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Hybrid Life Cycle Assessment of Large Scale Hydrogen Production Facilities

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Abstract

An environmental assessment of three designs for a large-scale hydrogen production facility is performed using a Hybrid Life Cycle Assesment approach. The operational adaption of the hybrid framework for this case is shown in detail. The inventory establishment and assembly is explained. The impact assessment is performed by applying midpoint environmental theme indicators. The resulting impact potentials and their origins are presented and discussed for all three cases and for each impact category. It is shown through this comprehensive, life cycle assessment, that carbon emissions can be reduced by the introduction of carbon deposition and use of the produced hydrogen to generate process heat. This benefit, however, comes at the cost of increased impacts in other categories. These environmental repercussions are quantified and discussed.

Key words: Hybrid Life Cycle Assessment, Environmental Input-Output Analysis, Hydrogen Production

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1 Introduction

Hydrogen is seen by many as the most promising future energy carrier, continuing a historical trend towards cleaner, less carbon-rich fuels. The use of hydrogen as a fuel for the next generation of vehicles, with a fuel cell replacing

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the internal combustion engine, is being promoted by car manufactures, business magazines, analysts (eg. Ogden et.al [1]) and is seriously considered by oil companies. The demand for zero tailpipe emissions has been pushing for the development of this technology. However, large investments will be required in fuel production, infrastructure, car manufacture and organizational and social training before a hydrogen economy can be operational.

The application of Life Cycle Assessment (LCA) to evaluate a technology provides a better understanding of the environmental impacts that will be imposed if, or when, this technology is introduced. Hertwich and Strømman [2] have compared available LCA studies of hydrogen production. The results for hydrogen production via steam reforming of natural gas without carbon capture vary between[1] 59.4 kg CO_2/GJ [3], 80.2 kg CO_2/GJ [4] and 111.5 kg CO_2/GJ [5]. Maclean [6] reports a scatter of 25 to 325 kg CO_2/GJ for various hydrogen production processes in the literature reviewed. Differences in the results presented in the literature for steam reforming can only partly be explained in terms of the size or design of the facilities. An incomplete accounting for the upstream processes and assumptions regarding the production of electricity are likely to account for the rest. Depending on which LCA result is used, hydrogen-driven fuel cell cars either offer an opportunity to substantially reduce CO2 emissions caused by private transport or are not better than improved gasoline-driven internal combustion engine (ICE) cars [2, 5]. A reliable assessment of the emissions associated with hydrogen production is therefore a prerequisite for the evaluation of hydrogen as a future fuel and of fuel-cell cars as a proposed alternative to ICE cars. If policy makers decide on the introduction of hydrogen as a transportation fuel, assessments of different production alternatives are also required to select a desirable pathway for technology introduction, such as those presented by Barreto et.al [7]. This also concerns the capture and deposition of CO_2 from the hydrogen production process, that is whether, and if yes, when and how, it should happen. The results from this study are hence useful for future assessment of transportation systems (well-to-wheel studies) and for the development of energy scenarios such as those developed for the IPCC by Nakicenovic et.al [8].

In collaboration with Norsk Hydro, we established an inventory for one of their proposed designs of a large-scale hydrogen production plant with a daily production rate of 850 000 Nm^3 H_2. This is equivalent to 85 PJ/yr or 2700MW output. In Figure 1, the box "operation of plant" displays the process flow of the hydrogen production plant. The plant is based on an oxygen-fired autothemal reformer (ATR). The produced hydrogen is of fuel grade quality and leaves the process plant at a pressure of 100 bar. The base design plant has a first law efficiency of 72%.

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[1] Please note that all energy notations in this paper are LHV

In this study, three variations of this base design are investigated. These variations concern the carbon contained in the process feed and in the fuel of the auxiliary heaters. In the original design, the carbon in the natural gas of both the process feed and in the boiler feed is emitted as CO_2. This case is throughout the text denoted as NG. The basic carbon capture and deposition option, denoted NGD, is to contain and deposit the CO_2 produced from the process feed. The heaters are kept fueled with natural gas so the CO_2 emissions from the heaters are still present. The third option is to deposit the CO_2 from the process feed, as in the NGD case, and use the produced hydrogen to fire the boilers. This case is refereed to as H.

The heat and mass flows in the three systems are identical except for the heaters, which are fed with natural gas in the first two cases and produced hydrogen in the last. As for the carbon capture and absorbtion, only the CO_2 absorption process is an integral part of the chemical process design, so the deposition of CO_2 can be added to the process plant inventory without requiring any changes in the process plant design.

The research goal of this work is to reveal what the main environmental impacts of these three designs of ATR-based hydrogen production are and where they originate in the system.

2 Methods

It is necessary to establish an inventory for plant engineering, construction, and operation in order to assess the life cycle of the plant from the design to the end of its operational life. It is cumbersome and often difficult to establish process inventory data for many of the processes involved in these various life cycle steps. Therefore, the LCA practice is apply cutoff rules. This can lead to partially accounting of data. A hybrid LCA approach, proposed by various authors [9–14], offers alternative ways to deal with these processes. A hybrid LCA approach allows for monetary inputs to the processes in addition to the standard material and energy-based process inputs in LCA. The present study, presents one of the first applications of a hybrid LCA.

We briefly present the basics of input-output methodology to explain how the environmental stressors associated with monetary inputs are generated. We will then show how this is combined with the process flow matrix in our application of a hybrid LCA approach.

Economic input-output analysis was developed by Leontief [15] to display and analyze the interactions between different sectors of the economy. He also pioneered environmental input-output analysis and his article [16] initiated a thorough discussion of this application of input-output analysis [17–21]. Applications of environmental input-output modelling (EIO) in scenario analysis and in LCA includes references [22–27].

The core of an input-output model is the requirements, or coefficients, matrix A. The columns of this matrix describe the intermediate inputs an industry buys, from itself and other industries, to produce one unit of output. In Eq. 1 the industry output vector, x, is the sum of the final demand vector, y, plus the industry activity required to supply input to the production, the intermediate demand, Ax.

$$Ax + y = x \tag{1}$$

Solving for x to find the resulting industry output for a given demand y;

$$(I - A)x = y \Leftrightarrow x = (I - A)^{-1}y \tag{2}$$

x will then represent the production of a set of commodities or activities in all industrial sectors to achieve a certain final demand y. $(I-A)^{-1}$ is known as the Leontief inverse. These equations will naturally work with A describing, not only monetary flows, but also mass and energy flows as in LCA. We denote all these types of $(I - A)$ matrices, as L, Leontief matrices. Recommended background literature on input-output analysis includes [15, 28–31]. For a thorough introduction to the mathematics of LCA see [32].

National accounts track the make and use of commodities by different sectors in the economy. There are different approaches to combine these make-and-use tables to generate industry-by-industry or commodity-by-commodity coefficient matrices. The most common ones are the industry-technology and the commodity-technology assumption [31]. The industry-technology assumption implies that different commodities produced within one industry uses the same technology. The commodity-technology assumption says that one commodity will be produced using the same technology in all industries. In other words, we have to choose whether the technology belongs to the industry or to the commodity. An overview of various other approaches is given in [33].

We have used the Norwegian input-output tables, at the Multi-Sector-Growth (MSG) aggregation level from 1997 with emission intensities from the same year. Due to the high aggregation level, only 40 sector by 54 commodities, the commodity-technology assumption is difficult to apply due to real differences in production technology within the aggregated commodity groups. The industry technology assumption is therefore applied in this case. Imports are treated as if they were produced in a foreign economy that was identical to the Norwegian economy.

