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FISSION OR FOSSIL?

A Comparative Hybrid Life Cycle Assessment of Two Different Hydrogen Production Methods

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FOREWORD

Working with the thesis has been an interesting and exciting experience; a process of many ups and downs. I have received a lot of hints, tips, comments, advice and moral support from friends, colleagues and others. I would like to thank the following persons for their help and support:

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SAMMENDRAG

Det har blitt gjennomført en komparativ hybrid livsløpsanalyse av to ulike metoder for hydrogenproduksjon. Produksjon av hydrogen fra termokjemisk vannsplitting med kjernekraft har blitt sammenliknet med hydrogenproduksjon fra naturgassreformering med CO_2-fjerning. Resultatene viser at de to metodene har til dels svært forskjellige miljøpåvirkninger. Kjernekraftalternativet har lavere påvirkning på globalt oppvarmingspotensial, forsuring og eutrofiering, men til dels meget høyere verdier for andre påvirkningskategorier. Det har imidlertid ikke blitt gjort noen vektingsprosedyre på resultatene, og det vil ikke kåres en "vinner". De ulike miljøpåvirkningenes relative betydning forblir dermed en utfordring for eventuelle beslutningstakere.

Videre har analysen vist viktigheten av å inkludere økonomiske inputs i en komparativ analyse; ordinær prosess-LCA kan slå skjevt ut ved at en relativt større andel av miljøbelastningene kan bli telt med for et case enn for et annet.

Et annet analytisk funn er at å unngå dobbeltelling av material-inputs i input-output delen av analysen kan ha stor innvirkning på resultatene for enkelte påvirkningskategorier. En prosedyre for å unngå dobbeltelling bør derfor alltid gjennomføres når man utfører en hybrid-LCA.

SUMMARY

A comparative hybrid life cycle assessment was conducted to assess two different methods for hydrogen production. Environmental impacts from nuclear assisted thermochemical water splitting are compared to hydrogen production from natural gas steam reforming with CO_2-sequestration. The results show that the two methods have significantly different impacts. The nuclear alternative has lower impacts on global warming potential, acidification and eutrophication, but very much higher for some of the other impact categories. A weighting procedure is not applied, hence no overall "winner" can be proclaimed. The different impacts relative importance remains a challenge for eventual decision makers.

Further the assessment has demonstrated the importance of including economic inputs in a comparative assessment; ordinary process-LCA may produce distorted results since a larger fraction of impacts can be accounted for in one case than in another.

Another analytical finding is that avoiding double counting of material inputs in the input-output part of the assessment, significantly affects the results of some impact categories. A procedure to avoid double counting should therefore always be applied when performing a hybrid LCA.

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1. INTRODUCTION

1.1 Background

Hydrogen is currently being promoted as a possible future energy carrier. It provides the opportunity for high efficiency conversion to electricity in a fuel cell without corresponding emissions to air except from water vapor. In light of a growing fear of the environmental consequences from the release of greenhouse gases this favors its use in applications such as the transport sector. Hydrogen is not an energy source, it does not occur naturally in great proportions, and has to be produced from primary energy sources. For hydrogen to be environmentally preferable as an energy carrier, it therefore has to be *produced* in such a manner that the total environmental repercussions is lower than those of other energy carriers such as gasoline. Hydrogen can be produced from fossil fuels, biomass and splitting of water. Several publications provide comprehensive reviews of hydrogen production methods [1, 2, 3]. Two candidates for large-scale production of hydrogen in the near future are nuclear assisted thermochemical water splitting and natural gas steam reforming. They may both serve as hydrogen producing technologies in the transition to a hydrogen fueled future, even though, of course, long term hydrogen production will have to be based on renewables due to exhaustion of fossil resources. It is therefore interesting to investigate their relative environmental performance to gain a better understanding of the possible roads to the hydrogen society.

A comparative hybrid life cycle assessment (LCA) was conducted to assess the environmental performance of two such systems and to highlight differences in their ecological profile. This method combines the strengths of ordinary LCA-methodology and economic input-output analysis. For the production of hydrogen by natural gas reforming, inventory data from a study performed by Anders Strømman [4] was used as basis for the environmental assessment. The major part of the work in this thesis has therefore consisted of establishing an inventory for a hydrogen producing nuclear system, and performing a comparative environmental assessment on the basis of the two inventories. Chapter 2 provides the reader with the necessary background theory for the assessment, including Life Cycle Assessment (LCA) methodology. Advantages of applying a hybrid approach and include economic inputs to processes, and the computational basis for the assessment are treated in detail. Chapter 3 provides an overview of the

nuclear system considered, including choices and assumptions made during the inventory-phase of the assessment. A summary of the inventory is presented, while the more detailed assumptions and data used to calculate it are presented i annex A. The results of the impact assessment are presented in chapter 4. This chapter also includes a more detailed assessment of the nuclear system. Discussions and conclusions are located to chapter 5.

2. METHODOLOGY

2.1 Life cycle assessment

Life cycle assessment (LCA) is an analytic tool developed for assessing the environmental impacts of a product or service throughout its entire life cycle, from resource extraction to final disposal. The idea behind such an approach is that the total environmental performance cannot be assessed by studying only processes, one has to see those processes as part of a system fulfilling one or more functions. By applying a life cycle approach one is able to assess possible shifting of environmental impacts from one part of a system to another or from one *type* of impact to another.

LCA is formalized in the International Organization for Standardization standards 14040-43 [5, 6, 7, 8]. The framework of an LCA can be summarized as follows [5]:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

and is to be interpreted as an iterative process where the different phases may be reconsidered or redefined on the basis of findings in a later phase. The following chapters will describe these phases in more detail.

2.1.1 Goal and scope definition

In this part of the study, the importance of stating the intended applications of the analysis and to whom it is to be communicated is emphasized in ISO 14040 [5]. This stage should also clearly state the function(s) of the system, and define a *functional unit* that the system can provide and that will be the basis for the assessment. The functional unit is an expression for the function that the system fulfill. As an example one could see the function of a car as providing a certain transport need i.e. the car is not a function *per se*.

Further an overview of the system should be presented, including drawing *system*

boundaries that define the degree of detail in the inventory analysis. This involves making choices about which activities in the system to include or exclude from analysis [6]. A choice of leaving all capital equipment out of the analysis may for example be a way of significantly reducing the data needs in the inventory analysis, but it should of course be noted that important parts of the system may be left out.

It is convenient to separate the system into *unit processes*, each described with inputs and outputs to other unit processes and the *environmental flows* (i.e. raw materials and emissions) arising from one unit of output from the process.

All omissions of processes and inputs/outputs must further be clearly stated and justified [6]. The scope and system boundaries will often be based on the goal and purpose of the study (e.g. company-internal product comparison will often have a different scope than an LCA that is intended for use in policy decisions). A major problem concerning this is excellently demonstrated by the sentence "Resources need not be spent on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study" in ISO 14041 [6]. The problem is that these inputs and outputs are unknown and their impacts not yet assessed. You don't actually know what is left out. This presents one of the dilemmas when performing LCAs, the problem of knowing in which detail the analysis should be conducted. A possible way to deal with such problems is presented in chapters 2.2 and 2.3.

The scope of the study is likely to be altered by findings later in the assessment as LCA is an iterative procedure and choices regarding the scope and system boundaries are often made and altered for pragmatic reasons.

2.1.2 Inventory analysis

The inventory stage of an LCA is the implementation of the data collection plan derived during goal and scope definition. The unit processes chosen to be included should be described in more detail and the methods for collecting or calculating data for the processes should be documented [6]. The data collection may consist of collecting process-specific data directly by measurements, collecting data from literature sources or calculating data by modelling of the process. Often a combination of these techniques is required to obtain the desired set of inputs and outputs from the unit processes. If unit processes has multiple inputs or product outputs allocation procedures or other techniques can be used to assign environmental inputs and -outputs to the product output under study. There is also a number of LCA-databases that contain life cycle data for a number of generic processes (e.g. steel production, electricity generation by source or country etc.).

Some of these will be used in this assessment and are mentioned in chapter 3.

The results from the initial inventory analysis may alter the system boundaries on the basis of sensitivity analysis. Processes may be omitted from the system, while new processes may be included.

2.1.3 Impact assessment

The impact assessment (LCIA) is in short a quantification of the environmental stress the environmental inputs and outputs obtained in the inventory phase causes. ISO 14042 [7] divides this procedure into several steps described in the following sections.

Selection of impact categories

The selection of impact categories is the first step of LCIA. It should be consistent with the goal and scope of the study i.e. if the goal of the study is to provide life cycle greenhouse gas emissions of a system, only a category of global warming potential should be applied. This will of course inhibit the ability to assess shifts in environmental impacts, and the natural approach would therefore be to include as many impact categories as possible at least in comparative studies. The inclusion may be limited by lack of existing classification and characterization methods for some impact categories, and new methods will have to be developed to include these.

Classification

After selecting impact categories all (if possible) environmental inputs and -outputs from the inventory analysis should be assigned as contributors to one or more of these. Some outputs may only affect one impact category while others may contribute to a whole range of them.

Characterization

When all inputs and outputs are assigned to impact categories, a quantification of their contribution to these has to be done. This is called characterization and calculates the impacts of different environmental flows to a common indicator unit in the impact categories. It is normally done by using pre-developed *characterization factors*. The calculation of such factors vary between impact categories i.e. the characterization factors for an impact category like *"Global Warming potential"* are derived in a different way than those of a category as *"Human Toxicity Potential"*. The impact categories may be either mid- or end-point indicators [9] reflecting at what point of the so-called *impact chain* they are. Midpoint indicators refer to the intervention of an environmental area such

as global warming, while endpoint indicators reflect the actual value lost of these interventions e.g. crop damage from increased temperature. Assumptions and value choices made in the production of the factors should be clearly stated in the assessment method [7]. Such choices may regard time-horizon of the impacts, dose-response relationships or the flow of a chemical substance in the environment. There is a number of pre-developed impact assessment methods; those used in this assessment are discussed in chapter 4.

Normalization, grouping and weighting (optional)

Normalization, grouping and weighting are all optional elements of an LCA according to ISO 14042 [7], and will not be described or used in this assessment.

2.1.4 Interpretation

Consistency with goal and scope of the study is regarded a main issue in ISO 14043 [8] when interpreting the results of an LCA. This means that conclusions should be drawn keeping in mind what was the initial purpose of performing the assessment, since this purpose has an influence on the following phases in the study.

2.2 Environmental input-output analysis

Another way to determine system-wide environmental flows is to combine economic input-output analysis with environmental data on the different economic sectors of the economy. This approach was first introduced by Wassily Leontief in 1970 [10]. The idea is that a given demand of commodities from an economic sector will induce economic activity in other sectors. If it is possible to calculate the total induced economic activity from a given demand, one could combine these results with environmental data of the sectors in the economy to produce total inventories for a given demand. The methodology is further developed since 1970; the following introduction to basic economic input-output analysis adapted from the United Nations [11].

First it is convenient to establish the nomenclature to be used in the calculations, this is given in table 2.1. National statistics provide intermediate make- and use tables at different levels of aggregation. From these tables the intermediate make and -use matrices are derived through some manipulation to obtain the same dimensions.

Matrices **B, C** and **D** can be constructed through the calculations in table 2.1. Two different assumptions can be used to derive a matrix **A** that describe the economic flows between industries or commodities; the *industry technology-* and *com-*

Tab. 2.1: Basic nomenclature for the Make- and Use framework

Nomenclature	Name	Explanation
^{T}		The transpose of a matrix
$\hat{}$		The diagonalized vector
$^{-1}$		The matrix inverse
m		Number of products
n		Number of industries
$\mathbf{i}_m$		Vector with all m elements=1
$\mathbf{i}_n$		Vector with all n elements=1
$\mathbf{U}_{m,n}$	Intermediate Use matrix	Derived from national statistics
$\mathbf{M}_{m,n}$	Intermediate- and final Make matrix	Derived from national statistics
$\mathbf{q}_m$=$\mathbf{M}\cdot\mathbf{i}_m$	Product intermediate- and final output vector	
$\mathbf{g}_n$=$\mathbf{M}^T\cdot\mathbf{i}_n$	Industry intermediate- and final output vector	
$\mathbf{B}_{m,n}$=$\mathbf{U}\cdot\hat{\mathbf{g}}^{-1}$	Intermediate input structure matrix	
$\mathbf{C}_{m,n}$=$\mathbf{M}\cdot\hat{\mathbf{g}}^{-1}$	Output structure matrix	
$\mathbf{D}_{n,m}$=$\mathbf{M}^T\cdot\hat{\mathbf{q}}^{-1}$	Market share matrix	

modity technology assumptions respectively. The industry technology assumption says that all commodities produced by an industry is produced with the same input structure i.e. with the same technology. In the same way the commodity technology assumption says that all commodities of one type are produced with the same input structure regardless of which industry that produce them. Under the industry technology assumption, the matrix $\mathbf{A}$ is derived through equations 2.1 and 2.2:

$$\mathbf{A}_{IO(ii)} = \mathbf{D}\cdot\mathbf{B} \tag{2.1}$$

$$\mathbf{A}_{IO(cc)} = \mathbf{B}\cdot\mathbf{D} \tag{2.2}$$

$\mathbf{A}_{IO(ii)}$ describes the economic inputs to different industrial sectors in the economy on the basis of one unit economic output. The same interpretation goes for $\mathbf{A}_{IO(cc)}$, the only difference being that it describes inputs to commodity-groups instead of industrial sectors. The total, industry-wide, demand for commodities or industrial activity arising from a given final demand described by vector $\mathbf{y}$, can then be calculated by equation 2.3.

$$\mathbf{A}_{IO}\cdot\mathbf{x}+\mathbf{y}=\mathbf{x}\Leftrightarrow\mathbf{x}=(\mathbf{I}-\mathbf{A}_{IO})^{-1}\cdot\mathbf{y} \tag{2.3}$$

The vector $\mathbf{x}$ describes the total demand induced in the economy by an initial final demand $\mathbf{y}$; $(\mathbf{I}\text{-}\mathbf{A}_{IO})^{-1}$ is named the *Leontief inverse* after Wassily Leontief. If we have a matrix $\mathbf{E}_{IO}$ containing the environmental burdens arising from one

economic unit of industrial activity, the total environmental burdens **e**, are easily calculated by:

$$\mathbf{e} = \mathbf{E}_{IO}^{T} \cdot \mathbf{x} \tag{2.4}$$

Vector **e** now contains the entire inventory set of emissions and raw material inputs from a demand **y**. Impact assessment can be performed by multiplying **e** with a characterization matrix **C** that contains the impact factors discussed in chapter 2.1.3. This results in a set of impacts **b** within different impact categories, shown in equation 2.5.

$$\mathbf{b} = \mathbf{C} \cdot \mathbf{e} \tag{2.5}$$

The input-output approach makes it possible to calculate the total environmental burdens arising from a demand of sector activity or commodities in theory without applying any system boundaries or cut-off procedures. The disadvantage is of course that the statistical input-output data are often highly aggregated and don‘t distinguish between demanding for example one economic unit worth of Lada or one economic unit of Mercedes. For a more detailed introduction to input-output analysis see for example [12].

