy requirements as well as the released emissions are calculated. For estimating CO_2 emissions of the the nuclear fuel cycle according to ISO 14040 ff the background database of EcoInvent (version 1.2) [15] is applied on the one hand and the results of own calculations for burn-up and enrichment on the other hand. The reference process chain for Germany is based on two categories of mines. The underground mine with an average ore grade of about 0,172 % U_3O_8 and the open pit mine with an average ore grade of about 0,127 % U_3O_8. Both uranium mines are representative for actual mines in operation. In comparison to other open-pit and underground mines our reference mines produce solely uranium. In the reference chain, underground mines supply 48 % and open-pit mines supply 52 % of the uranium demand.

It is important to emphasize that an in-situ leaching is not considered, which is relevant for uranium production in sand-stone deposits. Since 2002, the amount of in-situ leaching increases from 15 % of the uranium world productions to 19 % in 2005. The increase in in-situ leaching since 2002 resulted from extended production in Australia, Kazakhstan and Uzbekistan. Whereas, in particular the increasing demand of natural uranium of the Russian Federation will be supplied by Kazakhstan and Uzbekistan in-situ mines. However, if in the LCA uranium production in-situ leaching is considered, it can be assumed that the total LCA energy expenditures of the uranium mine would be reduced. Therefore, the CO_2 emissions will also decrease.

For the next process steps of the nuclear fuel cycle, uranium milling, preparation and the conversion to uranium hexafluoride (UF_6) the materials loss for each process step is 5 %. Currently, the process of enriching the U_{235} content up to 3 - 5 % is carried out by utilizing two enrichment technologies, gaseous diffusion and centrifugation. At first the gaseous diffusion was developed, in which UF_6 gas is pumped through a series of diffusion membranes. The lighter U_{235} passes through the porous walls of the diffusion vessels slightly faster than U_{238}, resulting in a higher concentration of U_{235} in product assay. The centrifuge technology is a more recent technology in which uranium hexafluoride (UF_6) gas is spun at high speed in a series of centrifuges. This yields to force the heavier U_{238} isotope closer to the outer wall of the centrifuges, leaving a higher concentration of U_{235} in the centre of each centrifuge. Although the capacity of a single centrifuge is smaller than that of a single diffusion stage, its capability to separate isotopes is greater. Centrifuge stages normally consist of a

large number of centrifuges in parallel and gaseous diffusion in cascades. The centrifugation only requires electrical energy for the rotation of the cylinders, and some heat in order to maintain an axial convention of UF_6 [16]. The gaseous diffusion technology is significant more energy intensive than the centrifugation technique. The electricity intensity of gaseous diffusion is about 50 times higher than of the centrifugation technique, which contributes significant (due to the background CO_2 emissions of the electricity mixture) to the front-end nuclear fuel cycle LCA CO_2 emissions.

In the case of Germany, we assumed that 95 % of the separative work is furnished by centrifugations and 5 % by gaseous diffusion plants. The required separative work unit accounts for the enrichment of a fuel element with 4,2 % U_{235} and a Tails-Assay of 0,3 % to 5,7 kg SWU/kg U. The equilibrium fuel composition during the operational phase of the pressurized water reactor is 4,2 % U_{235}, therefore the average burn-up of the fuel element amounts 53,5 MWd_{th}/kg U. For analysing the milling, conversion and enrichment plant the infrastructure data of EcoInvent was used. For electricity inputs needed for the LCA modules the European electricity mix UCTE was applied.

All reactor data for the pressurized water reactor (1000 MW_{el}) are derived from the EcoInvent database [15]. Further, it is assumed a net efficiency of 33 % and a reactor operating time of 40 years. With regard to the disposal of the nuclear waste solely the once-through concept is considered.