The economic input-output coefficient matrix, A was generated in accordance with the UN handbook on input-output table compilation and analysis [31] and Statistics Norway [34].

Applying the industry technology assumption to generate an industry-by-industry coefficient matrix A, we obtain Eq. 3.

$$x = (I - DB)^{-1}y \tag{3}$$

Where B and D, respectively, are the normalized make-and-use tables as defined in Table 1, [31].

c	Number of commodities	
n	Number of industries	
U	The use matrix	(c, n)
M	The make matrix	(c, n)
$g = M'i$	industry intermediate and final output vector	(n)
$q = Mi$	commodity intermediate and final output vector	(c)
$B = U\hat{g}^{-1}$	the domestic intermediate input structure matrix	(c, n)
$D = M'\hat{q}^{-1}$	the domestic market share matrix	(n, c)

Table 1: Vectors and matrices from the Norwegian national accounts

The Leontief matrix for the economic input output part of the hybrid model denoted L_{io} is now established as shown in Eq. 4

$$L_{io} = I - DB \tag{4}$$

The process database used is IDEMAT 2001 [35], converted into matrix form. All the inputs and outputs in the process database have been normalized to a unit output of the process. Variations in units have been adjusted for and set to standard SI units. The IDEMAT 2001 database is generated as a Leontief matrix for this purpose but in order to avoid misunderstandings we denote the normalized process matrix as P. Thus the corresponding Leontief matrix is given as in Eq. 5.

$$L_p = I - P \tag{5}$$

The system assembly, describing the various components of the hydrogen production plant, is represented by matrix S_a, see Table 2. The matrices S_p and

S_c describe the process input and the commodity input to the processes in S_a, respectively.

The three sub matrices of the S matrix containing the system inventory and assembly are shown in Eq. 6. The matrix legend is found in Table 2.

a	assembly processes	
p	background processes	
c	commodities	
n	industries	
S_a	System assembly	(a, a)
S_p	Input processes	(p, a)
S_c	Input of commodities	(c, a)
S_s	Input from industries	(n, a)

Table 2: S-matrices

$$S = \begin{bmatrix} S_a \\ S_p \\ S_c \end{bmatrix} \tag{6}$$

$$S_n = DS_c \tag{7}$$

The emission intensities for the MSG input-output matrices are on a sector basis and the final demand is on a commodity basis. One option to deal with this is to find the corresponding industry demand to a given commodity demand for use with an industry-by-industry matrix.

This is done in Eq. 7 showing the multiplication of sub-matrix S_c with the market share matrix D to find the S_n matrix containing the industry demand. From this a new S matrix containing S_s with purchases from industries can be assembled as shown in Eq. 8.

$$S = \begin{bmatrix} S_a \\ S_p \\ S_n \end{bmatrix} \tag{8}$$

A Leontief matrix L describing all the processes and activities connected to hydrogen production, i.e. the entire life cycle, is then compiled from the individual sub-matrices describing the various sub-systems: the foreground physical flows, the background physical flows, the background economic flows, and their interconnectivity.

$$L = \begin{bmatrix} I - S_a & 0 & 0 \\ -S_p & I - P & 0 \\ -S_n & 0 & I - DB \end{bmatrix} \tag{9}$$

By formulating a vector containing a demand for the functional unit of 1 GJ H2, y_a the output processes and industries can be calculated as shown in Eq. 10

$$\begin{bmatrix} I - S_a & 0 & 0 \\ -S_p & I - P & 0 \\ -S_n & 0 & I - DB \end{bmatrix}^{-1} \begin{bmatrix} y_a \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} x_a \\ x_p \\ x_n \end{bmatrix} \tag{10}$$

Matrix E, containing the coefficients of emission and resource use related to the system flows, was assembled following the compartment structure in the LCA software SimaPro [36]. The six groups are: raw material use, air emissions, water emissions, solid emissions, soil emissions, and non-material emissions. E has the following structure:

$$E = \begin{bmatrix} E_s \\ E_p \\ E_n \end{bmatrix} = \begin{bmatrix} E_{a,raw} & E_{a,air} & E_{a,wat} & 0 & 0 & 0 \\ E_{p,raw} & E_{p,air} & E_{p,wat} & E_{p,sold} & E_{p,soil} & E_{p,nmat} \\ 0 & E_{n,air} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

With a total of 503 processes described in IDEMAT2001 and number of emissions in the various compartments being 2331, E has 561 rows by 2331 columns. However the emissions inventory is not complete for all compartments. The emission data for the Norwegian economy only contains greenhouse gases and heavy metals plus particulate matter to air. Therefore only sub-matrix $E_{n,air}$ contains values in the E_n matrix. The E_p Matrix is the emissions inventory for the IDEMAT 2001 database by Delft University of Technology [35]. E_s is the emissions inventory for the processes modelled in this study, containing emissions to air and water.

The vector e in Eq. 12 describes the life cycle inventory of emissions and resource uses of a functional unit specified in y.

$$e = E'L^{-1}y \tag{12}$$

The life cycle impact assessment used in this study consists of characterization of emissions and resource use following [37]. The structure of matrix W containing the characterization factors is shown in Eq. 13

$$W = \begin{bmatrix} W_{raw,ADP} & \cdots & W_{namt,ADP} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ W_{raw,EP} & \cdots & W_{namt,EP} \end{bmatrix} \tag{13}$$

The vector f containing the set of indicators can then be calculated as shown in Eq. 14.

$$f = WE'L^{-1}y \tag{14}$$

3 Data

The inventory, established in matrix S, is based on a detailed process plant design in combination with detailed cost estimates for the design, construction and operation of the plant, all provided by Norsk Hydro[38]. Figure 1 shows the process diagram for the plant with natural-gas fired heaters and deposition of CO_2 (case NGD). Aggregated Inventory data is presented in Appendix C.

The process diagram is identical for the system without deposition except for the difference that the carbon deposition part is not included.

In the lower left corner of Figure 1, the engineering of the plant, which also includes administration and commissioning, is modelled with monetary flows based on capital cost estimates. The construction phase of the plant offers some challenges with respect to establishment of inventory data. The site preparation and cover is modelled by accounting for materials and transport, all process data. Modelling of the remaining processes in the construction phase, including piping and interconnecting systems, electric system, instruments and equipment requires much effort. One of the challenges faced is how to establish a reliable inventory for the process equipment in the plant. Applying the process chain approach requires a substantial amount of data acquisition to