2.3 Hybrid life cycle assessment

Recently some work has been done to combine the strengths of process LCA and environmental input-output analysis (see for example [13, 14]). While process LCA provides detailed data on the ”close” parts of the system that is assessed, input-output analysis can offer to calculate the environmental burdens arising further out in the system. The construction of an industrial facility will not only require materials as cement, steel, wood etc., usually accounted for in a process-LCA, but also a significant amount of services from carpenters, electricians and others. They all use equipment and energy doing their job, and the input-output approach offers the possibility to include these inputs through demanding services from an economic sector. The difference between the cost of some sort of equipment and the cost of the materials needed for its construction could be demanded from a sector such as for example *construction services*. This results in an induced demand in the whole economy and a set of environmental impacts that can be added to the impacts from process-LCA to yield total environmental impacts.

There is a risk of double counting when this approach is applied. The economic sector of construction services will contain inputs from other sectors e.g. *metal products industry*. Since process-LCA already has accounted for material inputs, efforts should be made to subtract the purchases containing the materials covered by process-LCA. We are simply not demanding the average industry output or commodity. How this can be done will be discussed in chapter 2.4.

2.4 Computational structure

The computations in LCA are best performed within a matrix framework, allowing for more flexible and sophisticated analysis. This is mainly straightforward mathematics and general matrix theory will not be explained further.

Before the theoretical framework is described it is convenient to explain the symbols that are used. This is done in table 2.2.

Tab. 2.2: Explanation of variables used in the calculations

Symbol	**Explanation**
n	number of foreground processes
m	number of environmental flows
q	number of impact categories
r	number of background processes
s	number of industrial sectors or commodity groups
$\mathbf{A}_f$(n,n)	Foreground matrix
$\mathbf{A}_{LCA}$(r,r)	Background matrix
$\mathbf{A}_{IO}$(s,s)	Input-Output matrix
$\mathbf{S}_{LCA}$(r,n)	Background process input matrix
$\mathbf{S}_{IO}$(s,n)	Industrial sector input matrix

As discussed in chapter 2.1 unit processes along the life cycle of a product or service can be identified. These may be called *foreground processes*. Environmental flows to and from these can be collected. However, foreground processes will often have inputs from other processes and the term *background processes* denotes these. The foreground processes can be organized in a matrix $\mathbf{A}_f$ with a corresponding matrix $\mathbf{E}_f$. $\mathbf{A}_f$ describes the unit flows between foreground processes, and $\mathbf{E}_f$ the environmental flows arising from one unit of each process. Examples are given in equation 2.6 and 2.7.

$$\mathbf{A}_f = \begin{pmatrix} a_{f(1,1)} & a_{f(1,2)} & \cdots & a_{f(1,n)} \\ a_{f(2,1)} & a_{f(2,2)} & \cdots & a_{f(2,n)} \\ \vdots & \vdots & \ddots & \vdots \\ a_{f(n,1)} & a_{f(n,2)} & \cdots & a_{f(n,n)} \end{pmatrix} \tag{2.6}$$

This matrix, from now on called the *foreground matrix* describes a system where the production of one unit of process 1 requires $a_{f(1,1)}$ of its own output, $a_{f(2,1)}$ units of process 2 and $a_{f(n,1)}$ units of process n. The same interpretation goes for

processes 2 to n.

$$\mathbf{E}_f = \begin{pmatrix} e_{f(1,1)} & e_{f(1,2)} & \cdots & e_{f(1,m)} \\ e_{f(2,1)} & e_{f(2,2)} & \cdots & e_{f(2,m)} \\ \vdots & \vdots & \ddots & \vdots \\ e_{f(n,1)} & e_{f(n,2)} & \cdots & e_{f(n,m)} \end{pmatrix} \tag{2.7}$$

The different processes are assigned to environmental flows of different types so that production of one unit of process 1 results in $e_{f(1,1)}$ units of environmental flow 1, $e_{f(1,2)}$ units of environmental flow 2 and $e_{f(1,m)}$ units of environmental flow m etc. In practice the $\mathbf{E}_f$ matrix is composed of sub-matrices separating environmental flows to different compartments. This is illustrated by equation 2.8.

$$\mathbf{E}_f = \left(\mathbf{E}_f, \text{raw} \,\middle|\, \mathbf{E}_f, \text{air} \,\middle|\, \mathbf{E}_f, \text{water} \,\middle|\, \mathbf{E}_f, \text{soil} \,\middle|\, \mathbf{E}_f, \text{solid} \,\middle|\, \mathbf{E}_f, \text{non material} \right) \tag{2.8}$$

There is also developed different LCA-databases, connecting processes to each other. These may be called $\mathbf{A}_{LCA}$. The corresponding emission matrix will then be $\mathbf{E}_{LCA}$. These matrices can be used to model background processes needed as inputs to the different processes in the foreground matrix. The demands can be assembled in a matrix $\mathbf{S}_{LCA}$ shown in equation 2.9.

$$\mathbf{S}_{LCA} = \begin{pmatrix} s_{LCA(1,1)} & s_{LCA(1,2)} & \cdots & s_{LCA(1,n)} \\ s_{LCA(2,1)} & s_{LCA(2,2)} & \cdots & s_{LCA(2,n)} \\ \vdots & \vdots & \ddots & \vdots \\ s_{LCA(r,1)} & s_{LCA(r,2)} & \cdots & s_{LCA(r,n)} \end{pmatrix} \tag{2.9}$$

The matrix should be read so that one unit output of foreground process 1 requires $s_{LCA(1,1)}$ units of LCA-database process 1 and so on. LCA-databases often contain hundreds of processes.

As discussed in chapter 2.3 efforts have been made to combine the strengths of process-LCA and input-output LCA. The difference between the price of a unit equipment and the cost of its material inputs can be called *value added* (VA). Equation 2.10 shows its formal expression.

$$VA = EC - \sum_i W_i \cdot MC_i \tag{2.10}$$

where EC is the total cost of a unit equipment, W_i is the weight of material i used in the equipment and MC_i is the unit cost of material i. We can now calculate VA values for each of the unit processes. The VA must be assigned to an industrial sector or a commodity group, e.g. *Equipment manufacturing* if there is a sector

called that present in the input-output matrix.

We recall the matrix $\mathbf{A}_{IO}$ from chapter 2.2 and its corresponding emission matrix $\mathbf{E}_{IO}$. The demand of the different foreground processes from the background economy can now be assembled of the VA values into a matrix $\mathbf{S}_{IO}$ as shown in equation 2.11.

$$\mathbf{S}_{IO} = \begin{pmatrix} s_{IO(1,1)} & s_{IO(1,2)} & \cdots & s_{IO(1,n)} \\ s_{IO(2,1)} & s_{IO(2,2)} & \cdots & s_{IO(2,n)} \\ \vdots & \vdots & \ddots & \vdots \\ s_{IO(s,1)} & s_{IO(s,2)} & \cdots & s_{IO(s,n)} \end{pmatrix} \tag{2.11}$$

Demand of $s_{IO(1,1)}$ economic units from economic sector 1 as input to foreground process 1 is the sum of all VA needed from this sector. The same interpretation goes for the other values.

The matrices $\mathbf{A}_f$, $\mathbf{A}_{LCA}$, $\mathbf{A}_{IO}$, $\mathbf{S}_{LCA}$ and $\mathbf{S}_{LCA}$ can now be arranged into a large matrix $\mathbf{A}$ as shown in equation 2.12.

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_f & 0 & 0 \\ \mathbf{S}_{LCA} & \mathbf{A}_{LCA} & 0 \\ \mathbf{S}_{IO} & 0 & \mathbf{A}_{IO} \end{pmatrix} \tag{2.12}$$

Corresponding $\mathbf{E}$-matrices can be arranged into one large $\mathbf{E}$-matrix:

$$\mathbf{E} = \begin{pmatrix} \mathbf{E}_f \\ \mathbf{E}_{LCA} \\ \mathbf{E}_{IO} \end{pmatrix} \tag{2.13}$$

With a given demand of foreground processes,

$$\mathbf{y} = \begin{pmatrix} \mathbf{y}_f \\ 0 \\ 0 \end{pmatrix} \tag{2.14}$$

the total induced demand of processes, $\mathbf{x}$, can be calculated using the technique from equation 2.3. This is shown in equation 2.15.

$$\mathbf{x} = \begin{pmatrix} \mathbf{x}_f \\ \mathbf{x}_{LCA} \\ \mathbf{x}_{IO} \end{pmatrix} = \left[I - \begin{pmatrix} \mathbf{A}_f & 0 & 0 \\ \mathbf{S}_{LCA} & \mathbf{A}_{LCA} & 0 \\ \mathbf{S}_{IO} & 0 & \mathbf{A}_{IO} \end{pmatrix} \right]^{-1} \cdot \begin{pmatrix} \mathbf{y}_f \\ 0 \\ 0 \end{pmatrix} \tag{2.15}$$

The total environmental flows, $\mathbf{e}$, arising as a result of the induced process activity are calculated by equation 2.16.

$$\mathbf{e} = \mathbf{E}^T \cdot \begin{pmatrix} \mathbf{x}_f \\ \mathbf{x}_{LCA} \\ \mathbf{x}_{IO} \end{pmatrix} \tag{2.16}$$

The impact assessment results, **b**, are now calculated by multiplying the **e**-vector with a characterization matrix **C**:

$$\mathbf{b} = \mathbf{C} \cdot \mathbf{e} \tag{2.17}$$

The **C**-matrix is described in equation 2.18.

$$\mathbf{C} = \begin{pmatrix} c_{(1,1)} & c_{(1,2)} & \cdots & c_{(1,m)} \\ c_{(2,1)} & c_{(2,2)} & \cdots & c_{(2,m)} \\ \vdots & \vdots & \ddots & \vdots \\ c_{(q,1)} & c_{(q,2)} & \cdots & c_{(q,m)} \end{pmatrix} \tag{2.18}$$

where q is the number of impact categories. The factor $c_{(1,1)}$ is the characterization factor of environmental flow 1 to impact category 1 i.e. how strong one unit release of environmental flow 1 affects impact category 1 etc.

The matrix structure of the computations gives the possibility to make other flexible analysis as well. Exploration of process contributions to the different impacts and contributions from foreground, background and input-output parts of the system can be performed with simple straight-forward matrix manipulations.

One can easily calculate the contribution of each process in **A** to all of the impact categories in **C** by diagonalizing the total demand vector. Equation 2.16 then becomes:

$$\mathbf{e^*} = \mathbf{E}^T \cdot \hat{\mathbf{x}} \tag{2.19}$$

And a matrix **b*** describing the impact results for each process is calculated by:

$$\mathbf{b^*} = \mathbf{C} \cdot \mathbf{e^*} \tag{2.20}$$

To calculate impact contributions from foreground processes, one simply sets the $\mathbf{x}_{LCA}$ and $\mathbf{x}_{IO}$ parts of **x** to zero so that

$$\mathbf{x^*} = \begin{pmatrix} \mathbf{x}_f \\ 0 \\ 0 \end{pmatrix} \tag{2.21}$$

and proceeds with equations 2.16 and 2.17. The same approach is used to calculate contributions from background processes and input-output part of the system.

It might be interesting to find the impact contributions of the different foreground processes including all their upstream impacts. The total upstream demand for a foreground process i can be calculated by:

$$\mathbf{x^{**}}_i = (\mathbf{I\text{-}A})^{-1}\mathbf{x}_i \tag{2.22}$$

where $\mathbf{x}_i$ denotes the i'th column vector of $\hat{\mathbf{x}}$. The upstream impacts to process i are then calculated following equations 2.16 and 2.17. It is important to note that this procedure produces all upstream impacts, also those arising from the demand of other foreground processes. To calculate the individual impacts from each foreground process it is thus necessary to subtract impacts from other foreground processes demanded by the process in question. This procedure is therefore only possible where no feedback (e.g. process 1 needs input of process 2 and process 2 needs input of process 1) occurs in the $\mathbf{A}_f$-matrix.

As mentioned in chapter 2.3 there is a risk of double counting when using a hybrid approach to the assessment. Inputs already accounted for in foreground- or background processes may be counted for again when demanding an average industry output or commodity from the input-output system. Even though material costs are subtracted, the input from an economic sector will induce activity in material producing sectors. This problem and possible ways to eliminate it has been explored by Anders Strømman [15]. One of the simple ways is to subtract the activity induced in the material producing sectors by negative inputs in the $\mathbf{S}_{IO}$-matrix. It is however important that only the industries whose materials are accounted for through foreground- or background processes are subtracted. This is all done under the assumption that the products of the material producing sectors are identical to those acquired from the foreground- and background processes. The approach is called the *single coefficient transfer method* (SCPT) and may be preferred for its simplicity although the computational flexibility of the system will be limited to some degree [15].