Table 1 summaries the main characteristics of the reference process chain

Table 1: Main characteristics of the reference process chain

Process step	Characterisation
Uranium mining	Open-pit mine (0,172 % U_3O_8) Underground mine (0,127 % U_3O_8)
Uranium preparation	Natural uranium into U_3O_8
Conversion	U_3O_8 into UF_6
Enrichment	Gaseous Diffusion Gaseous Centrifugation
Fuel fabrication	Fuel elements for a PWR
Nuclear Power Plant	Pressurized Water Reactor (PWR), Net-Power: 1000 MW_{el} Net-efficiency: 33,0 % Lifetime: 40 years
Conditioning	Conditioning for long term storage
Final repository	Disposal of LLW, ILW, HLW

4 RESULTS

4.1 Reference process chain

The development of the LCA in according to the PCA results that along with the life cycle of the reference process chain 6,82 g CO_2/kWh_{el} have been emitted.

Figure 1 presents the distribution of the specific CO_2 emissions during the reference process chain. In regard to the reference process chain, the LCA CO_2 emissions from construction of the nuclear power plant are the most important contributor and amounts 2,00 g CO_2/kWh_{el}. The estimates of the CO_2 emissions from constructing the power plants are mainly based on the steel and concrete materials and their following background processes. After that, the process steps of the front end of the nuclear fuel cycle follow: uranium preparation (1,37 g CO_2/kWh_{el}), conversion (1,18 g CO_2/kWh_{el}) and uranium enrichment (1,03 g CO_2/kWh_{el}). For the back-end of the fuel cycle (dismantling the nuclear power plant, conditioning and repository) the LCA CO_2 emissions are low and contribute only 0,69 g CO_2/kWh_{el} (accumulated). In general, Germany´s reference process chain of the nuclear fuel cycle is not comparable to other countries baselines due to the high amount of the centrifugation (95 %) enrichment technique. The deployment of the centrifugation and their following grid-emissions factor reduce the CO_2 emissions significantly.

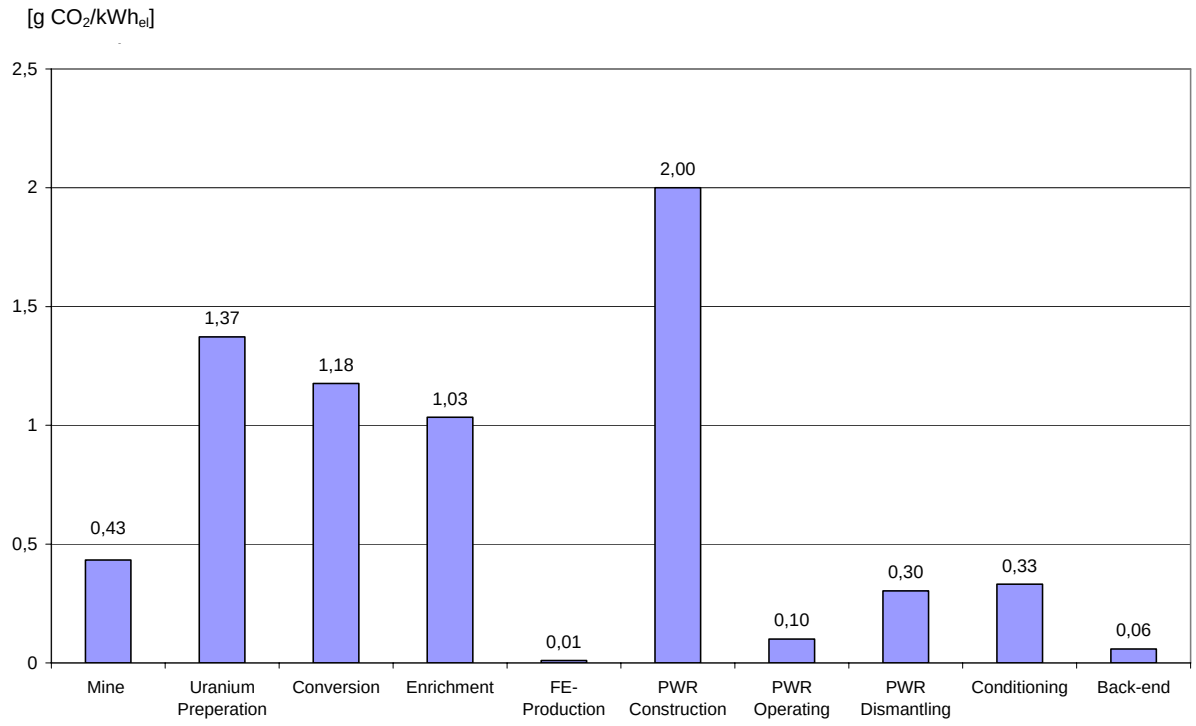

Figure 1: Estimates of the CO_2 emissions from the reference chain of Germany.