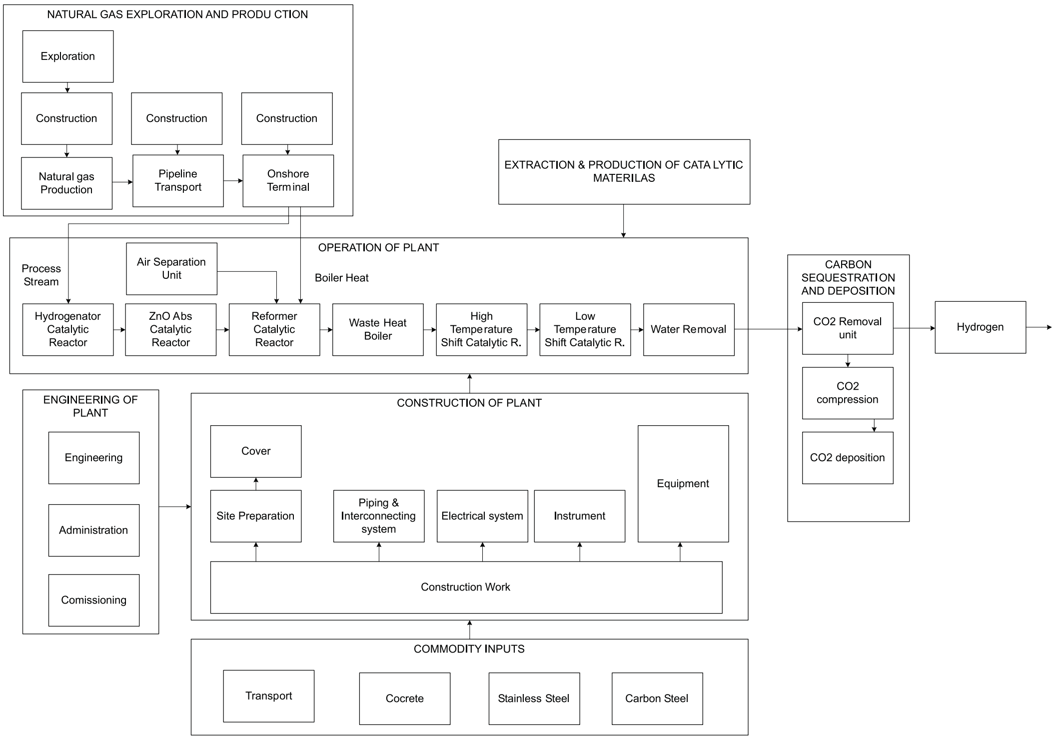

Fig. 1. Process flow diagram for case NGD

describe the manufacturing process for various items of process equipment, such as heat exchangers, boilers, and columns. One frequently adopted option is to only account for the material used. This would, however, impose the assumption that the manufacturing of the equipment can be ignored from an environmental perspective. Since no detailed analysis of the production of such equipment could be found we had no basis for supporting such an assumption. Also, a high fraction of the cost for the process equipment is related to the manufacturing, indicating substantial resource use in this process. Based on this we decided to apply a hybrid approach to solve this problem. From the capital cost estimates we know the purchase price and the installment cost of each unit of equipment.

Detailed estimates, provided by Norsk Hydro, give us the weight (W), materials and cost (EC) of each unit of equipment (U). Identifying material costs (MC) then enables us to calculate the value added (VA) in the production of the equipment. Environmental impact from the production is then modelled through a purchase of services from the economy equal to the value added in production, see Eq. 15. Mining, extraction and production of the steel is modelled through the use of process-based LCA. This is shown in Eq. 16 and the combined approach is illustrated in Figure 2[2].

Input-output coefficients should be adjusted to avoid double counting of the

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[2] NOK is the international currency abbreviation for Norwegian Kroner.

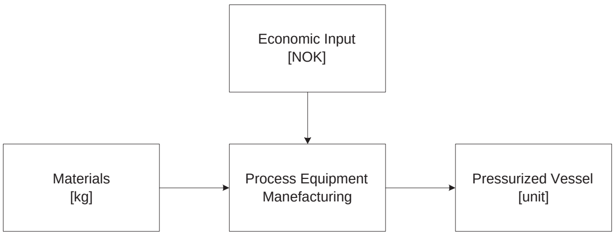

Fig. 2. Application of a hybrid approach to process equipment inventory

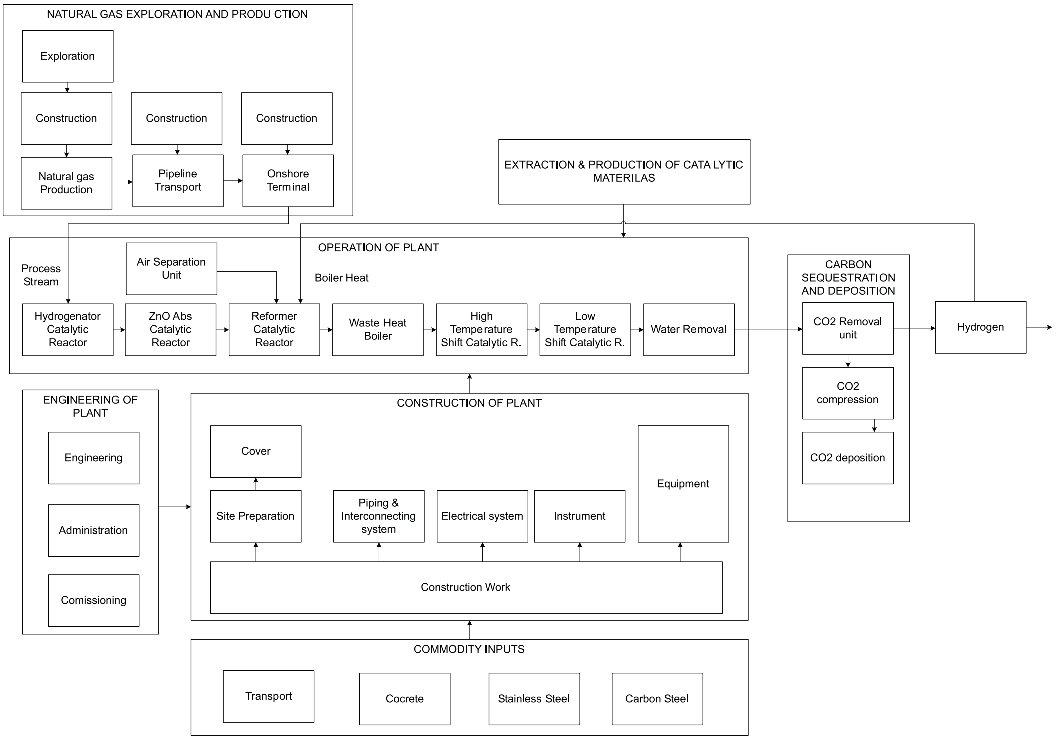

Fig. 3. Process flow diagram for system with hydrogen fired boilers

material inputs. However, this was not done since it would also disturb the upstream paths for other processes. This could be avoided by introducing several tailored L_{io} matrices but this was not found to be worthwhile here since few of the foreground processes have entries both in the S_c and S_p matrices.

$$S_{c(c,a)} = VA_{(c,a)} = EC_{(a)} - \sum_{p} W_{(a,p)} MC_{(p)} \qquad \forall (c,a) \in U \qquad (15)$$

$$S_{p(p,a)} = W_{(a,p)} \qquad \forall\ (p,a) \in U \qquad (16)$$

The process flow diagram for the system with hydrogen-fed heaters is shown in Figure 3 and is identical to diagram for the plant with natural-gas fired heaters except for the feed loop of hydrogen going into the heaters.