One of these limitations occur when we want to examine how "far out" in the system impacts occur by so-called *tierwise expansion*. The concept of this can be illustrated by a machine producing some sort of product we want to analyze the life cycle impacts of. This machine will have direct emissions and raw materials use contributing to the impacts of tier 0. However, it will also have inputs from background processes and economic sectors. The *direct emissions* from the activity induced in these will be the impacts of tier 1. The direct impacts arising from the induced activity in the processes used by these would be impacts from tier 2 etc. Equation 2.15 can be rewritten to:

$$\mathbf{x} = \sum_{n=0\rightarrow\infty} \mathbf{A}^n \cdot \mathbf{y} \tag{2.23}$$

The demand for processes in tier n can be calculated by equation 2.24.

$$\mathbf{x}_n = \mathbf{A}^n \cdot \mathbf{y} \tag{2.24}$$

Impacts from the activity in tier n are calculated following equations 2.16 and 2.17. The impacts can be shown either as the contribution to the total impact

from each tier or as cumulated impacts.

As we saw above, the approach for avoiding double counting, SCPT, can no longer be used since it will subtract the negative inputs one tier "too early". The solution is to assemble the negative and positive inputs in two different matrices **A** and run a tierwise expansion of both. The positive impacts of each tier can then be subtracted the negative impacts arising from the negative inputs we have used to avoid double counting. It is, however, important to remember that the impacts of tier n should be subtracted the negative impacts of tier (n-1). This method to avoid double counting is called the *parallel expansion single coefficient transfer method* (PE-SCPT) [15].

3. SYSTEM DESCRIPTION AND INVENTORY DATA

The assessment has been conducted according to the framework described in chapter 2, with the aim of comparing hydrogen production from natural gas steam reforming and nuclear power. The natural gas based system includes inputs and outputs from natural gas extraction, processing to produce hydrogen, separation and CO_2 sequestration. Data from this case is provided by Anders Strømman who has established an inventory for such a system [4]. The main part of the assessment has therefore been to build an inventory for nuclear production of hydrogen and to assess the impacts from the two different technologies.

First a choice of nuclear hydrogen production technology had to be done, since no commercial large scale facility of this kind has yet been realized. Three main alternatives exist [16]:

- Electrolysis of water or other solutions. This is based on first producing electricity, then using it in electrolysis.
- Natural gas steam reforming based on nuclear heat.
- Thermochemical water cracking. High temperature heat supplies energy to a chemical process to split water into its two components, hydrogen and oxygen.

The main difference between the three methods lies in the required coolant outlet temperature from the nuclear reactor. Electrolysis is of course possible with present technology with an outlet temperature of modern pressurized water reactors (PWR). The disadvantage of this technology is that the efficiency is limited by the electrical efficiency of the nuclear power plant, around 33 % for PWRs [17]. In addition there will be some loss of efficiency in the electrolysis process thereby reducing the overall efficiency further to approx. 24 % [18].

Nuclear heat can assist natural gas steam reforming as can any heat source at least to some degree. This technology is not chosen however, due to the similarity of the natural gas case, the heat supply being the main difference.

The remaining technology is thermochemical water cracking, a technology described by the industry itself as a promising and realistic option for large scale

hydrogen production in the future [19, 18]. Numerous chemical cycles can, combined with heat, produce hydrogen from water. A large survey has been conducted and the most realistic processes evaluated to find the cycle best suited for coupling with nuclear heat. A process called the Iodine-Sulphur (I-S) cycle is regarded most attractive [19]. The process needs an outlet coolant temperature at least above 850 degrees celcius. This implies new reactor technology to supply the heat. A range of different technologies are expected to be able to deliver such temperatures [19]:

- High temperature gas cooled reactors
- Liquid heavy metal cooled reactors
- Molten salt cooled reactors

General Atomics (GA) has performed a feasibility study and found a helium cooled high temperature reactor most suited for the task [19]. The concept is called the Hydrogen-Modular Helium Reactor (H_2-MHR) and will deliver the required high temperatures (950 degrees outlet temperature). This is the chosen technology for the assessment and is preferred for various reasons:

- The availability of data is better than for any other concept.
- The technology has a detailed progress plan for implementation and is therefore seen as more realistic.
- It is described as very safe, the reactor being virtually meltdown proof and its fuel and spent fuel very proliferation resistant, making it more politically acceptable.

The reactor will use uranium as fuel with an average enrichment of approx. 13 % U-235 [20]. Some will be 19.9 % U-235 and some will be natural uranium (0.71 % U-235). There is also plans for using plutonium fuels but this will not be considered in this study. Nor will the possibility of reprocessing be included as this may be difficult given the properties of spent fuel (the fuel consists of coated particles and is quite diluted in fissile material [21]) and also raise proliferation issues. A once-through uranium fuel cycle is therefore applied.

Nuclear power generation is a big and complex discipline, ranging over numerous different technologies and fuel cycles, each with their own characteristics. The first part of the assessment was therefore to gain a better understanding of the system and its different components and find out how nuclear hydrogen production relates to the existing system. Figure 3.1 gives a simplified overview of the nuclear hydrogen producing system.

In principle it shares most of the current nuclear system processes (except for more exotic fuel cycles and fuel cycle with reprocessing). The main difference is that the electricity producing unit is replaced by hydrogen production. However it also differs in the internal characteristics of the unit processes e.g. reactor technology and enrichment level. The demand of the different unit processes is different too. The system analyzed can be divided into eight main stages:

- Mining
- Milling
- Conversion
- Enrichment
- Fuel production
- Heat production in nuclear reactor
- Hydrogen production
- Spent fuel management

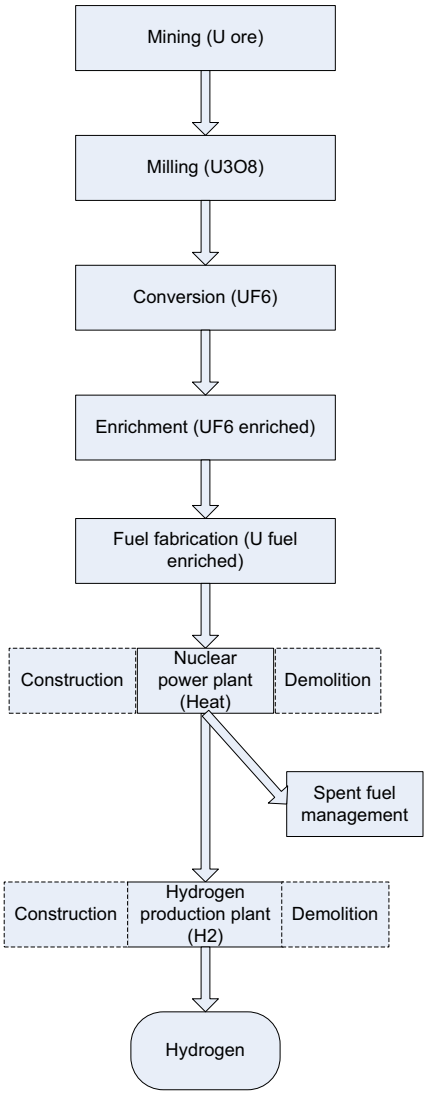


Fig. 3.1: Overview of the nuclear hydrogen production system

The mining stage provides uranium from nature, and through milling uranium is concentrated in the form U_3O_8. The conversion stage converts U_3O_8 to the form UF_6 needed in the enrichment process. Enrichment brings concentration of the fissile isotope U-235 to a desired level. In fuel production the chemical composition is altered once again to UO_2 (light water cooled reactors) or UC, UC_2 or UCO (gas cooled reactors). The fuel is then irradiated through use in a nuclear reactor, generating heat for the hydrogen production process. Hydrogen is produced through thermochemical water splitting. Different chemical reactions supported by catalyst chemicals and heat produce hydrogen and oxygen from the input of pure water. The production of 1 TJ hydrogen (higher heating value, HHV) delivered at approx. 37 bars[1] is the basis for the assessment. This is not a "true" functional unit as described in chapter 2.1.1, since hydrogen is not a function in itself. However if the assumed

[1] see chapter 3.7

utilization of the hydrogen is the same in a comparative assessment, a so-called "cradle to gate" assessment provides the necessary information for comparison.

The different unit processes and their respective inputs and outputs are described in the following. Two LCA-databases and one input-output database are used to provide background processes and economic inputs to the foreground processes[2]. It is assumed zero loss of uranium throughout the fuel cycle. Key choices and assumptions are mentioned and discussed, the more detailed assumptions are included in appendix A.

It should further be noted that the hybrid approach described in chapter 2.3 is only applied to the nuclear heat facility and the hydrogen production unit. It proved difficult to obtain inventory data and prices for the inputs from the fuel cycle. Fuel cycle foreground processes are therefore modeled entirely with inputs from LCA-database processes. They are put into the foreground matrix however, since all the radionuclide emissions are changed in the E-matrix and other modifications (see chapter 3.4) are made to the processes in the LCA-database. It is however assumed that the input data in the LCA-database are covering most sub processes thus minimizing the VA described in chapter 2.4 for each of the foreground fuel cycle processes. The construction and demolition of the fuel cycle facilities are included in the LCA-database data.

3.1 Mining

The first step of the fuel chain is mining of uranium. The uranium is located in the ore together with other minerals. Out of the uranium found in nature the fissile isotope U-235 is only present in a concentration of 0.71 %. Uranium can be mined with three different technologies:

- Open pit mining
- Underground mining
- In-situ leaching

[2] These are:

- ETH-ESU 96 [22]
- Idemat 2001 [23]
- The Dutch input-output database denoted IO OECD Europe [24]. European OECD data are used due to strange sectorial aggregation in the Dutch national part of the database

the two first being self-explaining, and in-situ leaching meaning that the uranium is dissolved underground and pumped to the surface. Data on radionuclide emissions from mining used in this assessment are based on data from the United Nations Committee on the Effects of Atomic Radiation (UNSCEAR) [25]. These data has been normalized to one kg uranium in product output. Other emission data and input data are taken from the LCA-database ETH-ESU 96 [22]. This process also includes radionuclide emissions, but the average data of UNSCEAR are preferred to those. Of the total uranium 50 % is assumed to be mined underground and 50 % from open pit mining. The sensitivity of this assumption will be discussed in chapter 4. The assessment does however not distinguish between radionuclide emissions from these, they are assumed to be the same per kg uranium extracted. Tables 3.1 and 3.2 shows the inputs to the mining process and its radionuclide emissions.

Tab. 3.1: Process inputs for the mining of 1 kg uranium in ore

Process name	**Database**	**Value**	**Unit**
Uranium in ore (open mine) U	ETH-ESU 96	0.50	kg
Uranium in ore (underground mine) U	ETH-ESU 96	0.50	kg

Tab. 3.2: Radionuclide emissions from the mining of 1 kg uranium

Emission	**Value**	**Unit**
Rn222 to air	3.54E+08	Bq

After the ore is extracted it is sent to the uranium mill.

3.2 Milling

In the milling stage the ore undergoes a number of different processes to produce uranium peroxide. This includes [26]:

- Mechanical preparation; crushing.
- Leaching; dissolving the uranium in presence of an alkali or acid.
- Solid-liquid separation; filtering and settling.
- Purification; precipitation and redissolving.
- Concentrate production; Precipitation, filtration, drying and packing.

The large fraction of the ore that is separated is called mill tailings and are usually disposed of in ponds close to the mill, and covered by rock and soil

after some time [25]. These tailings continue to exhale radon gas for thousands of years, the rate being described as approx. constant for 10000 years. Mill tailings can further be divided in operational and abandoned tailings [25]. In this assessment operational tailings is treated as a part of the milling process while abandoned tailings are given a unit process of its own to allow for easy exploration of how varying time horizons affect impact results (see chapter 4). As for the mining process, mill and mill tailings radionuclide emissions are taken from the UNSCEAR estimates normalized to one kg uranium in product and one kg in product per year respectively. Other emissions and process inputs are taken from the LCA-database ETH-ESU 96. The data are presented in table 3.3, 3.4 and 3.5.

Tab. 3.3: Process inputs for the milling of 1 kg uranium

Process name	**Database**	**Value**	**Unit**
Uranium from mining[a]	Foreground process	1.00	kg
Uranium natural in concentrate U[b]	ETH-ESU 96	1.00	kg
Mill tailings[c]	Foreground process	1.00	kg

[a] This is the input of the process mining in chapter 3.1

[b] Subtracted the inputs of mining processes

[c] This corresponds to the mill tailings emissions of one year. To calculate the emissions over 10000 years the input should be changed to 10000 kg

Tab. 3.4: Radionuclide emissions from the milling of 1 kg uranium

Emission	**Value**	**Unit**
Pb210 to air	9.43E+01	Bq
Pb210 to water	4.72E+01	Bq
Po210 to air	9.43E+01	Bq
Ra226 to air	9.43E+01	Bq
Ra226 to water	8.25E+01	Bq
Rn222 to air	1.08E+08	Bq
Th230 to air	9.43E+01	Bq
Th230 to water	5.90E+01	Bq
U234 to air	1.89E+03	Bq
U238 to air	1.89E+03	Bq
U238 to water	1.42E+03	Bq

Tab. 3.5: Radionuclide emissions from the tailings arising from 1 kg uranium production in mill

Emission	**Value**	**Unit**
Rn222 to air	4.72E+06	Bq/yr

3.3 Conversion

The conversion process is the transformation of U_3O_8 to UF_6 through chemical reactions [26]:

- Dissolving, filtering, purification and precipitation to ammonium diuranate
- Calcination to produce uranium trioxide
- Reduction to uranium dioxide
- Fluorination with HF to produce UF_4
- Conversion to UF_6 with fluorine, crystallization and liquification

Radionuclide emissions are provided by a follow-up of the ExternE[3] study [27], presenting an update of the data in the main ExternE report [26]. These data are regarded more up-to-date than the emissions in the ETH-ESU 96 database. The data have been normalized to one kg of uranium in product (see appendix A for details). Other emissions and process inputs however, are taken from the ETH-ESU 96 database. Tables 3.6 and 3.7 present conversion data.