4.2 Sensitivity analysis

A sensitivity analysis has been conducted in order to verify their effect of parameter variations on the reference chain results. According to the reference chain numerous parameter were varied and in a sensitivity analysis new considered.

The following alternatives were carried out:

- Insertion of fuel elements with a higher and a lower burn-up (A and B)
- Operating time of nuclear power plant (C)
- Variation of the amount of centrifugation and gaseous diffusion (D)
- Ore-grade of the uranium mine (E and F)
- Choice of the background electricity mix (G)

Figure 2 presents the results of the LCA CO_2 emissions of the alternatives according to the schedule (A-G).

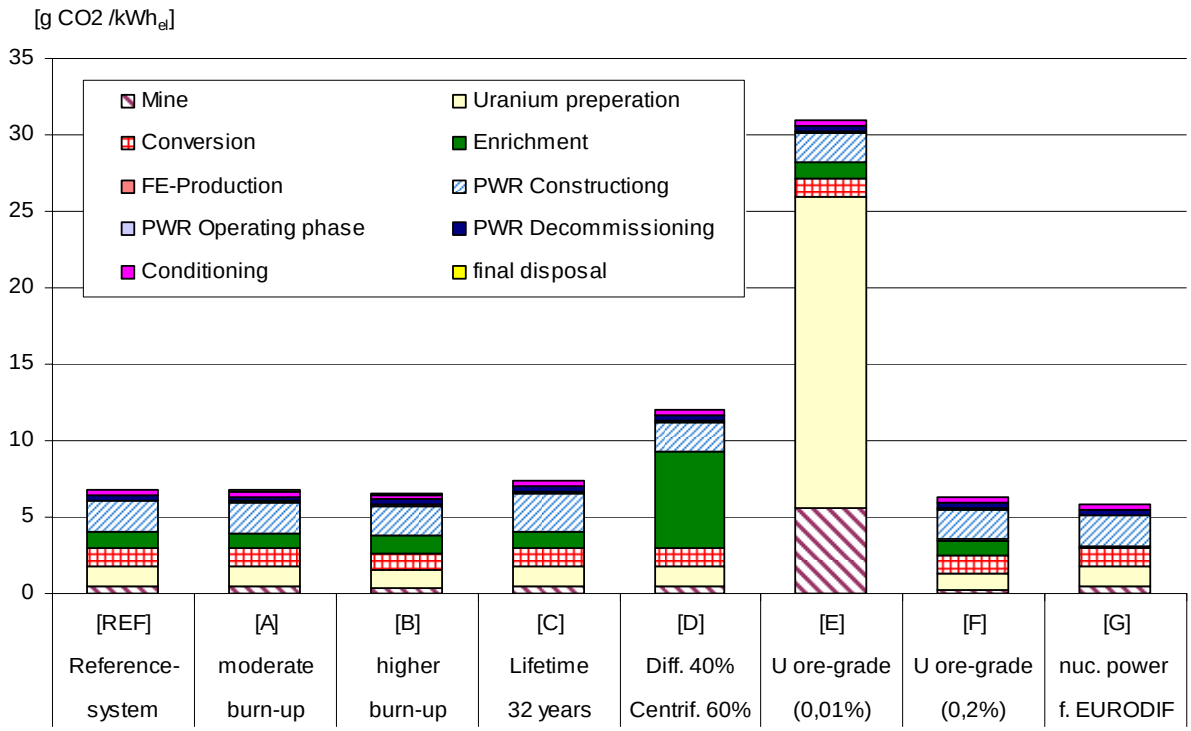

Figure 2: Estimates of the CO_2 emissions of alternative (A-G) fuel cycle characteristics in comparison to the reference process chain (REF) for Germany.