$I-S_a$

	Unit	Natural Gas	Opr.Hydrogenator Cat.	Opr.Desulparization.Cat	Opr.Prereforming.Cat.	Opr.ATR.Cat.	Opr.of HTS.Cat.	Opr.of LTS.Cat.	Opr.Methanator.Cat.	Boiler Operation	Capture CO2	Depositioin CO2	Operation of Plant pr yr	OSBL	ISBL	ASU	EAC	Construction of the plant	Plant Life Cycle
Natural Gas Prod	PJ NG	1	0	0	0	0	0	0	0	-1	0	0	-98.0	0	0	0	0	0	0
Opr. of Hydrogenator Catalyst	PJ H2	0	1	0	0	0	0	0	0	0	0	0	-85.3	0	0	0	0	0	0
Opr. of Desulparization Catalyst	PJ H2	0	0	1	0	0	0	0	0	0	0	0	-85.3	0	0	0	0	0	0
Opr of Prereforming Catalyst	PJ H2	0	0	0	1	0	0	0	0	0	0	0	-85.3	0	0	0	0	0	0
Opr. of ATR Catalyst	PJ H2	0	0	0	0	1	0	0	0	0	0	0	-85.3	0	0	0	0	0	0
Opr of HTS Catalyst	PJ H2	0	0	0	0	0	1	0	0	0	0	0	-85.3	0	0	0	0	0	0
Opr of LTS Catalyst	PJ H2	0	0	0	0	0	0	1	0	0	0	0	-85.3	0	0	0	0	0	0
Opr. of Methanator Catalyst	PJ H2	0	0	0	0	0	0	0	1	0	0	0	-85.3	0	0	0	0	0	0
Boiler Operation	PJ NG	0	0	0	0	0	0	0	0	1	0	0	-20.9	0	0	0	0	0	0
Capture CO2	kton/PJ H2	0	0	0	0	0	0	0	0	0	1	-65	0	0	0	0	0	0	0
Deposition CO2	PJ H2	0	0	0	0	0	0	0	0	0	0	1	-85.3	0	0	0	0	0	0
Operation of Plant	pr yr	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	-20
OSBL	p	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	-1	0
ISBL	p	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	-1	0
ASU	p	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0
EAC	p	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0
Construction of the plant	p	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1
Plant Life Cycle	p	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

$-S_p$

	Unit	Natural Gas	Opr.Hydrogenator Cat.	Opr.Desulparization.Cat	Opr.Prereforming.Cat.	Opr.ATR.Cat.	Opr.of HTS.Cat.	Opr.of LTS.Cat.	Opr.Methanator.Cat.	Boiler Operation	Capture CO2	Depositioin CO2	Operation of Plant pr yr	OSBL	ISBL	ASU	EAC	Construction of the plant	Plant Life Cycle
Fe2O3	kg/PJ H2	0	0	0	0	0	-2603	0	0	0	0	0	0	0	0	0	0	0	0
Al2O3	kg/PJ H2	0	-797	-97	-1.2	-862	0	-1.2	-2681	0	0	0	0	0	0	0	0	0	0
NiO	kg/PJ H2	0	-39	0	-1137	-511	0	0	-465	0	0	0	0	0	0	0	0	0	0
SiO2	kg/PJ H2	0	0	0	-95	-1.6	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr2O3	kg/PJ H2	0	0	0	-34	0	-266	0	0	0	0	0	0	0	0	0	0	0	0
ZnO	kg/PJ H2	0	0	-1288	0	0	0	-1807	0	0	0	0	0	0	0	0	0	0	0
MoO3	kg/PJ H2	0	-139	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CuO	kg/PJ H2	0	0	0	0	0	-47	-2973	0	0	0	0	0	0	0	0	0	0	0
CaO	kg/PJ H2	0	0	0	-177	-223	0	0	0	0	0	0	0	0	0	0	0	0	0
S	kg/PJ H2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MgO	kg/PJ H2	0	0	0	0	0	0	0	-233	0	0	0	0	0	0	0	0	0	0
Carbon Steel	Mton	0	0	0	0	0	0	0	0	0	0	0	0	-5.39	-5.64	-4.92	0	0	0
Stainless Steel	Mton	0	0	0	0	0	0	0	0	0	0	0	0	-6.28	-6.75	-5.89	0	0	0
Concrete	Mton	0	0	0	0	0	0	0	0	0	0	0	0	-2.49	0	0	0	0	0
Personnel Transport	Gm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-25.6	0	0
Trailer Transport	tMm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-21.2	0	0

$-S_c$

	Unit	Natural Gas	Opr.Hydrogenator Cat.	Opr.Desulparization.Cat	Opr.Prereforming.Cat.	Opr.ATR.Cat.	Opr.of HTS.Cat.	Opr.of LTS.Cat.	Opr.Methanator.Cat.	Boiler Operation	Capture CO2	Depositioin CO2	Operation of Plant pr yr	OSBL	ISBL	ASU	EAC	Construction of the plant	Plant Life Cycle
Building Construction Services	mill NOK	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mechanical Constr Services	mill NOK	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Offshore Construction Srevices	mill NOK	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Financial Services	mill NOK	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Fig. 4. S - Matrices

Data for the the natural gas exploration and production, found in the top left corner of Figure 3, is directly adapted from a corporate LCA study for Norsk Hydro and Statoil [39]. The inventory for the operation of the plant is based on the detailed process design data. How the inventory is compiled according to Eq. 6 is shown in Figure 4. The $I - S_a$ matrix is displayed in the full dimension used for calculation. The S_p and S_c matrices are displayed only with rows that have inputs. For the calculation all IDEMAT 2001 processes and Norwegian economy sectors have to be included since the extent and depth of upstream value chains are unknown. For confidentiality reasons no breakdown of the cost data in the S_c matrix can be shown. The matrices should be read column-wise. Each column contains the inputs per unit output of the given process. The inputs are the negative numbers off the diagonal, while the diagonal of matrix $I - S_a$ is unity since the inputs are per unit output. The relation between the various processes modelled in this study is listed in matrix $I - S_a$. In the column Operation of plant per year the inputs required for the annual operation of the plant is listed. Here it can be read that a total of 98 PJ of Natural Gas is required per year. The catalyst use per PJ hydrogen is listed in columns 2 to 7. The material inputs per PJ of H_2 produced are listed in the S_p matrix. Data on the consumption of metals for the production of catalyst are based on vendor data [40]. The annual production of hydrogen, 85.3 PJ, is used to scale the catalyst consumption in order to find the total catalyst usage per year. The energy input to the heater operation is 20.9 PJ natural gas per year which constitutes about 25% of the total energy output. For the case with hydrogen-fed heaters the $I - S_a$ matrix is reformulated so that the energy input to the heaters is a fraction of the total lifetime production corresponding to an annual energy input of 20.9PJ per year. In the column, deposition CO_2, the amount of CO_2 that is captured from the process stream, 65 kton/PJ H_2 is listed. The inventory for the construction of the plant is structured according to the structure of the cost estimate for the plant, the OSBL (Outside Battery Limit), ISBL (Inside Battery Limit), ASU (Air Separation Unit) and EAC (Engineering and Construction). The plant life cycle is established by adding together inputs from the construction of the plant and twenty years of operation of the plant. Demolition of the plant is not included in this study since a large majority of materials in the plant will be recycled due to their value and then become a part of another life cycle.

4 Results

Having established the inventory data, found total output and emissions the next step is to perform impact assessment. This is done by using environmental themes indicators from Guinée ed. [37]. This section, discusses the impact potentials of the three cases. First the overall results are presented. Then the most important aggregated processes, source processes and emissions for each category are identified. Finally the contribution of various inventory sources are briefly discussed in the context of hybrid LCA.