Tab. 3.6: Process inputs for the conversion of 1 kg uranium

Process name	**Database**	**Value**	**Unit**
Uranium from milling	Foreground process	1.00	kg
Uranium natural in UF6 U[a]	ETH-ESU 96	1.00	kg

[a] Subtracted process inputs from milling

Tab. 3.7: Radionuclide emissions from the conversion of 1 kg uranium

Emission	**Value**	**Unit**
U234 to air	1.74E+01	Bq
U234 to water	5.52E+02	Bq
U235 to air	7.55E-01	Bq
U235 to water	2.37E+01	Bq
U238 to air	1.64E+01	Bq
U238 to water	5.22E+02	Bq

[3] Big EU-initiative to calculate the external costs of energy production

3.4 Enrichment

In the enrichment phase, natural uranium containing 0.71 % of the fissile U-235 (the rest being U-238 and traces of U-234), is processed to gain a product that is richer in this fissile isotope. A U-235 concentration of 19.9 % is required for the H_2-MHR reactor. This will be used together with natural uranium in the fuel to gain an average enrichment of about 13 % [20]. The tailings resulting from the process are called depleted uranium, the product known to be used in ammunition due to its high density. It is however low radioactive and not included in the assessment. The tailings enrichment, x_t, are assumed to be 0.3 % U-235 [17, 20]. The amount of natural uranium required to produce one kg uranium at enrichment level x_p is given by the mass balance in equation 3.1.

$$\text{Natural uranium required} = \frac{x_p - x_t}{x_n - x_t} \tag{3.1}$$

where x_n is the natural enrichment of 0.71 %.

The enrichment is mainly performed by two different techniques; gas diffusion or gas centrifuge. Gas diffusion requires much more energy per unit of separative work and is expensive [28]. The technique is therefore expected to be phased out over some time [20]. Since it is still present to a high degree in the current system however, 50 % of enrichment is assumed to be performed by gas diffusion and 50 % by centrifuge. The sensitivity of this assumption on impact results will be explored in chapter 4. Data for enrichment has only been found in the enrichment range of approx. 3-4 %. It was necessary to adjust these to account for the higher enrichment level of 19.9 % needed for H_2-MHR fuel. All emissions and process inputs are assumed to scale with natural uranium input. The ratio between natural uranium needed for production of one kg uranium for use in light water reactors and production of one kg uranium with 19.9 % U-235 has been used to adjust emissions as well as process inputs. This assumption is supported by Ken Schultz in General Atomics [20]. As for the conversion process radionuclide emissions are taken from [27]. There is however no distinction between radionuclide emissions from gas diffusion and centrifuge enrichment. They are assumed to be equal. The sensitivity of this assumption can also be explored in chapter 4. Process inputs and other emissions are taken from the LCA-database ETH-ESU 96. All emissions and inputs are normalized to one kg uranium in enriched product. Tables 3.8 and 3.9 present process inputs and radionuclide emissions from the enrichment process.

Tab. 3.8: Process inputs for the enrichment of 1 kg uranium at 19.9 % U-235

Process name	**Database**	**Value**	**Unit**
Uranium from conversion	Foreground process	47.80	kg
Uranium enriched 3.25% URENCO U[a]	ETH-ESU 96	0.50	kg
Uranium enriched 3.25% EURODIF U[a]	ETH-ESU 96	0.50	kg

[a] Modified to account for higher enrichment level and subtracted inputs of conversion process

Tab. 3.9: Radionuclide emissions from the enrichment of 1 kg uranium

Emission	**Value**	**Unit**
U234 to air	5.02E+01	Bq
U234 to water	1.00E+01	Bq
U235 to air	2.56E+00	Bq
U235 to water	5.02E-01	Bq
U238 to air	2.64E+01	Bq
U238 to water	5.28E+00	Bq

3.5 Fuel production

Currently most reactors use fuel in the form of UO_2. The H_2-MHR however will use coated spherical particles of UCO. Since there is little information available about this fuel production technique, it is assumed that the inputs and emissions are the same that for UO_2 fuel production, on the basis of one kg uranium in product. For this process the ETH-ESU 96 database-values were used. The radionuclide emissions however, are adjusted to the amount of natural uranium required to produce fuel containing one kg uranium. This is to adjust for the higher enrichment level of the fuel i.e. assuming that these emissions will be higher due to higher enrichment. These data are taken from the report of Dreicer and colleagues [27] and modified according to appendix A. Table 3.10 and 3.11 present the data. The amounts of natural uranium and uranium enriched to 19.9 % are calculated from the information that the average enrichment in the fuel is 13 %.

Tab. 3.10: Process inputs for the production of fuel elements containing 1 kg uranium

Process name	**Database**	**Value**	**Unit**
Enriched uranium	Foreground process	0.64	kg
Uranium from milling	Foreground process	0.36	kg
Uranium 3.7% in fuel element PWR D U[a]	ETH-ESU 96	1.00	kg

[a] Subtracted input of enriched uranium

Tab. 3.11: Radionuclide emissions from the production of fuel elements containing 1 kg uranium

Emission	**Value**	**Unit**
U234 to air	7.92E-01	Bq
U234 to water	1.14E+03	Bq
U235 to air	5.28E-02	Bq
U235 to water	7.55E+01	Bq
U238 to air	1.95E-01	Bq
U238 to water	2.80E+02	Bq

3.6 Heat production in reactor

Fuel assemblies from the fuel production are loaded into the reactor. The fission process is controlled so that it reaches a steady-state fission rate by control rods lowered between the fuel elements. U-235 is fissile i.e. it gives rise to fission with slow neutrons [28]. The fission process is basically that a U-235 nucleus emits neutrons and when another U-235 nucleus is hit by a neutron, it splits into two lighter nuclei and emits on average 2.42 neutrons plus gamma rays. The new neutrons again give rise to more fissions. The total mass after the fission process is smaller than before, the rest has been converted to energy through Einsteins‘ famous relationship $E = mc^2$. The energy is utilized as heat removed by a reactor coolant, in this case helium. The helium is heat exchanged to an intermediate cooling loop, and the heat transferred to the hydrogen production plant at approx. 900 degrees celcius. The plant is constructed of four 600 MWth modules to reach an overall thermal effect of 2400 MWth.

Materials data for construction and use of the plant has been taken from a Swedish study [29]. Radionuclide emissions are provided by a report from IAEA [30]. Economic data for the n‘th of a kind plant is provided by General Atomics [19]. Process inputs for the construction and use of the plant are shown in tables 3.12 and 3.13. Deconstruction of the plant is included in construction data. Emission data are presented in table 3.14. It is assumed that no other emissions occur from the plant. Assumptions and modifications of the background data are explained in appendix A.

Tab. 3.12: Process inputs for construction of the nuclear plant

Process name	Database	Value	Unit
Explosives ETH U	ETH-ESU 96	1.262E+05	kg
Mineral wool ETH U	ETH-ESU 96	1.065E+05	kg
Aluminium ingots I	Idemat 2001	2.904E+04	kg
Concrete I	Idemat 2001	5.227E+07	kg
Copper I	Idemat 2001	4.065E+05	kg
Lead I	Idemat 2001	6.582E+04	kg
PVC (s) I	Idemat 2001	2.253E+05	kg
Spruce, European I	Idemat 2001	4.956E+06	kg
Steel I	Idemat 2001	1.328E+07	kg
Titanium I	Idemat 2001	1.936E+04	kg
Base metal industry, OECD Europe[a]	IO OECD Europe	-2.74E+07	USD
Building and installation industry, OECD Europe[b]	IO OECD Europe	1.53E+08	USD
Building material industry, OECD Europe[c]	IO OECD Europe	-4.43E+06	USD
Chemical, rubber and plastics industry, OECD Europe[c]	IO OECD Europe	-2.09E+07	USD
Machine and electrical equipment industry, OECD Europe	IO OECD Europe	5.42E+08	USD
Metal products industry, OECD Europe[c]	IO OECD Europe	-2.89E+07	USD
Public (government) and other services, OECD Europe	IO OECD Europe	4.73E+07	USD
Wood industry, OECD Europe[c]	IO OECD Europe	-1.33E+06	USD

[a] Negative input to avoid double counting
[b] Added 2.115E+07 USD to include deconstruction
[c] Negative input to avoid double counting

Tab. 3.13: Process inputs for the production of 1 TJ heat in reactor

Process name	Database	Value	Unit
Construction of NPP	Foreground process	2.45E-07	p
Fabrication of fuel	Foreground process	1.16E-01	kg
Spent fuel management	Foreground process	3.27E-03	m3
LLW management	Foreground process	2.26E-03	m3
Aluminium ingots I	Idemat 2001	4.34E-03	kg
Copper I	Idemat 2001	3.60E-02	kg
Lead I	Idemat 2001	9.83E-03	kg
PVC (s) I	Idemat 2001	3.36E-02	kg
Steel I	Idemat 2001	1.32E-01	kg
Titanium I	Idemat 2001	2.89E-04	kg
Base metal industry, OECD Europe[a]	IO OECD Europe	-4.39E+01	USD
Chemical, rubber and plastics industry, OECD Europe[a]	IO OECD Europe	-3.35E+01	USD
Machine and electrical equipment industry, OECD Europe	IO OECD Europe	8.67E+02	USD
Metal products industry, OECD Europe[a]	IO OECD Europe	-4.63E+01	USD
Public (government) and other services, OECD Europe	IO OECD Europe	1.30E+02	USD

[a] Negative input to avoid double counting

Tab. 3.14: Radionuclide emissions from the production of 1 TJ heat in reactor

Emission	**Value**	**Unit**
Ar41 to air	1.86E+07	Bq
Ba140 to water	2.89E-01	Bq
Cs137 to water	2.05E+02	Bq
H3 to air	9.31E+06	Bq
I131 to water	4.56E+00	Bq
Kr85 to air	3.73E+07	Bq
waste heat to air	4.80E+05	Bq
Xe133 to air	9.31E+06	Bq

3.7 Hydrogen production

Heat supplies various chemical reactions in the hydrogen plant with energy. The main reactions and their respective required temperatures are shown below [18].

$$\begin{aligned} I_2 + SO_2 + 2H_2O &\longrightarrow H_2SO_4 + 2HI \\ &\sim 120°C \\ H_2SO_4 &\longrightarrow \frac{1}{2}O_2 + SO_2 + H_2O \\ &\sim 800°C \\ 2HI &\longrightarrow I_2 + H_2 \\ &\sim 450°C \end{aligned}$$

Water and heat are supplied to the process and oxygen and hydrogen are extracted. The chemicals are then used in the next loop. The hydrogen is delivered at 22-50 bar depending on process conditions [20]. Materials and economic data are provided from the same sources as the reactor data. Assumptions and modifications are shown in appendix A. Further it is assumed no direct emissions from the hydrogen plant, but to be able to account for the use of water and iodine in the process, these are required as raw material, see tables 3.18 and 3.17.

Tab. 3.15: Process inputs for the construction of the H_2-plant

Process name	Database	Value	Unit
Explosives ETH U	ETH-ESU 96	9.675E+04	kg
H2 ETH U	ETH-ESU 96	2.000E+03	kg
H2SO4 ETH U	ETH-ESU 96	1.000E+05	kg
Mineral wool ETH U	ETH-ESU 96	8.161E+04	kg
Aluminium ingots I	Idemat 2001	2.226E+04	kg
Concrete I	Idemat 2001	4.006E+07	kg
Copper I	Idemat 2001	3.116E+05	kg
Lead I	Idemat 2001	5.045E+04	kg
PVC (s) I	Idemat 2001	1.727E+05	kg
Spruce, European I	Idemat 2001	3.799E+06	kg
Steel I	Idemat 2001	1.018E+07	kg
Titanium I	Idemat 2001	1.484E+04	kg
Base metal industry, OECD Europe[a]	IO OECD Europe	-2.41E+07	USD
Building and installation industry, OECD Europe[b]	IO OECD Europe	3.04E+07	USD
Building material industry, OECD Europe[c]	IO OECD Europe	-3.88E+06	USD
Chemical, rubber and plastics industry, OECD Europe[d]	IO OECD Europe	1.01E+08	USD
Machine and electrical equipment industry, OECD Europe	IO OECD Europe	4.75E+08	USD
Metal products industry, OECD Europe[e]	IO OECD Europe	-2.54E+07	USD
Wood industry, OECD Europe[e]	IO OECD Europe	-1.16E+06	USD

[a] Negative input to avoid double counting
[b] Added 1.621E+07 USD to include deconstruction
[c] Negative input to avoid double counting
[d] Subtracted 1.835E+07 USD to avoid double counting
[e] Negative input to avoid double counting

Tab. 3.16: Process inputs for the production of 1 TJ hydrogen in H_2-plant

Process name	Database	Value	Unit
Construction H2-plant	Foreground process	4.71E-07	p
Operation NPP	Foreground process	1.92E+00	TJ
H2SO4 ETH U	ETH-ESU 96	1.69E-01	kg
Aluminium ingots I	Idemat 2001	6.14E-03	kg
Copper I	Idemat 2001	5.10E-02	kg
Lead I	Idemat 2001	1.39E-02	kg
PVC (s) I	Idemat 2001	4.77E-02	kg
Steel I	Idemat 2001	1.87E-01	kg
Titanium I	Idemat 2001	4.10E-04	kg
Base metal industry, OECD Europe[a]	IO OECD Europe	-4.11E+01	USD
Chemical, rubber and plastics industry, OECD Europe[b]	IO OECD Europe	1.63E+02	USD
Machine and electrical equipment industry, OECD Europe	IO OECD Europe	8.12E+02	USD
Metal products industry, OECD Europe[c]	IO OECD Europe	-4.34E+01	USD
Public (government) and other services, OECD Europe	IO OECD Europe	1.51E+02	USD

[a] Negative input to avoid double counting
[b] Subtracted 3.136E+01 USD to avoid double counting
[c] Negative input to avoid double counting

Tab. 3.17: Raw material inputs for the production of 1 TJ hydrogen

Emission	Value	Unit
I (Raw material)	3.59E+00	kg
water (Raw material)	5.10E+01	kg

Tab. 3.18: Initial iodine inventory for the H_2-plant

Emission	Value	Unit
I (Raw material)	2.120E+06	kg

3.8 Spent fuel management

Spent fuel from the reactor is highly radioactive and has to be cooled in an intermediate storage before final disposal. There has yet not been built any final storage facilities for high radioactive waste so process input data for this is from a planned geological repository in Switzerland that is modelled in ETH-ESU 96. It is assumed no radioactive (routine) emissions from neither the spent fuel management nor the treatment of low radioactive waste. These emissions would probably be neglectable [22]. Tables 3.19 and 3.20 shows the use of LCA-database processes for the radioactive waste from the plant.