Differences in the CO_2 emissions of the nuclear energy chain can be influenced by fuel element parameters (burn-up), as well as enrichment parameters (grade of enrichment, tails-assay). For example, in alternative A the assumed burn-up of the fuel elements decreases from 53,5 MWd_{th}/kg U in the reference chain (REF) to 45,6 MWd_{th}/kg U, which was the average burn-up of spent fuel elements pressurized water reactors in Germany 2005. The required separative work is equal to the reference process chain and the energy output (burn-up) of the fuel element is about 15 % lower than in the reference process chain. That results in higher CO_2 emissions (8,12 g CO_2/kWh_{el}).

The life cycle CO_2 emissions per kWh_{el} are reduced of about 5 % (6,50 g CO_2/kWh_{el}) compared to the reference process chain, if a fuel element is inserted with a higher burn-up (63,7 MWd_{th}/kg U versus 53,5 MWd_{th}/kg U in REF) and upgraded fuel parameters (enrichment product assay: 4,8 % U_{235} versus 4,2 % U_{235} in REF; tails-assay: 0,25 % versus 0,30 % in REF).

Another important parameter is the operating lifetime of the reactor (alternative C). In Germany, the present nuclear law calls for the closure of all reactors by the 2020s, subject to a limit on total nuclear electricity generation. In line with this, the average lifetime of all the reactors is about 32 years. Unlike the lifetime of 40 years, according the original technical lifetime, the specific CO_2 emissions of the reactor (construction and dismantling) increase up to 25 %. The entire CO_2 emissions of alternative C amounts 7,40 g CO_2/kWh_{el}.

Although Germans enriched uranium is nearly completely provided by centrifugation technique, in alternative D it is assumed, that 40 % of the separative work will be enriched by the up to 50 times more energy-intensive diffusion technique (reference process chain: 5 % diffusion). The life-cycle CO_2 emissions increase of up to 12,00 g CO_2/kWh_{el}.

In figure 2, the two following columns (alternatives E and F) present the life-cycle CO_2 emissions by different uranium concentrations in the ore. The energy demand for mining and milling from ores increases with its decreasing concentration. In future the ore-grade of uranium deposits will be in the range of 0,01 % to 0,2 %. However, it could be expected that more uranium mines will go in

operation with lower uranium grades. But also in future uranium will be produced in mines with an ore grade above 0,2 %. The expected minimum ore-grade in uranium will be 0,01 % in future. For example, uranium mining with an ore grade of 0,01 % (REF: open-pit 0,172 % U_3O_8 and underground 0,127 % U_3O_8) leads to an increased energy demand for mining and preparation and to cumulative higher emissions of CO_2 (30,96 g CO_2/kWh_{el}). In comparison to the life-cycle CO_2 emissions of the reference process chain their CO_2 emission rise up to a factor of four to five.

The last alternative analysis of the reference fuel cycle estimates the sensitivity of the life-cycle emissions by various background electricity mixtures for all the processing steps. In the case of alternative G the diffusion enrichment plant is directly supplied by nuclear power. This single variation of the background process results in a reduction of the cumulative life-cycle CO_2 emissions from 1 g CO_2/kWh_{el} to 5,86 g CO_2/kWh_{el}. However, if all required electricity in the entire fuel cycle will be produced by nuclear power, the specific CO_2 emissions amounts only 5,50 g CO_2/kWh_{el}.

5 CLASSIFICATION OF THE RESULTS

The results of the reference process chain and the alternatives A – G show that the life-cycle CO_2 emissions of nuclear power ranging between 6 – 12 g CO_2/kWh_{el}. The restrictive-case alternative E assumes a high energy intensity of the nuclear fuel preparation and high CO_2-intensity. This results to specific CO_2 emissions of 31 g CO_2/kWh_{el}.

In table 2 studies are summarized which have investigated the CO_2 life-cycle emission for nuclear power according to ISO 14040 ff. It can be identified that the results of this study (reference process chain: 6,82 g CO_2/kWh_{el}) are within the range of the other studies. In [5] the low burn-up level may be due to the enrichment of only 3 % U_{235}.