Table 3
Assessment results

kg eq/GJ H_2	NG	NGD	H		NGD/NG	H/NG
ADP	1.07E-01	1.07E-01	1.17E-01	Sn-eq.	100%	109%
GWP	8.44E+01	1.96E+01	6.35E+00	CO_2-eq.	23%	8%
ODP	2.30E-09	2.30E-09	3.05E-09	CFC-11-eq.	100%	132%
HTP	4.90E-01	8.59E-01	1.13E+00	1.4-DCB-eq.	175%	231%
FAETP	4.36E-03	4.47E-03	5.91E-03	1.4-DCB-eq.	103%	136%
MAETP	1.07E+02	1.07E+02	1.23E+02	1.4-DCB-eq.	100%	116%
TAETP	3.43E-04	4.88E-04	6.34E-04	1.4-DCB-eq.	142%	185%
PCOP	7.00E-04	7.29E-04	7.83E-04	C_2H_2-eq.	104%	112%
AP	1.31E-02	1.34E-02	1.70E-02	SO_2-eq.	102%	129%
EP	8.70E-04	8.81E-04	1.05E-03	PO_4^--eq.	101%	103%

The impact potentials for the production of 1 GJ of hydrogen from the three designs assessed in this study are listed in table 3. In addition, the table also lists the environmental impacts of the H and NGD cases relative to the NG case. The H case has generally higher impact potentials in all categories except

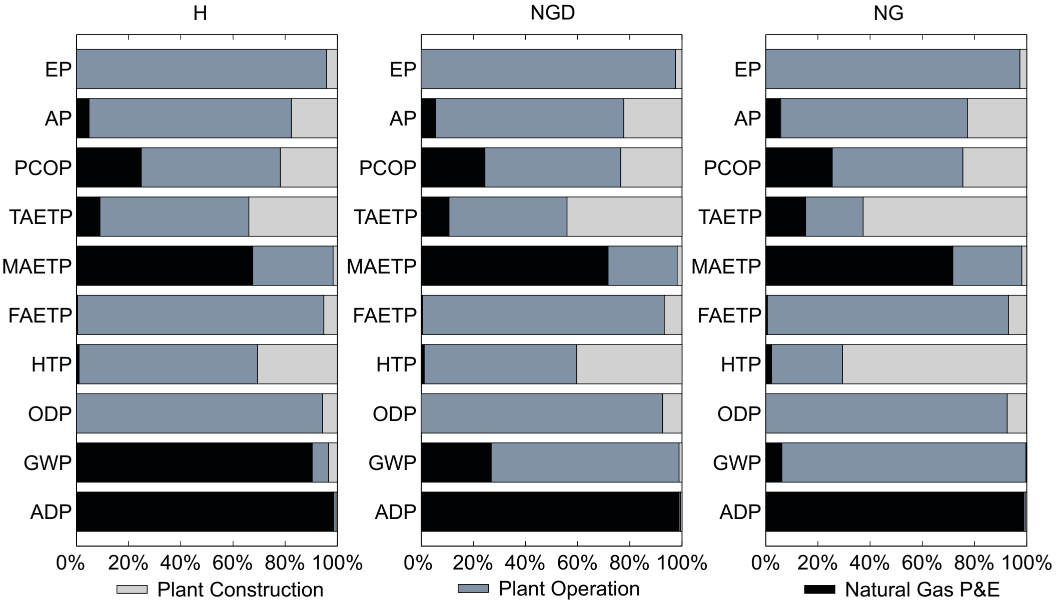

Fig. 5. Process Contributions

for global warming where it has less than 10% of the impacts of the *NG* case. The *NGD* case has very similar impact potentials across the categories as the *NG* case except for global warming where it has much lower impact and for the HTP and TAETP categories where the deposition process drives the impacts up.

To allow for a different assessment of the results from this study, the most important emissions for each impact category and case is shown in Appendix B.

The abiotic depletion potential is mainly due to natural gas extraction and is therefore higher for the *H* than the *NG* and *NGD* due to lower overall efficiency, since some of the produced hydrogen is fed into the heaters. Thus a higher overall natural gas feed is required to maintain the same output of hydrogen. Even though there is a lot of steel of various alloys going into the construction of this hydrogen production facility, over the life cycle of the facility the amount of natural gas extracted for production of H2 constitutes 97% of the abiotic depletion potential. This is reflected in Figure 5.

The global warming potential is respectively 23% and 8% of the base cases for *NGD* and *H*. The *NG* case has a total of $84.4 kgCO_2eq/GJH_2$ while the *NGD* case produces 19.6 $kgCO_2eq/GJH_2$ and the *H* case generates as little as $6.4 kgCO_2eq/GJH_2$. About 95% of the total CO2 emissions in the *NG* case is generated in the operation phase of the plant, see Figure 5. The remaining 5% is mainly due to upstream emissions for natural gas extraction and production. In the operations phase of this plant there are two main CO_2 emission sources. (1) The CO_2 from the process stream which is only absorbed not deposited.

(2) The CO_2 emissions from the natural-gas fired heaters which are used to generate process heat. Due to the deposition of the captured CO_2 from the process stream, the NGD case is only 23% of the NG case. Of the CO_2 emissions generated by NGD, 75% are due to the natural gas fired heaters and a little less than 25% are due to natural gas production and extraction, see Figure. 5. For the H design, the CO_2 emissions form the process heaters are eliminated by burning produced hydrogen. This reduces the overall first law efficiency of the plant from 72% to 66%, causing a higher demand for natural gas input. This results in an increase in the amount of upstream greenhouse emissions. However the global warming potential for this case is only 8% of the NG case, see the second row of Table 3.

The ozone-depleting emissions originate from the background processes required for the operation of the plant. This impact is however quite low. For the human toxicity potential the NGD and H cases are respectively 75% and 131% higher than the NG case, see Table 3. This is due to the lower efficiency of the plant, causing an increased requirement of inputs per functional unit. The human toxicity is mainly due to upstream PAH emissions from the production of metals.

For the freshwater eco-toxicity potential, however, the differences are much lower. The NGD case is only a few percent higher than the NG case, for H the freshwater eco-toxicity potential is 36% higher than in the NG case.

The main compound contributing to the marine eco-toxicity potential is HF originating from the extraction and production of natural gas. The higher natural gas use in the H case explains the 18% increase compared to the other cases.

The terrestrial eco-toxicity potential is 42% and 85% higher for the NGD and H than for NG respectively. Here also the effects of additional required inputs for CO_2 deposition in two of the cases and the lower efficiency of the H case cause the differences. The majority of the impact potentials originate both from the operations phase and construction phase of the facilities. The most important compounds are heavy metals, especially Hg,Ni,Zn and As from natural gas extraction, metal and steel production and background coal-based electricity generation.

The photochemical ozone creation potential is very similar for all three cases. The majority of these emissions origin from the operation phase of the plant. But less that half are related to on site operational processes. Emissions of CO from the heaters constitute about 15% of the NGD and NG cases. In the H case there are obviously no CO emissions from the heaters. Even though, the H case has a 12% higher impact potential than the NG case due to emissions related to catalyst metal production and natural gas extraction and production. The increased catalyst and natural gas use is a result of the lower efficiency of the H case.

The main contribution to the acidification potential are SO_2 emissions from metals used as catalysts. Nickel production alone constitutes about 45% of the acidification potential. Together copper and nickel production accounts for 60% of the acidification potential. Emissions from the heaters include both NO_x (40ppm@3% O_2), which is the dominant contributor in this case, and some SO_2 due to the sulphur content of the natural gas. In total, the emissions of NO_x contribute to about 25% of the total acidification potential. The impact from the NGD case is only 2% higher than that of the NG case. The H case however has an impact potential that is 39% higher than the NG case, again due to the lower efficiency.

The eutrophication potential for the three cases is almost identical. There is only a 3% difference, because of a sole dominating contributor. As much as 95% of the total is due to NO_x emission from the heaters. Since the same amount of process heat is required for all the cases and the NO_x emissions are assumed to be the same for the natural gas and hydrogen fired combustors [41], there is only small variation in the eutrophication potential.