Tab. 3.19: Process inputs the treatment of 1 m^3 low radioactive waste (LLW)

Process name	Database	Value	Unit
Low radioactive waste U	ETH-ESU 96	1.00E+00	m3

Tab. 3.20: Process inputs for the treatment of 1 m^3 spent fuel

Process name	Database	Value	Unit
RA waste interim storage C U[a]	ETH-ESU 96	1.00E+00	m3

[a] This process contains input of final storage in deep geological repository as well

The inventory of all processes is summarized in appendix B.1.

3.9 Short system description of hydrogen production from natural gas

Hydrogen can be produced by natural gas steam reforming. The inventory data used in this assessment are provided by Anders Strømman [4]. These include data for gas exploration and extraction, the hydrogen producing process, and sequestration of the CO_2 arising from the process. The CO_2 arising from the natural gas fired boiler that sustain the reforming process is, however, not sequestered. Delivery pressure is 37 bars, hence there is no need to add compression to any of the systems since the nuclear hydrogen plant can deliver hydrogen in the range 22-50 bars without additional compression [20].

4. RESULTS

Not much has been done to evaluate the life cycle environmental burdens arising from nuclear hydrogen production, but some work assess nuclear electricity production. This includes the ExternE studies [26], which focus mainly on the life cycle external costs arising from the release of radionuclides in the nuclear fuel cycle and the potential for accidents, excluding numerous other possible environmental issues. The Swedish electrical company Vattenfall has conducted LCAs for their different electricity producing technologies, including nuclear power [29]. Some work has also been done in Korea [31, 32]. Other studies apply a life cycle approach to assess nuclear power generation, but fails to include a comprehensive list of impacts, focusing on selected impact categories [33, 34, 35]. There is also nuclear LCA data as a part of the database ETH-ESU 96 [22].

For the impact assessment two different methods were used; the CML 2000 baseline method[1] and the Eco-Indicator 99 method[2] All CML baseline indicators are included, but to be able to assess impacts from radiation, the radiation impact category from Eco-Indicator 99 has been used. All CML indicators are at midpoint (see chapter 2.1.3), whereas the radiation impacts are evaluated at endpoint. Indicator names and units is shown in table 4.1.

All matrix calculations were performed in MATLAB after the LCA-databases and input-output database were exported from SIMAPRO [38].

[1] This method is developed by Center for Environmental Studies at University of Leiden. For more information and background reports consult the LCA website at Leiden, http://www.leidenuniv.nl/interfac/cml/ssp/projects/lca2/index.html

[2] For details see methodology report [36] and its annex [37].

Tab. 4.1: Impact Categories used in the assessment

Impact category	**Full name**	**Indicator**
ADP	Abiotic Depletion Potential	kg Sb-equivalents
GWP	Global Warming Potential	kg CO_2-equivalents
ODP	Ozone Layer Depletion Potential	kg CFC 11-equivalents
HTP	Human Toxicity Potential	kg 1,4 DB-equivalents[a]
FAETP	Fresh Water Aquatic Ecotoxicity Potential	kg 1,4 DB-equivalents[a]
MAETP	Marine Aquatic Ecotoxicity Potential	kg 1,4 DB-equivalents[a]
TETP	Terrestrial Ecotoxicity Potential	kg 1,4 DB-equivalents[a]
PCOP	Photochemical Oxidation Potential	kg C_2H_2-equivalents
AP	Acidification Potential	kg SO_2-equivalents
EP	Eutrophication potential	kg PO_4^{3-}-equivalents
R	Radiation Human Health Impacts as a result of ionizing radiation	Disability Adjusted Life Years (DALY)

[a] 1,4 Diclorobenzene- equivalents

4.1 Comparison with hydrogen production from natural gas

Environmental impacts arising from the production of 1 TJ (HHV) hydrogen were calculated using the computational framework described in chapter 2.4. The results are shown in table 4.2.

Tab. 4.2: Impact assessment results for the production of 1 TJ (HHV) hydrogen from nuclear thermochemical water splitting and natural gas steam reforming

	Nuclear	**Natural gas**	**Ratio, Natural gas/Nuclear [%]**
ADP	9.75E+00	5.4E-01	6
GWP	2.46E+03	1.3E+04	532
ODP	1.19E-02	5.4E-04	5
HTP	3.88E+03	1.0E+03	26
FAETP	6.67E+02	9.1E+00	1
MAETP	1.98E+06	3.7E+04	2
TETP	5.45E+00	2.3E+00	43
PCOP	9.93E-01	9.0E-01	90
AP	1.61E+01	2.4E+01	149
EP	7.88E-01	3.3E+00	417
R	8.98E-05	8.5E-09	0

We see that the natural gas case performs better for 8 out of 11 impact categories. It should be noted though, that the characterization of toxic impacts are generally more uncertain than other impact categories [39]. For MAETP especially, many characterization factors are known to be very wrong [40]. Since

this assessment does not apply any weighting procedure to the results, it is not possible to declare an overall "winner" for hydrogen production. This will have to be based on the decision makers' own value judgements on the relative importance of the different impact categories. It is however interesting to investigate the difference in where the impacts occur for the two options. Figures 4.1 and 4.2 shows the contribution of foreground-, background- and input-output processes to the different environmental impacts.

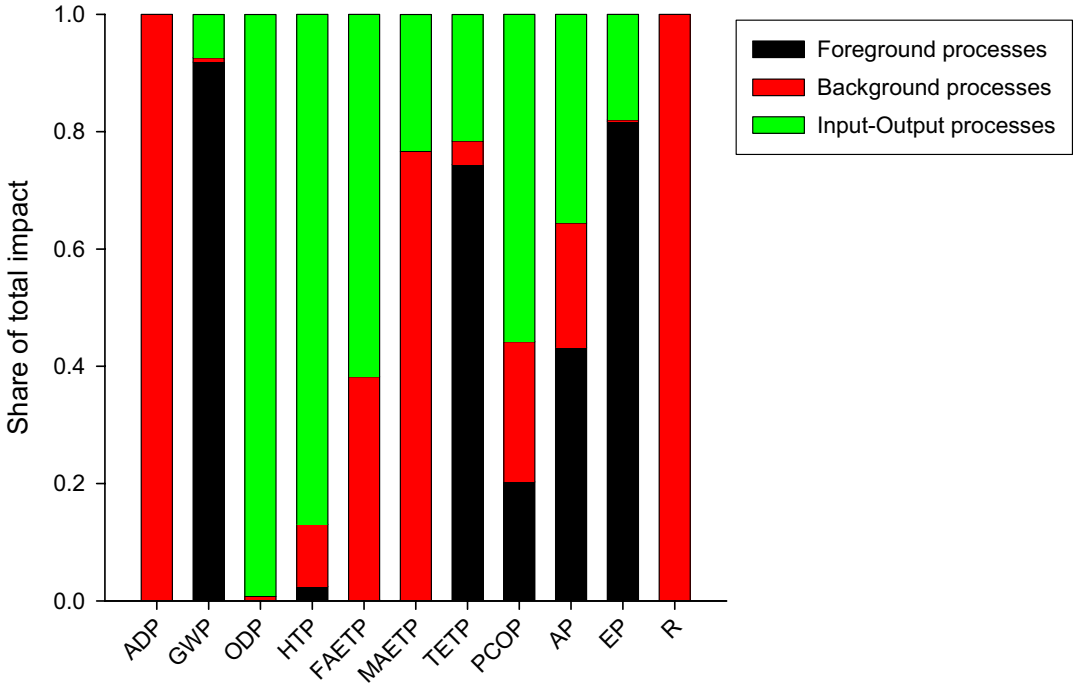


Fig. 4.1: Impacts of hydrogen production from natural gas from foreground, background and economic inputs

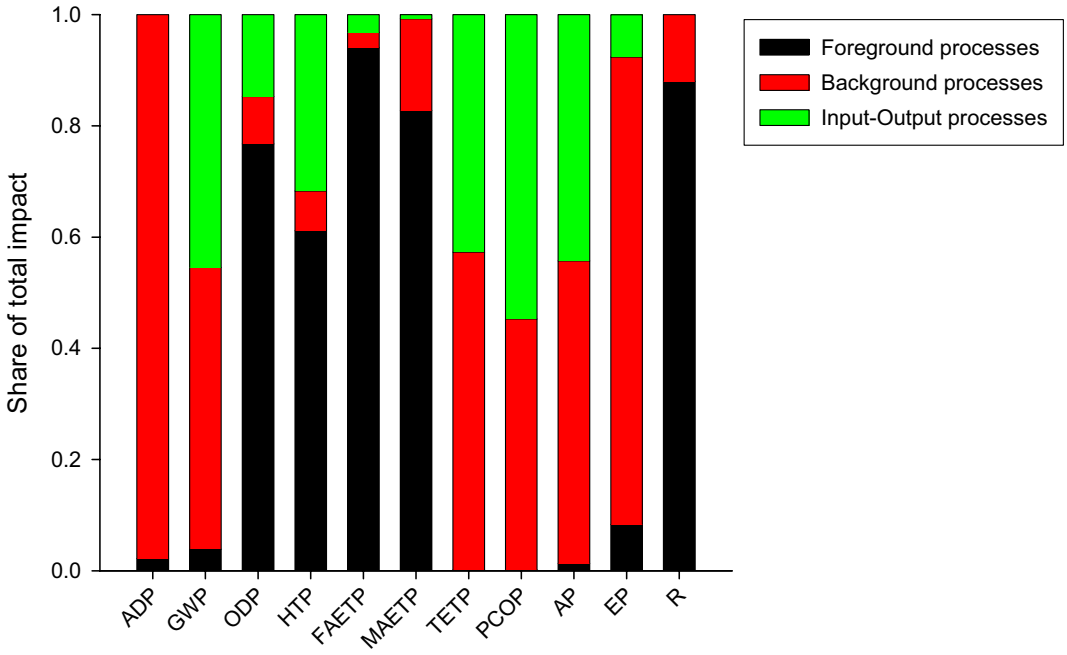
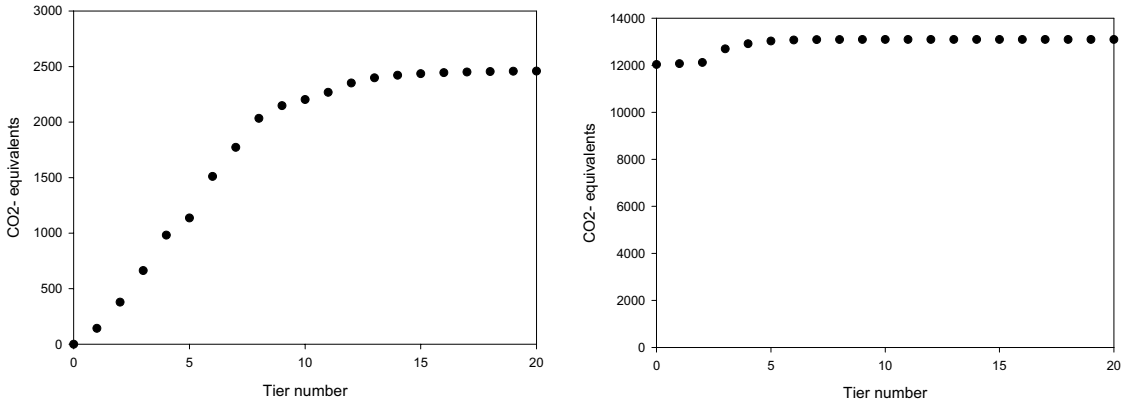


Fig. 4.2: Impacts of nuclear hydrogen production from foreground, background and economic inputs

For ADP almost all of the impact comes from background processes i.e. inputs from LCA-databases. Remember though, that the input-output database lacks almost all raw material inputs [24]. The GWP however, shows a large difference between the systems. Almost all greenhouse gas emissions in the natural gas case occur in the foreground processes whereas for the nuclear case, economic inputs and background processes dominate the impacts. This is not so strange considering the use of natural gas to fuel the steam reforming process for natural gas. For the ODP, HTP, FAETP and MEATP categories we see that the foreground processes play a much more important role in the nuclear system. The major part of the impacts comes from fuel cycle activities (see appendix B.2). In impact categories TETP, PCOP, AP and EP however, foreground processes contribute larger in the natural gas case. The radiation impacts from the nuclear system is dominated by foreground contributions, and in a 10000 yr perspective (see chapter 4.2.9) it‘s share is almost 100 %. For the natural gas case, radiation impacts occur only in the background system. Generally we see that input-output contributions are significant for both cases.