Table 2: CO_2 emissions of the nuclear power system of available studies which are calculated with the PCA approach according ISO 14040 ff

Reference	**Reactor Power**	**Operating time Reactor**	**CO_2**	**Comment**
	[MW_{el}]	[Years]	[g CO_2/kWh_{el}]	
[4]	1030	40	3,27	35 % of the CO_2 emissions from uranium mining/milling and uranium preparation Uranium production: 42 % open-pit (0,03 % U_3O_8), 37 % underground (0,06 % U_3O_8), 21 % in-situ leaching Enrichment: 80 % centrifugation
[3]	625	40	5,05	36 % of the CO_2 emissions from uranium mining/milling and uranium preparation Enrichment: 100 % centrifugation
[17]	1000	40	8,88	26 % of the CO_2 emissions from uranium mining/milling and uranium preparation Enrichment: 10 % centrifugation Electricity mix: Swiss
[18]	1000	40	10,70	60 % of the CO_2 emissions from uranium enrichment Enrichment: 76 % centrifugation Electricity mix: German Using of MOX-Fuel elements
[5]	1000	30	15,00	59 % of the CO_2 emissions from uranium preparation, 3 % mining, 3 % enrichment Enrichment: 100 % centrifugation

In comparison to the cumulative emissions of 16,00 g CO_2/kWh_{el} and 15,90 g CO_2/kWh_{el} in previous LCA studies of the IER the emissions of this study are significant under this results. The CO_2

emissions estimated here reflect the results of a PCA. The difference to [10] is caused by the different LCA approaches. Basically, the hybrid approach provides higher LCA results for emissions and materials requirement. The results in [11] can disaggregated into 6,28 g CO_2/kWh_{el} from the monetize valuation and in 9,63 g CO_2/kWh_{el} from material and energy analysis. These results show, that this PCA study is in good correlation with the amount of the PCA in [11].

Thus, further investigations are necessary to confirm the projected results of the sensitivity analysis. For example, the increasing demand of uranium has significant effects of the distribution of future uranium production centers and methods. Production mines which using in-situ leaching are expected to increase in future. There is currently no database for in-situ leaching at a level available that could be used in a LCA. Around 10 to 15 % of the current produced uranium is mined as co-product/by-product. By mining uranium as co-product/by-product it is difficult to disaggregate the share of materials- and energy expenditures from the other crude materials (mostly copper and gold). Beyond this, emissions must also be proportional disaggregated.

A further important parameter is the enrichment of uranium. It could be expected that in future the gaseous diffusion plants will be displaced by centrifugation plants. When the diffusion technology is totally displaced by centrifugation, the life cycle CO_2 emissions would be much lower.

In the case of reprocessing the requirement for natural uranium will be reduced to 10 – 20 %. On the one hand this leads to lower CO_2 emissions by the uranium mining and on the other hand to significant reductions in the other front-end steps of the fuel cycle. A background electricity mixture with low carbon intensity could decrease the CO_2 emissions of the nuclear fuel cycle up to 20 %. Future light water reactor concepts with a higher efficiency and a higher net electricity power can also contribute to a reduction in CO_2 emissions. Far better, CO_2 emissions can be decreased by using advanced reactor designs which have significant higher burn-up rates. This advanced reactor designs could be fast neutron reactors or high converters. Such reactors are more efficient at converting fertile material than ordinary thermal reactors because of the arrangement of fissile and fertile materials. Fast neutron reactors can utilise uranium at least 60 times more efficiently than a normal reactor, which leads to substantial lower material and energy expenditures during the nuclear process chain. A high converter has the potential to enhance the uranium utilization by a factor of four.

6 CONCLUSIONS

The sensitivity analysis illustrate that uncertainties in the grade of the uranium ore and the enrichment technique have major influence on the results. The result for the process chain analysis of the typical German nuclear fuel cycle is 7 g CO_2/kWh_{el}. In future, uranium with lower ore grades will increase the specific CO_2 emissions. On the other hand a more efficient utilization of the fissile and fertile materials will decrease the fuel consumption. However, advanced reactor concepts are not analysed in this study. Therefore, improvements of the fuel utilization in new reactor designs will reduce the specific CO_2 emissions of the nuclear substantial.

The effect of uranium with low-grade on CO_2 emissions is negligible in contrast to emissions of fossil power systems.

From a CO_2 (GHG) emission perspective nuclear power plants are very attractive since they have a huge GHG life-cycle reduction potential.

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