5 Discussion

Many would intuitively assume that the most important environmental impacts of hydrogen production originates from its operation. It is therefore interesting to note that over a wide range of impact categories none of the main processes: plant operation, natural gas production, and plant construction, can be ignored without losing significant contributions to several of the impact categories.

In addition to the origin of impacts from the various life-cycle phases, the importance of the various data inventories is of interest with respect to the methodological contribution of the hybrid approach used here. The inventories, that are described above are the foreground system, background processes and background economy. The contributions of these to the various impact categories are shown in Figure 6. It can be seen that none of the sub-inventories can be disregarded without losing significant contributions made to several impact categories. The foreground system, which includes emissions inventory compiled in this study, and the background LCA, generally have the highest contributions. The background economy, however, has high contributions in some of the toxicity indicators. Naturally, the relative importance of the sub-inventories is dependent on the case and how the inventory is modelled, so no general conclusions can be drawn about the additional contribution of the

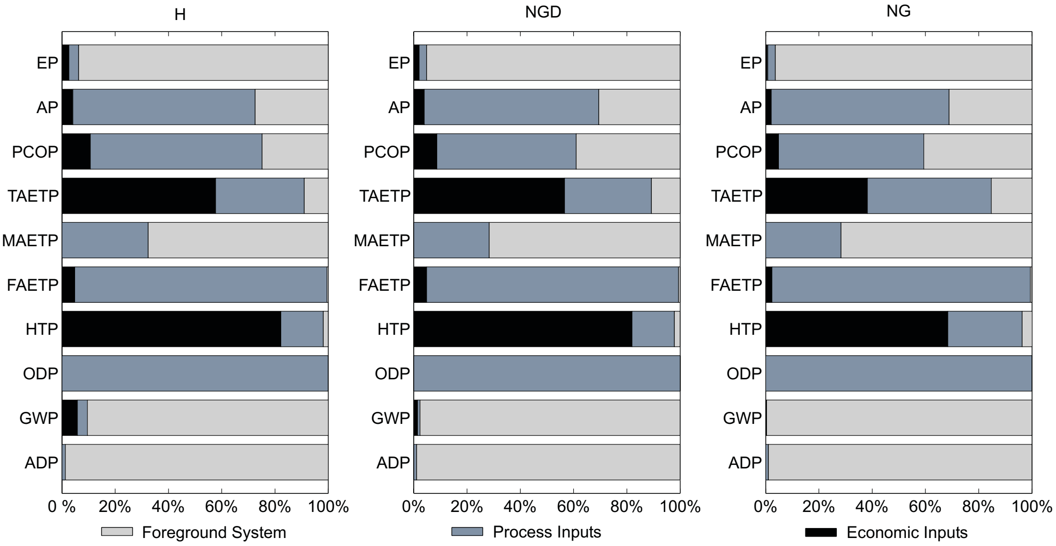

Fig. 6. Inventory Contributions

hybrid approach.

In the context of environmental management, it is interesting to see across categories where the impacts occur. Impacts that are occurring in the operation of the plant or first tiers of sub-processes are close enough to the plant owners so that they are able to address and initiate actions to reduce environmental impacts. This is the case for the majority of the impacts of ADP,GWP,EP. For the rest, a large fraction of the impacts occur far upstream in the value chain for the plant and are thus out of reach of the owner of the plant given that alternative inputs are not feasible. Regulatory action may be required to reduce these impacts.

A number of uncertainties and conditions affect this assessment. It has been carried out based on a detailed process design and cost calculation. If the facility is actually built, there will be changes and adjustments in design and operation. Materials may come from different sources than the ones assumed here. We expect that these changes will be of minor importance for the GWP, but they may be very relevant for some of the other pollutants that dominate other impact categories, such as HF and PAHs. There is uncertainty about the applicability of the data, in the inventory. The process data comes from a Dutch data base, the input-output data from Norway. In practice, materials may come from all over the world and manufacturing will also take place in different countries. As the age of equipment, pollution control requirements, industry structure, and energy sources all differ, there can be a significant difference in the pollution produced when manufacturing identical equipment or delivering identical services in different countries. These uncertainties can only be quantified through a comparative assessment, which is time consuming. Hertwich et al. [42] have compared the emission intensities of Norwegian products with those from important trading partners and found differences up to a factor of 10 using I/O tables. An additional uncertainty is related to the transport of the equipment, because national pollution statistics under IPCC conventions neglect the use of bunker fuels (ocean ship transport and airplanes between take-off and landing). Variations connected to the country of origin affect only the economic and process inputs in Figure 6. Here the economic inputs are more strongly affected than the process inputs. We are hence fairly confident about the categories of abiotic resource use, global warming, and eutrophication. The impact assessment, meaning the application of the factors in matrix W, is also uncertain [43]. This uncertainty is larger for the toxicity, acidification and eutrophication categories than for the global categories of resource depletion, climate change and ozone depletion. For these categories, the impacts also depend on location.

6 Conclusions

In our comprehensive hybrid life-cycle assessment, we have quantified in detail the environmental impacts related to hydrogen production based on natural gas reforming. We have shown to what extent hydrogen, produced by this technology, is not a completely carbon free fuel. Even when carbon from the process stream of such a plant is captured and deposited, compared to combustion of natural gas, a third of the CO_2 emissions still remains due to the heater emissions. In order to really lower the CO_2 emissions it is necessary to either sequester and deposit CO_2 from the heaters, make a closed ATR system or, as we have suggested, use the produced hydrogen to generate the required heat. This lowers the efficiency of the plant from 72% to 66% but reduces the global warming potential to only 8% of the base case. This benefit, however comes at the cost of an increase of other impact categories ranging from 109% to 231% of the base case. Given the overall importance of CO_2 emissions in this life cycle, such a shift in impacts would still be desirable. However other options to reduce these impacts should still be considered.

7 Acknowledgements

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A Assessment Nomenclature

Table A.1
Environmental assessment indicators nomenclature

ADP	Abiotic Depletion Potential	Sn-eq.
GWP	Global Warming Potential	CO_2-eq.
ODP	Ozone Depletion Potential	CFC-11-eq.
HTP	Human Toxicity Potential	1.4-DCB-eq.
FAETP	Fresh-Water Aquatic Eco-Toxicity Potential	1.4-DCB-eq.
MAETP	Marine Aquatic Eco-Toxicity Potential	1.4-DCB-eq.
TAETP	Terrestial Eco-Toxicity Potential	1.4-DCB-eq.
PCOP	Photochemical Ozone Creation Potential	C_2H_2-eq.
AP	Acidification Potential	SO_2-eq.
EP	Eutrophication Potential	PO_4^--eq.

B Environmental Impact Inventory

Here the emissions and flows, for all cases, that constitutes more than 0.5% of each impact category are presented. In doing this, it is the authors intention to allow for assessment of the results with other methods. However the selection of emission presented are based on the assessment method used in this study.