To illustrate how the difference in where the impacts occur in the two systems, a tierwise expansion (see chapter 2.4) of the GWP was done. The results are shown in figure 4.3.



(a) Nuclear hydrogen production (b) Hydrogen from natural gas

Fig. 4.3: Accumulated GWP from production of hydrogen from each tier

We see that while the GWP for the natural gas alternative converges to its final value after about 5 tiers of calculation, the same convergence does not occur until after 10-15 tiers in the nuclear case. Note that the tierwise expansion only gives an *indication* of the tier contribution as the organization of the $\mathbf{A}_f$-matrix will highly influence the contributions from the first tiers. Full tierwise expansion of all impacts can be seen in appendix B.3.

4.2 Deeper into the results of nuclear hydrogen production

To gain a better understanding of the environmental performance of the nuclear system, as well as identifying areas of improvement, it is interesting to identify the upstream impacts for each foreground process. These results are shown in figure 4.3.

Tab. 4.3: Total upstream impacts for the different foreground processes (in % of total)

Foreground process	ADP	GWP	ODP	HTP	FAETP	MAETP	TETP	PCOP	AP	EP	R
Constr. NPP	2	5	1	3	0	0	4	8	6	1	0
Constr. H2-plant	2	6	3	3	0	0	6	7	6	1	0
Mining	9	5	1	26	78	39	4	4	6	25	65
Milling	30	16	2	38	16	40	17	17	25	38	22
Mill tailings	0	0	0	0	0	0	0	0	0	0	1
Conversion	34	16	1	2	0	9	6	6	8	16	0
Enrichment	3	6	80	1	1	6	2	2	3	2	9
Fuel fabrication	0	0	0	0	0	0	0	0	1	0	0
Spent fuel mgmt.	17	9	2	2	1	5	27	10	10	11	3
Mgmt. of LLW	0	0	0	0	0	0	0	0	0	0	0
Operation NPP	0	18	2	15	2	0	18	26	20	3	0
Operation H2-plant	2	19	9	11	1	0	17	19	16	3	0

To be able to identify the most important *directly* contributing processes, these can be viewed in appendix B.2. The following chapters discuss the different impact categories.

4.2.1 Abiotic depletion potential

We see that milling, conversion and spent fuel management upstream processes are the greatest contributors to this impact category. If we dig deeper into the numbers the upstream use of coal, oil and gas are the most important processes (see table B.6). It should be noted that upstream spent fuel management impacts would be reduced significantly if the fuel rods are pushed out of the fuel assembly before disposal (see appendix A.7).

4.2.2 Global warming potential

For the global warming potential the most important contributions comes from upstream the operation of the power plant, hydrogen plant, conversion and milling. Most of this is due to induced activity in background and input-output matrix (see table B.7). The GWP impacts are quite evenly distributed, i.e. not many large contributors, the ten largest contributors accounting for only about 60 % of total.

4.2.3 Ozone depletion potential

The ozone depletion impacts are totally dominated by the enrichment process, accounting for 80 % of totals. Table B.8 shows that almost all of this is coming directly from the enrichment process. We also see that the results of this impact category is sensitive to the assumption that 50 % of the enrichment is performed with each of the technologies. Gas centrifuge enrichment has significantly lower ODP impacts than gas diffusion.

4.2.4 Human toxicity potential

Mining and milling are the most important contributions to this impact category, alone accounting for more than 60 % of impacts. From table B.9 it can be seen that this is mostly the direct impacts from the mining and milling processes. Further there a significant difference between open pit and underground mining, meaning that the HTP is somewhat sensitive to choice of mining technology. The impacts from the operation of reactor and hydrogen plant are mostly due to induced economic activity.

4.2.5 Fresh water aquatic ecotoxicity potential

The mining process is by far the most important contributor to the FAETP, close to all coming directly from the mining process (table B.10). There is only minor difference between the different mining technologies. The milling process is the other large contributor, the rest more evenly distributed on background- and input-output processes.

4.2.6 Marine aquatic ecotoxicity potential

Mining and milling covers about 80 % of the impacts in this category. Again almost all of the impacts come directly from the mining and milling processes. There is a small difference between underground and open pit mining, underground mine performing best (table B.11). The result is thus sensitive to a small degree of the mining technology assumption.

4.2.7 Terrestrial ecotoxicity potential, photochemical oxidation potential and acidification potential

Upstream impacts from spent fuel management, milling and operation of reactor/hydrogen plant dominate these impact categories (about 70-80 % of total). They are therefore sensitive to the assumption of no fuel rod pushout when disposing spent fuel. Tables B.12, B.13 and B.14 shows the direct process contributions to the impacts. We see they almost entirely come from background and input-output processes. This is further emphasized in figure 4.2.

4.2.8 Eutrophication potential

Mining and milling contribute most to the eutrophication potential, closely followed by the conversion process and spent fuel management. The dominating direct impacts mainly come from background processes in the LCA-database (table B.15).

4.2.9 Radiation

Mining of uranium is the most important contributor to human health impacts from radiation. But, as we recall from chapter 3.2, the mill tailings continue to exhale radon gas at a constant rate for more than 10000 years. If we take this into account the total radiation impact increases to 7,9E-03 DALY, and the mill tailings share of total goes from under 1 % to account for almost 99 % of the routine radiation impacts (see tables B.16 and B.17). This implies that efforts towards reducing the radiation impacts from from the nuclear cycle should be directed at improved management of mill tailings. UNSCEAR [25] points out that radon emissions from tailings are highly dependent on how they are treated. It also follows that the radiation impacts are not sensitive to the assumptions on mining- and enrichment technology.

5. DISCUSSION AND CONCLUSIONS

5.1 General

The assessment has shown that a hybrid approach to LCA is needed to assess the total environmental impacts from the life cycle. For some impact categories a significant amount of the impacts come from the acquisition of economic activities. One of the most important lessons from this is that ordinary process-LCA fails to calculate all impacts from the life cycle. This might not be a big problem as long as the goal of the LCA is to learn more about a product and identify areas of improvement potential. But; in a comparative assessment, a significantly larger fraction of impacts may be accounted for in one system or for one impact category than in another through process-LCA. Figures 4.1 and 4.2 illustrated the difference between the natural gas case and nuclear hydrogen production. It is obvious that only performing a process-LCA can lead to wrong conclusions.

Since the input-output processes are important contributors to some of the impact categories, the results are sensitive to the assignment of costs to economic sectors. This procedure has been done based on the authors subjective understanding of correlation between different costs and the names of the economic sectors. Better documentation of the input-output database could improve the accuracy of such a procedure.

Applying the procedure to avoid double-counting (see chapter 2.4) of impacts proved to have a significant effect on some of the impact categories. Category values with and without subtracting double counted materials are shown in appendix B.4. The results show that not accounting for this may lead to wrong conclusions; up to 41 % deviation for some impact categories and 20 % for GWP (in % of final results).

5.2 Results of impact assessment

As discussed in chapter 4, natural gas derived hydrogen performs better for all impact categories but GWP, AP and EP. Results from the impact assessment does, however, not prioritize between the different impact categories i.e. no weighting procedure is applied. It is therefore impossible to claim an overall best alternative

for hydrogen production, comparison between the two alternatives can only be done impact category by impact category. If weighting should be required, references [41] and [42] provide an overview and discussion of the different approaches to weighting in LCA.

General observation from the impacts of nuclear hydrogen production is that construction of the reactor/hydrogen plant, fuel fabrication and management of low level waste don‘t contribute to more than 8 % of impacts in any impact category. Aquatic toxic impacts are mainly due to mining and milling activities. Generally it can also be claimed that impacts from nuclear hydrogen production arise further away from the foreground system than the natural gas case (see the tierwise expansion of impacts in figures B.1 and B.2).

Improved management of mill tailings proved to be the most important strategy for reducing the human health impacts from ionizing radiation. This is due to the long term exhalation of radon gas from the tailings.

It should be kept in mind that the results are quite sensitive to the quality of the databases used since much of the inventory has been built from such processes. The input-output database contains highly aggregated data and it is also assumed that the structure of the economy in which the plant is built is equal to that of OECD Europe. Results could therefore be seen more as indicative than exact quantification of impacts.

5.3 On the issues of accidents and spent fuel management

It is hard to discuss aspects of nuclear power without commenting on the politically hot issues of accidents, proliferation and spent fuel management. In an LCA context only impacts resulting from routine operation are accounted. It should be mentioned that the reactor concept assessed in this thesis is described as meltdown proof and that it offers high proliferation resistance. The use of coated particles in the fuel is also said to maintain its integrity for at least a million years in a geologic repository [21]. It has not been the ambition to question this information and only routine impacts are included in the thesis.

The ExternE study [26] however, includes the risks of severe accidents and impacts from radionuclide releases from spent fuel repositories when calculating the total external cost of nuclear power. They do so by calculating the probability of different accident scenarios and estimate the impacts from each scenario. The total risk is the sum of all products of probability and impact. For waste management the migration of spent fuel radioactive waste from the repository is calculated. The experiences from ExternE shows that these risks in principle

could be included in an LCA, but the next question would then be: why stop there? A lot of other accidental situations may occur in the system. Gas tanks can explode, oil tankers may sink, workers can be run over by a truck etc. Without any formal criteria for which accidental situations to include, the selection of such may be based on pre-assessment prejudice. A discussion around these challenges could form the basis for further work.

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APPENDIX

A. ASSUMPTIONS, REFERENCES AND KEY DATA

A.1 Mining

Radionuclide emissions from mining were modified from the UNSCEAR [25] data using the following data:

- 1 GWa[1]= 250 tonnes U_3O_8 [25]
- adjusted with the weight ratio of uranium in U_3O_8

A.2 Milling

For milling and mill tailings emissions, the same assumptions as for mining data were used. A 5 year release from operational mill tailings before they are defined as abandoned is included in milling data [25].

A.3 Conversion

Radionuclide data for conversion were modified from the basis of one TWh,el to one kg uranium in product. This was done by adjusting data from Dreicer and colleagues [27]. The following assumptions were used:

- Dreicer says enrichment level for her data is 3-4 %, hence 3.5 % is assumed
- Discharge burn-up: 42.5 GWd[2]/MTIHM[3] [43]
- Tailings enrichment: 0.3 % [17]
- Thermal efficiency for electricity generation: 0.33 [17]

These are the only data needed to recalculate emissions to the basis of uranium in product.

[1] Gigawatt-year electricity
[2] Gigawatt-days thermal
[3] Metric tonne initial heavy metal

A.4 Enrichment

For the emissions the same assumptions as for conversion applies, but in addition emission data and process inputs need to be adjusted for the enrichment to 19.9 % instead of 3.5 %. This is done by assuming that emissions and inputs scale with natural uranium input. The data are adjusted with the ratio of natural uranium input needed for the enrichment to 19.9 % and enrichment to 3.5 %. For process inputs from LCA-database the data are for 3.25 % and the ratio is calculated from this. Equation 3.1 calculates the natural uranium requirement for one kg uranium at a given enrichment level. Tails enrichment are assumed to be 0.3 %.

An alternative assumption could have been used; that process inputs and -emissions scale with the amount of separative work units (SWU) needed in the process. This is the unit in which enrichment is actually sold. The separative work needed to produce one kg uranium at a given enrichment level x_p is shown in equation A.1 [17].

$$SWU = (2x_p - 1) \cdot ln(\frac{x_p}{1 - x_p}) + \frac{x_p - x_n}{x_n - x_t} \cdot (2x_t - 1) \cdot ln(\frac{x_t}{1 - x_t}) - \frac{x_p - x_t}{x_n - x_t} \cdot (2x_n - 1) ln(\frac{x_n}{1 - x_n}) \quad \text{(A.1)}$$

where x_t denotes tails enrichment, and x_n enrichment of natural uranium.

A.5 Fuel fabrication

The same assumptions as for enrichment apply to fuel fabrication except that the process inputs are assumed to scale with total mass of uranium instead of natural uranium input. The radionuclide emissions however, are assumed to scale with natural uranium input needed for 1 kg uranium in fuel. The share of natural and enriched uranium in the fuel is calculated by simple mass balance to achieve an average enrichment of 13 % U-235.

A.6 Reactor and hydrogen plant

Table A.1 shows material prices and other data used to construct the inventory for the nuclear power plant and the hydrogen plant.

Tab. A.1: Key values used in all calculations

Material costs	**Value**	**Unit**	**Comment**	**Source**
Steel	8	NOK/kg	Carbon steel	[44]
Cement	0.558	NOK/kg		[45]
Wood	387	NOK/m3	Avg. jan-may 2004	[46]
Copper	2452.85	eur/tonne	Avg. Mar. 2004	[47]
Lead	722.55	eur/tonne	Avg. Mar. 2004	[47]
Titanium	12.07	$/kg	Spot price 30/4/2004	[48]
PVC	0.5	$/lb	Spot price december 2000	[49]
Aluminium	1350.28	eur/tonne	Avg. Mar. 2004	[47]
Mineral wool	10	SEK/kg	Price request spring 2004	[50]
Explosives	Not possible to obtain		Neglected	
Other				
eur/$	0.88564		Avg. 2003	[51]
SEK/$	8.08492		Avg. 2003	[51]
NOK/$	7.08061		Avg. 2003	[51]
1 Ci	3.70E+10	Bq		[52]
Mass/volume wood	0.7			[23]
1lb =	0.454	kg		

A.6.1 Material inputs

For the calculation of material inputs, a number of assumptions had to be made:

- The two units together has the same material intensity per MW thermal effect as the Swedish nuclear power plant Forsmark 3 so that swedish LCA data [29] could be used. Allocation of the material inputs to the hydrogen plant and nuclear plant respectively, was based on the ratio between their total costs. The use of transformer oil is ignored since no electricity generation takes place.
- Plant lifetime 60 yrs [21]
- Discharge burn-up: 100 GWd/MTIHM [20]
- Capacity factor: 0.9 [21]

The amount of fuel needed to produce 1 TJ heat can be calculated by equation A.2.

$$M = \frac{Q}{B_d} \tag{A.2}$$

where M is the mass of uranium needed, Q is 1 TJ heat expressed in in GWd and B_d is the discharge burn-up. Given the efficiency of 52 % for the plant [19], the total heat demand for producing 1 TJ of hydrogen is 1.92 TJ. Inputs of construction to the use of the facilities is based on the 1 TJ share of total lifetime

heat- and hydrogen production.

Further the water use and iodine inventory were given by [19]. A 6 % per year chemical turnover was assumed [20].

A.6.2 Economic inputs

Economic cost data was provided by [19]. Only costs for the *actual* construction and chemicals were included. Interests and contingencies were therefore disregarded. Costs were assigned to economic sectors based on their respective names and the sparse information in the database-documentation.

For the subtraction of inputs to avoid double counting, the assignment of materials to economic sectors is shown i table A.2. The term "ratio" is the ratio of economic value bought by sector *Machine and electrical equipment industry, OECD Europe* from e.g. sector *Metal products industry, OECD Europe* divided by *Machine and electrical equipment industry, OECD Europe* total output.

Tab. A.2: Assignment of materials to economic sectors

Material	Ratio	Economic sector
Steel	0.0534	Metal products industry, OECD Europe
Copper,lead,aluminium,titanium	0.0506	Base metal industry, OECD Europe
Concrete, mineral wool	0.0082	Building material industry, OECD Europe
Wood	0.0025	Wood industry, OECD Europe
PVC	0.0386	Chemical, rubber and plastics industry, OECD Europe

For deconstruction of the facilities it was assumed that the *material values* pays for demolition and that the sector *Building and installation industry, OECD Europe* does this. The deconstruction costs were added to the construction inputs from this sector.

The disaggregated economic data for construction of the hydrogen plant had to be adjusted slightly to fit the size of the nuclear plant. This had already been done in the cost summary of Brown and colleagues [19], and the sub-costs were adjusted linearly to the difference in total costs.

Subtraction of material costs in the use phase was found to be negligible compared to other costs, so this subtraction was only performed in the construction phase.

A.7 Spent fuel management

For the management of spent fuel and low level waste from the nuclear power plant, data from ETH-ESU 96 were used. These include transport needs, materials and the construction of storage facilities, but assumes no radionuclide

emissions from the management of spent fuel and LLW. The amount of spent fuel and LLW is taken from an IAEA-report [30] and normalized to the amount per TJ heat produced in reactor. It was conservatively assumed that the spent fuel would be disposed of without fuel rod pushout. If the rods are pushed out, the spent fuel volume decreases to only 23 % of the original volume and the impacts from spent fuel management by the same factor. For the modification of data it was assumed that the MHTGR in the IAEA report had a capacity factor of 0.9. Other data needed for modification are given in the report.

B. ADDITIONAL DATA

B.1 The inventory matrices

Note: All rows containing only zeros have been removed from the matrices

Tab. B.1: The$\mathbf{A}_f$-matrix

Foreground process	Construction NPP[p]	Construction H2-plant[p]	Mining [kg U in U3O8@0.71%]	Milling [kg U in U3O8@0,71%]	Mill tailings[kg U out of mill]	Conversion [kg U in UF6@0.71%]	Enrichment [kg U in UF6@19.9%]	Fabrication [kg U in fuel@19.9%)]	Spent fuel management [m3 HLW]	LLW from plant [m3 LLW]	Operation NPP [TJ heat]	Operation H2-plant [TJ H2]
Construction NPP[p]	0	0	0	0	0	0	0	0	0	0	2.45E-07	0
Construction H2-plant[p]	0	0	0	0	0	0	0	0	0	0	0	4.71E-07
Mining [kg U in U3O8@0.71%]	0	0	0	1.00	0	0	0	0	0	0	0	0
Milling [kg U in U3O8@0,71%]	0	0	0	0	0	1.00	0	0.36	0	0	0	0
Mill tailings[kg U out of mill]	0	0	0	1.00	0	0	0	0	0	0	0	0
Conversion [kg U in UF6@0.71%]	0	0	0	0	0	0	47.80	0	0	0	0	0
Enrichment [kg U in UF6@19.9%]	0	0	0	0	0	0	0	0.64	0	0	0	0
Fabrication [kg U in fuel@19.9%)]	0	0	0	0	0	0	0	0	0	0	1.16E-01	0
Spent fuel management [m3 HLW]	0	0	0	0	0	0	0	0	0	0	3.27E-03	0
LLW from plant [m3 LLW]	0	0	0	0	0	0	0	0	0	0	2.26E-03	0
Operation NPP [TJ heat]	0	0	0	0	0	0	0	0	0	0	0	1.92
Operation H2-plant [TJ H2]	0	0	0	0	0	0	0	0	0	0	0	0

Tab. B.2: The $\mathbf{S}_{ETH}$-matrix

ETH-ESU 96 process	Unit	Construction NPP[p]	Construction H2-plant[p]	Mining [kg U in U3O8@0.71%]	Milling [kg U in U3O8@0,71%]	Mill tailings[kg U out of mill]	Conversion [kg U in UF6@0.71%]	Enrichment [kg U in UF6@19.9%]	Fabrication [kg U in fuel@19.9%)]	Spent fuel management [m3 HLW]	LLW from plant [m3 LLW]	Operation NPP [TJ heat]	Operation H2-plant [TJ H2]
Uranium 3.7% in fuel element PWR D U[a]	kg	0	0	0	0	0	0	0	1	0	0	0	0
Uranium enriched 3.25% URENCO U[b]	kg	0	0	0	0	0	0	0.5	0	0	0	0	0
Uranium enriched 3.25% EURODIF U[b]	kg	0	0	0	0	0	0	0.5	0	0	0	0	0
Uranium in ore (open mine) U[c]	kg	0	0	0.5	0	0	0	0	0	0	0	0	0
Uranium in ore (underground mine) U[c]	kg	0	0	0.5	0	0	0	0	0	0	0	0	0
Uranium natural in concentrate U[c]	kg	0	0	0	1	0	0	0	0	0	0	0	0
Uranium natural in UF6 U[c]	kg	0	0	0	0	0	1	0	0	0	0	0	0
Explosives ETH U	kg	126214	96749	0	0	0	0	0	0	0	0	0	0
H2 ETH U	kg	0	2000	0	0	0	0	0	0	0	0	0	0
H2SO4 ETH U	kg	0	100000	0	0	0	0	0	0	0	0	0	0.17
Low radioactive waste U	m3	0	0	0	0	0	0	0	0	0	1	0	0
Mineral wool ETH U	kg	106469	81614	0	0	0	0	0	0	0	0	0	0
RA waste interim storage C U[d]	m3	0	0	0	0	0	0	0	0	1	0	0	0

[a] This process is modified as explained in chapter 3.5, all the modified processes are treated as foreground processes in the calculations

[b] The process is modified, see chapter 3.4 and for details

[c] Modified according to chapter 3.1, 3.2 and 3.3

[d] This process includes the demand of 1m^3 of the process *Radioactive waste in final storage C U* i.e. final storage.

Tab. B.3: The $\mathbf{S}_{Idemat}$-matrix

Idemat 2001 process	Unit	Construction NPP[p]	Construction H2-plant[p]	Mining [kg U in U3O8@0.71%]	Milling [kg U in U3O8@0,71%]	Mill tailings[kg U out of mill]	Conversion [kg U in UF6@0.71%]	Enrichment [kg U in UF6@19.9%]	Fabrication [kg U in fuel@19.9%)]	Spent fuel management [m3 HLW]	LLW from plant [m3 LLW]	Operation NPP [TJ heat]	Operation H2-plant [TJ H2]
Aluminium ingots I	kg	2.904E+04	2.226E+04	0	0	0	0	0	0	0	0	4.34E-03	6.14E-03
Concrete I	kg	5.227E+07	4.006E+07	0	0	0	0	0	0	0	0	0	0
Copper I	kg	4.065E+05	3.116E+05	0	0	0	0	0	0	0	0	3.60E-02	5.10E-02
Lead I	kg	6.582E+04	5.045E+04	0	0	0	0	0	0	0	0	9.83E-03	1.39E-02
PVC (s) I	kg	2.253E+05	1.727E+05	0	0	0	0	0	0	0	0	3.36E-02	4.77E-02
Spruce, European I	kg	4.956E+06	3.799E+06	0	0	0	0	0	0	0	0	0	0
Steel I	kg	1.328E+07	1.018E+07	0	0	0	0	0	0	0	0	1.32E-01	1.87E-01

Tab. B.4: The $\mathbf{S}_{IO}$-matrix

Input-Output sector	Unit	Construction NPP[p]	Construction H2-plant[p]	Mining [kg U in U3O8@0.71%]	Milling [kg U in U3O8@0,71%]	Mill tailings[kg U out of mill]	Conversion [kg U in UF6@0.71%]	Enrichment [kg U in UF6@19.9%]	Fabrication [kg U in fuel@19.9%)]	Spent fuel management [m3 HLW]	LLW from plant [m3 LLW]	Operation NPP [TJ heat]	Operation H2-plant [TJ H2]
Base metal industry, OECD Europe	USD	-2.74E+07	-2.41E+07	0	0	0	0	0	0	0	0	-4.39E+01	-4.11E+01
Building and installation industry, OECD Europe	USD	1.53E+08	3.04E+07	0	0	0	0	0	0	0	0	0	0
Building material industry, OECD Europe	USD	-4.43E+06	-3.88E+06	0	0	0	0	0	0	0	0	0	0
Chemical, rubber and plastics industry, OECD Europ	USD	-2.09E+07	1.01E+08	0	0	0	0	0	0	0	0	-3.35E+01	1.63E+02
Machine and electrical equipment industry, OECD Eu	USD	5.42E+08	4.75E+08	0	0	0	0	0	0	0	0	8.67E+02	8.12E+02
Metal products industry, OECD Europe	USD	-2.89E+07	-2.54E+07	0	0	0	0	0	0	0	0	-4.63E+01	-4.34E+01
Public (government) and other services, OECD Europ	USD	4.73E+07	0	0	0	0	0	0	0	0	0	1.30E+02	1.51E+02
Wood industry, OECD Europe	USD	-1.33E+06	-1.16E+06	0	0	0	0	0	0	0	0	0	0

Tab. B.5: The transpose $\mathbf{E}_f$-matrix

Emission/Raw material	Unit	Construction NPP[p]	Construction H2-plant[p]	Mining [kg U in U3O8@0.71%]	Milling [kg U in U3O8@0,71%]	Mill tailings[kg U out of mill]	Conversion [kg U in UF6@0.71%]	Enrichment [kg U in UF6@19.9%]	Fabrication [kg U in fuel@19.9%)]	Spent fuel management [m3 HLW]	LLW from plant [m3 LLW]	Operation NPP [TJ heat]	Operation H2-plant [TJ H2]
I (raw)	kg	0	2.120E+06	0	0	0	0	0	0	0	0	0	3.59E+00
water (raw)	kg	0	0	0	0	0	0	0	0	0	0	0	5.10E+01
Ar41 to air	Bq	0	0	0	0	0	0	0	0	0	0	1.86E+07	0
Ba140 to water	Bq	0	0	0	0	0	0	0	0	0	0	2.89E-01	0
Cs137 to water	Bq	0	0	0	0	0	0	0	0	0	0	2.05E+02	0
H3 to air	Bq	0	0	0	0	0	0	0	0	0	0	9.31E+06	0
I131 to water	Bq	0	0	0	0	0	0	0	0	0	0	4.56E+00	0
Kr85 to air	Bq	0	0	0	0	0	0	0	0	0	0	3.72E+07	0
Pb210 to air	Bq	0	0	0	9.43E+01	0	0	0	0	0	0	0	0
Pb210 to water	Bq	0	0	0	4.72E+01	0	0	0	0	0	0	0	0
Po210 to air	Bq	0	0	0	9.43E+01	0	0	0	0	0	0	0	0
Ra226 to air	Bq	0	0	0	9.43E+01	0	0	0	0	0	0	0	0
Ra226 to water	Bq	0	0	0	8.25E+01	0	0	0	0	0	0	0	0
Rn222 to air	Bq	0	0	3.54E+08	1.08E+08	4.72E+06	0	0	0	0	0	0	0
Th230 to air	Bq	0	0	0	9.43E+01	0	0	0	0	0	0	0	0
Th230 to water	Bq	0	0	0	5.90E+01	0	0	0	0	0	0	0	0
U234 to air	Bq	0	0	0	1.89E+03	0	1.74E+01	5.02E+01	7.92E-01	0	0	0	0
U234 to water	Bq	0	0	0	0.00E+00	0	5.52E+02	1.00E+01	1.14E+03	0	0	0	0
U235 to air	Bq	0	0	0	0.00E+00	0	7.55E-01	2.56E+00	5.28E-02	0	0	0	0
U235 to water	Bq	0	0	0	0.00E+00	0	2.37E+01	5.02E-01	7.55E+01	0	0	0	0
U238 to air	Bq	0	0	0	1.89E+03	0	1.64E+01	2.64E+01	1.95E-01	0	0	0	0
U238 to water	Bq	0	0	0	1.42E+03	0	5.22E+02	5.28E+00	2.80E+02	0	0	0	0
waste heat to air	MJ	0	0	0	0	0	0	0	0	0	0	4.80E+05	0
Xe133 to air	Bq	0	0	0	0	0	0	0	0	0	0	9.31E+06	0

B.2 Most contributing processes to each impact category

Note: Processes starting with "0-Christian" are the modified database processes discussed in chapter 3. These are treated as part of the foreground processes.