Table B.1
Environmental impact inventory - Case H

ADP	natural gas	crude oil	coal				
kg/GJ_{H2}	3.41E+01	1.66E-01	1.16E-01				
	99.1%	0.5%	0.3%				
GWP	CO2	CH_4	N2O				
kg/GJ_{H2}	6.13E+00	5.79E-03	2.40E-04				
	96.49%	1.91%	1.17%				
ODP	Halon1301						
kg/GJ_{H2}	2.54E-10						
	100%						
HTTP	PAH's	NO_x	dioxin	HF			
kg/GJ_{H2}	1.95E-06	7.90E-03	4.43E-12	2.80E-06			
	95.9%	0.8%	0.7%	0.7%			
FAETP	PAH's	V	Ba	Ni	Se	Co	Cu
kg/GJ_{H2}	1.95E-06	2.18E-07	2.14E-06	1.28E-07	1.26E-07	5.00E-08	1.33E-07
	47.6%	22.1%	8.3%	6.9%	6.2%	2.9%	2.7%
MAETP	HF	Se	V	Ba			
kg/GJ_{H2}	2.80E-06	1.26E-07	2.18E-07	2.14E-06			
	93.0%	2.5%	1.8%	1.4%			
TAETP	Hg	V	Zn	As	Pb	Ni	
kg/GJ_{H2}	1.90E-08	2.18E-07	9.98E-07	6.44E-09	5.61E-07	4.11E-08	
	83.7%	9.5%	1.9%	1.6%	1.4%	0.8%	
PCOP	SO_x	CO	CH_4	NO_2			
kg/GJ_{H2}	1.07E-02	9.01E-03	5.79E-03	2.39E-04			
	63.5%	31.1%	4.4%	0.9%			
AP	SO_x	NO_x	NH_3				
kg/GJ_{H2}	1.07E-02	7.90E-03	6.77E-05				
	76.1%	23.3% %	0.6%				
EP	NO_x	NH_3					
kg/GJ_{H2}	7.90E-03	6.77E-05					
	97.6%	2.3%					

Table B.2
Environmental impact inventory - Case NGD

ADP	natural gas	crude oil	coal				
kg/GJ_{H2}	3.12E+01	1.52E-01	9.68E-02				
	99.2%	0.5%	0.3%				
GWP	CO_2	CH_4					
kg/GJ_{H2}	1.94E+01	4.94E-03					
	99.1%	0.53%					
ODP	Halon1301						
kg/GJ_{H2}	1.92E-10						
	100%						
HTTP	PAH's	NO_x	HF	dioxin	Se		
kg/GJ_{H2}	1.48E-06	6.63E-03	2.44E-06	3.35E-12	9.49E-08		
	95.7%	0.9%	0.8%	0.7%	0.6%		
FAETP	PAH's	V	Ba	Ni	Se	Mo	Zn
kg/GJ_{H2}	1.48E-06	1.65E-07	1.61E-06	9.63E-08	9.49E-08	5.30E-08	2.44E-07
	47.6%	22%	8.3%	6.9%	6.2%	0.6%	0.5%
MAETP	HF	Se	V	Ba			
kg/GJ_{H2}	2.44E-06	9.49E-08	1.65E-07	1.61E-06			
	93.9%	2.2%	1.5%	1.3%			
TAETP	Hg	V	Zn	As	Pb	Ni	
kg/GJ_{H2}	1.46E-08	1.65E-07	7.80E-07	4.97E-09	4.28E-07	3.38E-08	
	83.8%	9.3%	1.9%	1.6%	1.4%	0.8%	
PCOP	SO_2	CO	CH_4				
kg/GJ_{H2}	7.93E-03	1.16E-02	4.94E-03				
	52.3%	42.8%	4.1%				
AP	SO_x	NO_x	NH_3				
kg/GJ_{H2}	8.31E-03	6.63E-03	5.11E-05				
	74.6%	24.8%	0.6%				
EP	NO_x	NH_3					
kg/GJ_{H2}	6.63E-03	5.11E-05					
	97.8%	2.0%					

Table B.3

Environmental impact inventory - Case NG

ADP	natural gas	crude oil	coal				
kg/GJ_{H2}	3.12E+01	1.52E-01	9.68E-02				
	99.2%	0.5%	0.3%				
GWP	CO_2						
kg/GJ_{H2}	8.40E+01						
	98.93%						
ODP	Halon1301						
kg/GJ_{H2}	1.92E-10						
	100%						
HTTP	PAH's	NO_x	HF	dioxin	Se		
kg/GJ_{H2}	1.44E-6	6.63E-03	2.44E-06	3.35E-12	9.49E-08		
	92.5%	1.6%	1.4%	1.3%	1.1%		
FAETP	PAH's	V	Ba	Ni	Se	Mo	Zn
kg/GJ_{H2}	1.44E-6	1.65E-07	1.61E-06	9.63E-08	9.49E-08	5.30E-08	2.44E-07
	46.3%	2.6%	8.5%	7.1%	6.3%	0.6%	0.5%
MAETP	HF	Se	V	Ba			
kg/GJ_{H2}	2.44E-06	9.49E-08	1.65E-07	1.61E-06			
	93.9%	2.2%	1.5%	1.3%			
TAETP	Hg	V	Zn	As	Pb	Ni	
kg/GJ_{H2}	9.50e-9	6.77E-08	7.80E-07	4.97E-09	3.82E-07	3.38E-08	
	77.5%	13.2%	2.7%	2.3%	1.8%	1.2%	
PCOP	SO_2	CO	CH_4				
kg/GJ_{H2}	7.93E-03	1.16E-02	4.94E-03				
	52.3%	42.8%	4.1%				
AP	SO_x	NO_x					
kg/GJ_{H2}	8.31E-03	6.63E-03					
	74.5%	25.3%					
EP	NO_x	NH_3					
kg/GJ_{H2}	6.63E-03	2.05E-05					
	99.0%	0.8%					

C Inventory

In this Appendix aggregated inventory data on physical flows are presented. The plant cost estimates in the S_c matrix is confidential and values are indicated with a hyphen.

Inventory on catalysts usage and composition, table C.1 to C.7, is based on process design data from Norsk Hydro [38] and catalyst vendor data [40]. The functional unit of the catalyst usage is kg of catalyst per PJ_{H_2} produced in the NGD process.

Table C.1
Operation of Hydrogenator Catalyst

Inputs		
Al_2O_3	797	kg/PJ_{H_2}
NiO	39	kg/PJ_{H_2}
MoO_3	139	kg/PJ_{H_2}

Table C.2
Operation of Desulphurization Catalyst

Inputs		
Al_2O_3	97	kg/PJ_{H_2}
ZnO	1288	kg/PJ_{H_2}

Table C.3
Operation of Prereforming Catalyst

Inputs		
Al_2O_3	1.2	kg/PJ_{H_2}
NiO	1137	kg/PJ_{H_2}
SiO_2	95	kg/PJ_{H_2}
Cr_2O_3	34	kg/PJ_{H_2}
CaO	177	kg/PJ_{H_2}

Table C.4
Operation of ATR Catalyst

Inputs		
Al_2O_3	862	kg/PJ_{H_2}
NiO	511	kg/PJ_{H_2}
SiO_2	1.6	kg/PJ_{H_2}
CaO	223	kg/PJ_{H_2}

Table C.5
Operation of HTS Catalyst

Inputs		
Fe_2O_3	2603	kg/PJ_{H_2}
Cr_2O_3	266	kg/PJ_{H_2}
CuO	47	kg/PJ_{H_2}

Table C.6
Operation of LTS Catalyst

Inputs		
Al_2O_3	1.2	kg/PJ_{H_2}
ZnO	1807	kg/PJ_{H_2}
CuO	2973	kg/PJ_{H_2}

Table C.7
Operation of Methanator Catalyst

Inputs		
Al_2O_3	2681	kg/PJ_{H_2}
NiO	465	kg/PJ_{H_2}
MgO	233	kg/PJ_{H_2}

Table C.8
Operation of Boilers

Inputs		
Natural Gas	1	PJ_{NG}/PJ_{NG}
Output		
CO_2	56.5	$kton/PJ_{NG}$
CO	0.0160	$kton/PJ_{NG}$
SO_2	3.51×10^{-4}	$kton/PJ_{NG}$
NO_x	0.0263	$kton/PJ_{NG}$

Emission from boilers are assumed to be $40 ppmv\ NO_x$ @3% O_2 and $40 ppmv\ CO$ @3% O_2. Further sulphur content in natural gas feed to the boilers is assumed to be $\sim 10^{-6}$ mol sulphur per mol natural gas.