Tab. B.6: ADP

Process	%
Raw natural gas NL U	17.3
Crude oil production onshore U	15.9
Crude oil production offshore U	12.5
Raw natural gas GUS U	11.6
Coal from underground mine UCPTE U	11.2
Raw natural gas D U	8.2
Raw natural gas Alg. U	5.4
Raw natural gas N U	4.0
Crude lignite mine UCPTE U	3.5
Steel I	2.7

Tab. B.7: GWP

Process	%
Natural gas furnace >100kW Europe U	17.5
Chemical, rubber and plastics industry, OECD Europ	10.9
Electricity companies, OECD Europe	10.1
Transport services, OECD Europe	7.2
0-Christian(19,9%)Uranium enriched 3.25% EURODIF U	3.6
Diesel in building equipment U	3.6
Oil industry, OECD Europe	3.3
Machine and electrical equipment industry, OECD Eu	3.0
Base metal industry, OECD Europe	2.9
Residual oil Europe in boiler 1MW U	2.7

Tab. B.8: ODP

Process	%
0-Christian(19,9%)Uranium enriched 3.25% EURODIF U	67.4
Chemical, rubber and plastics industry, OECD Europ	13.2
0-Christian(19,9%)-Uranium enriched 3.25% URENCO U	9.4
Crude oil production onshore U	3.1
Uranium enriched 3.4% EURODIF U	2.6
Crude oil production offshore U	1.2
Tanker oceanic ETH U	1.1
Building and installation industry, OECD Europe	0.8
Production of other food for humans, OECD Europe	0.4
Uranium enriched 3.5% EURODIF U	0.2

Tab. B.9: HTP

Process	%
0-Christians-Uranium natural in concentrate U	35.7
0-Christians-Uranium in ore (underground mine) U	20.9
Machine and electrical equipment industry, OECD Eu	14.5
Electricity companies, OECD Europe	6.4
0-Christians-Uranium in ore (open mine) U	4.2
Oil industry, OECD Europe	3.0
Transport services, OECD Europe	2.9
Chemical, rubber and plastics industry, OECD Europ	1.8
Natural gas furnace >100kW Europe U	1.3
Residual oil Europe in boiler 1MW U	1.1

Tab. B.10: FAETP

Process	%
0-Christians-Uranium in ore (open mine) U	39.7
0-Christians-Uranium in ore (underground mine) U	38.3
0-Christians-Uranium natural in concentrate U	15.8
Machine and electrical equipment industry, OECD Eu	2.6
Crude oil production offshore U	0.9
Residual oil Europe in boiler 1MW U	0.6
Uranium in ore (open mine) U	0.3
Chemical, rubber and plastics industry, OECD Europ	0.2
0-Christian-Uranium 3.7% in fuel element PWR D U	0.2
Uranium in ore (underground mine) U	0.2

Tab. B.11: MAETP

Process	%
0-Christians-Uranium natural in concentrate U	36.3
0-Christians-Uranium in ore (underground mine) U	24.1
0-Christians-Uranium in ore (open mine) U	14.1
0-Christian(19,9%)Uranium enriched 3.25% EURODIF U	4.4
0-Christians-Uranium natural in UF6 U	3.8
HF ETH U	2.1
Lignite power plant in D U	2.1
Residual oil Europe in boiler 1MW U	1.7
Coal power plant in E U	1.5
Coal power plant in D U	1.2

Tab. B.12: TETP

Process	%
Residual oil Europe in boiler 1MW U	28.5
Machine and electrical equipment industry, OECD Eu	24.9
Chemical, rubber and plastics industry, OECD Europ	13.0
Residual oil in refinery furnace Europe U	4.7
Electricity oil I U	3.8
Freighter oceanic ETH U	1.9
Sinter ETH U	1.7
Steel I	1.6
Coal power plant in E U	1.4
Tanker oceanic ETH U	1.3

Tab. B.13: PCOP

Process	%
Transport services, OECD Europe	20.2
Base metal industry, OECD Europe	11.3
Electricity companies, OECD Europe	8.9
H2SO4 ETH U	6.7
Residual oil Europe in boiler 1MW U	4.9
Oil and Gas extraction, OECD Europe	4.1
Steel I	3.7
Machine and electrical equipment industry, OECD Eu	2.7
Sinter ETH U	2.6
Diesel in diesel generator offshore U	2.1

Tab. B.14: AP

Process	%
Electricity companies, OECD Europe	13.6
Base metal industry, OECD Europe	11.5
H2SO4 ETH U	10.4
Residual oil Europe in boiler 1MW U	7.9
Diesel in diesel generator onshore U	5.3
Oil and Gas extraction, OECD Europe	4.9
Diesel in building equipment U	4.3
Machine and electrical equipment industry, OECD Eu	3.8
Nickel enriched ETH U	2.8
Chemical, rubber and plastics industry, OECD Europ	2.5

Tab. B.15: EP

Process	%
Diesel in diesel generator onshore U	21.9
Diesel in building equipment U	19.8
Diesel in diesel generator offshore U	6.3
Natural gas furnace >100kW Europe U	5.9
0-Christians-Uranium natural in concentrate U	4.3
Animal husbandry/ Cattle breeding, OECD Europe	3.0
0-Christians-Uranium natural in UF6 U	2.9
Truck 28t ETH U	2.9
Truck 40t ETH U	2.4
Residual oil Europe in boiler 1MW U	2.2

Tab. B.16: R

Process	%
Mining [kg U in U3O8@0.71%]	65.2
Milling [kg U in U3O8@0,71%]	21.6
Spent fuel processing U	5.6
Electricity nuclear power plant in F (PWR) U	3.9
Electricity nuclear BWR CH U	1.1
Mill tailings[kg U out of mill]	0.9
Uranium in ore (underground mine) U	0.5
Electricity nuclear PWR CH U	0.4
Operation NPP [TJ heat]	0.4
Uranium natural in concentrate U	0.2

Tab. B.17: R-10000 yrs

Process	%
Mill tailings[kg U out of mill]	98.9
Mining [kg U in U3O8@0.71%]	0.7
Milling [kg U in U3O8@0,71%]	0.2
Spent fuel processing U	0.1
Electricity nuclear power plant in F (PWR) U	0.0
Electricity nuclear BWR CH U	0.0
Uranium in ore (underground mine) U	0.0
Electricity nuclear PWR CH U	0.0
Operation NPP [TJ heat]	0.0
Uranium natural in concentrate U	0.0

B.3 Accumulated impacts from each tier

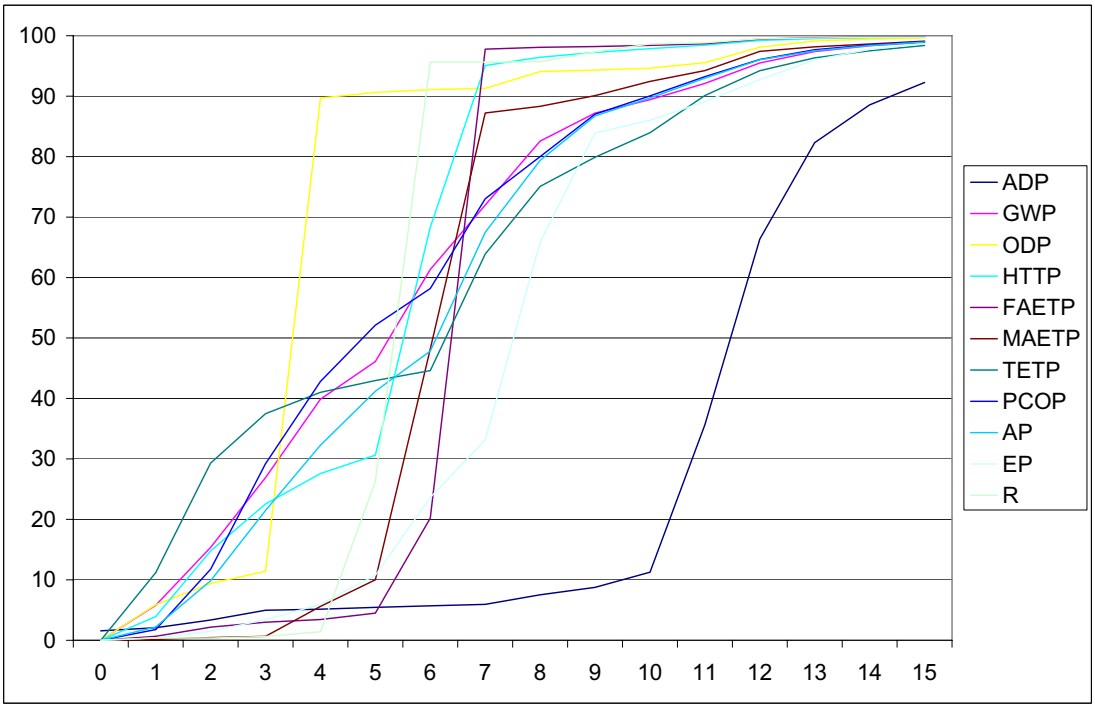

Fig. B.1: Accumulative impacts by tier number for nuclear hydrogen production in % of total

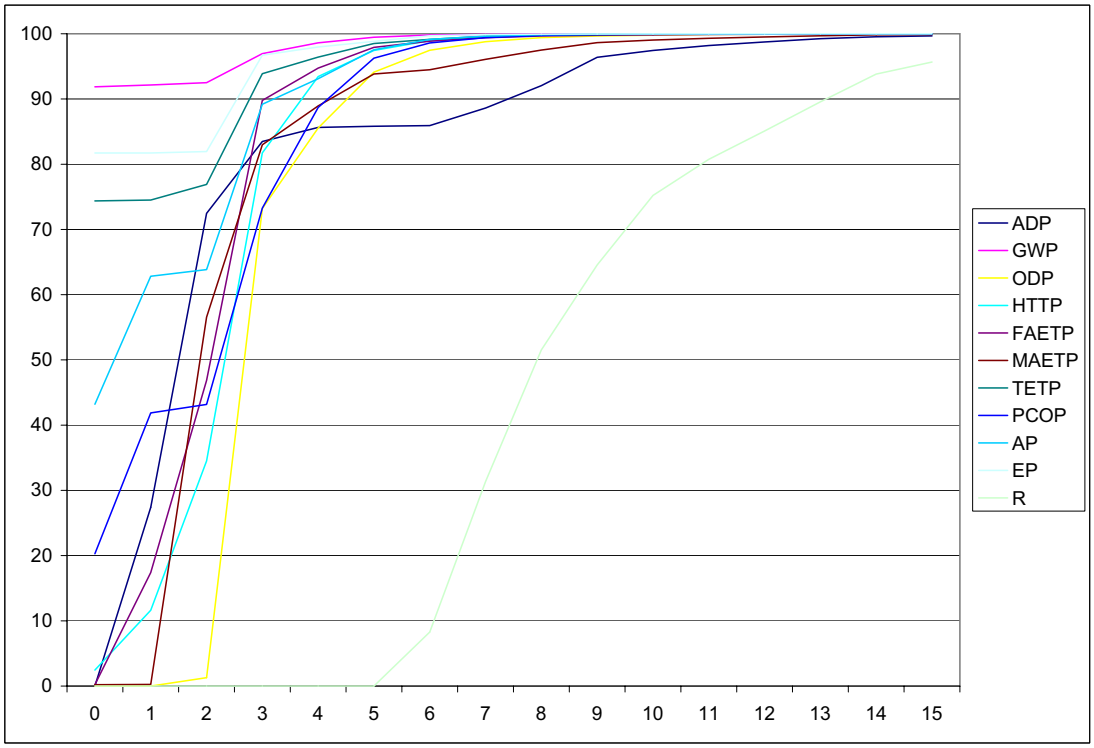

Fig. B.2: Accumulative impacts by tier number for natural gas hydrogen production in % of total

B.4 Importance of avoiding double counting

Tab. B.18: Comparison of impacts with and without accounting for double counting

Impact cat.	W.o. avoiding double counting	After subtr. double counting	Difference (in % of final results)
ADP	9.75E+00	9.75E+00	0
GWP	2.96E+03	2.46E+03	20
ODP	1.26E-02	1.19E-02	6
HTP	4.14E+03	3.88E+03	7
FAETP	6.70E+02	6.67E+02	0
MAETP	1.98E+06	1.98E+06	0
TETP	5.88E+00	5.45E+00	8
PCOP	1.40E+00	9.93E-01	41
AP	2.26E+01	1.61E+01	41
EP	8.02E-01	7.88E-01	2
R	8.98E-05	8.98E-05	0

Program for industriell økologi (IndEcol) er et tverrfaglig universitetsprogram etablert i 1998 for en periode på minst ti år ved Norges teknisk-naturvitenskapelige universitet (NTNU). Programmet omfatter et studieprogram opprettet i 1999 og et stort antall doktorgradsprosjekter og forskningsprosjekter rettet mot vareproduserende industri, energi- og byggesektoren. Tverrfaglig forskning og undervisning står sentralt ved IndEcol, og målet er å knytte sammen teknologiske, naturvitenskapelige og samfunnsvitenskapelige bidrag i letingen etter bærekraftige løsninger på produksjon og forbruk av energi og ressurser.

The Industrial Ecology Programme (IndEcol) is a multidisciplinary university programme established at the Norwegian University of Science and Technology (NTNU) in 1998 for a period of minimum ten years. It includes a comprehensive educational curriculum launched in 1999 and a significant number of doctoral students as well as research projects geared towards Norwegian manufacturing, energy and building industries. The activities at IndEcol has a strong attention to interdisciplinary research and teaching, bridging technology, natural and social sciences in the search for sustainable solutions for production and consumption of energy and resources.

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