Table C.9
Capture and Deposition of CO_2

Inputs		
CO_2	65.0	$kton/PJH2$
Mechanical Engineering Services	0.011	MNOK/ktonCO_2
Offshore Construction Services	0.034	MNOK/ktonCO_2

Note that energy usage for this process and compression to 80 bar is included in the process flow design, and therefore included in the overall efficiency of the plant. This means that this inventory data is complimentary to the process design data and therefor cannot be used separately.

All data in tables C.10 to C.13 is based on detailed cost and weight estimates supplied by Norsk Hydro [38]. Due to confidentiality no cost data is presented here.

Table C.10
Plant Construction - Outside Battery Limit

Inputs		
Carbon Steel	5.39	$Mton/plant$
Stainless Steel	5.39	$Mton/plant$
Concrete	2.49	$Mton/plant$
Building Construction Services	-	$MNOK/plant$
Mechanical Engineering Services	-	$MNOK/plant$
Financial services	-	$MNOK/plant$

Table C.11
Plant Construction - Inside Battery Limit

Inputs		
Carbon Steel	5.64	$Mton/plant$
Stainless Steel	6.75	$Mton/plant$
Building Construction Services	-	$MNOK/plant$
Mechanical Engineering Services	-	$MNOK/plant$
Financial services	-	$MNOK/plant$

Table C.12
Plant Construction - Air Separation Unit

Inputs		
Carbon Steel	4.92	$Mton/plant$
Stainless Steel	5.89	$Mton/plant$
Building Construction Services	-	$MNOK/plant$
Mechanical Engineering Services	-	$MNOK/plant$
Financial services	-	$MNOK/plant$

Table C.13
Plant Construction - Engineering and Construction

Inputs		
Personnel transport	25.6	$Gm/plant$
Trailer transport	21.2	$ktkm/plant$
Building Construction Services	-	$MNOK/plant$
Mechanical Engineering Services	-	$MNOK/plant$
Financial services	-	$MNOK/plant$

Table C.14 lists the inventory for the annual operation of the plant. Note that since the functional unit of most operation processes are per PJ_{H_2} the demand on each of these is equivalent to the annual production of hydrogen.

Table C.14
Annual Operation of plant

Inputs		
Natural Gas Production	98.0	PJ_{NG}/yr
Operation of Hydrogenator Catalyst	85.3	PJ_{H_2}/yr
Operation of Desulphurization Catalyst	85.3	PJ_{H_2}/yr
Operation of Prereforming Catalyst	85.3	PJ_{H_2}/yr
Operation of ATR Catalyst	85.3	PJ_{H_2}/yr
Operation of HTS Catalyst	85.3	PJ_{H_2}/yr
Operation of LTS Catalyst	85.3	PJ_{H_2}/yr
Operation of Methanator Catalyst	85.3	PJ_{H_2}/yr
Deposition of CO_2	85.3	PJ_{H_2}/yr

Table C.15
Construction of Plant

Inputs		
Plant Construction - Outside Battery Limit	1	*plant/plant*
Plant Construction - Inside Battery Limit	1	*plant/plant*
Plant Construction - Air Separation Unit	1	*plant/plant*
Plant Construction - Engineering and Construction	1	*plant/plant*

Table C.16
Plant Life Cycle - Construction and Operation

Inputs		
Plant Construction	1	*plant/lifetime*
Plant Operation	20	*yrs/liftime*

Assuming a lifetime of 20 years the plant life cycle from construction and throughout the usage phase requires 1 unit of construction and 20 years of operation.

References

[1] Ogden J. M, Steinburgler M. M, Kreutz T. G. A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development. Journal of Power Sources, 79:143–168, 1999.

[2] Hertwich E. G, Stromman A. H. The environmental assessment of the fuel cell car. NTNU, Trondheim, 2002.

[3] Blok K, Williams R, Katofsky R, Hendriks C. Hydrogen production from natural gas, sequestration of recovered co2 in depleted gas wells and enhanced natural gas recovery. Energy, 22(2-3):161–168, 1997.

[4] Marquevich M, Sonnemann G, F.Castells, Montane D. Life cycle inventory analysis of hydrogen production by the steam-reforming process: comparison between vegetable oils and fossil fuels as feedstock. Green Chemistry, 4(5):414–423, 2002.

[5] Weiss M, Heywood J, Drake E, Schafer A, AuYeng F. On the road in 2020: A life-cycle analysis of new automobile technology. mit el 00-003. Technical report, MIT Energy Laborotory, Cambridge, 2000.

[6] Maclean H, L.B.Lave. Life cycle assessment of automobile/fuel options. Environmantal Science and Technology, 37:5445–5452, 2003.

[7] Barreto L, Makihira A, Riahi K. The hydrogen economy in the 21st century: A sustainable development scenario. International Journal of Hydrogen Energy, 28(3):267–284, 2003.

[8] Nakicenovic N, Alcamo J. Special report on emissions scenarios (sres), a special report of working group iii of the intergovernmental panel on climate change. Technical report, Cambridge University Press, Cambridge, 2000.

[9] Marheineke T, Friedrich R, Krevitt W. Application of a hybrid-approach to the life cycle inventory analysis of a freight transport task. SAE Technocal Paper Series, 982201(Total Life Cycle Conference and Exposition, Austria), 1998.

[10] Treloar G, Love P, Fanrian O, Iyer-Ranga U. A hybrid life cycle assessment method for construction. Construction Management and Economics, 18:5–9, 2000.

[11] Lenzen M. A guide for compiling inventories in hybrid life-cycle assessments: some australian results. Journal of Cleaner Production, 10(6): 545–572, 2002.

[12] Nakamura S, Kondo Y. Input output analysis of waste management. Journal of Industrial Ecology, 6(39):63, 2002.

[13] Suh S. Functions, commodities and environmental impacts in an ecological-economic model. Ecologoical Economics, 48(4):451–467, 2004.

[14] Suh S. Materials and energyflows i nindustry and ecosystem networks. CML, Leiden NL, 2004.

[15] Leontief W. Input-Output Economics. Oxford University Press, New York, 1966.

[16] Leontief W. Environmental repercussions and economic structure - input-output approach. The Review of Economics and Statistics, 52(3):262–271, 1970.

[17] Flick W. A. Environmental reprocussions and economic structure - input-output approach - reply. The Review of Economics and Statistics, 56(1): 107–109, 1974.

[18] Leontief W. Environmental reprocussions and economic structure - input-output approach - reply. The Review of Economics and Statistics, 56(1): 109–110, 1974.

[19] Steenge A. Environmental repercussions and economic-structure - further comments. The Review of Economics and Statistics, 60(3):482–486, 1978.

[20] Moore S. Environmental repercussions and the economic-structure - some further comments. The Review of Economics and Statistics, 63(1):139–142, 1981.

[21] Lee K. A generalized input-output model of an economy with environmental-protection. The Review of Economics and Statistics, 64 (3):466–473, 1982.

[22] Duchin F, Lange G. The future of the environment: Ecological economics and technological change. Oxford University Press, New York, 1994.

[23] Lave L, Cobas-Flores E, Hendrickson C, McMichael F. Using input-output-analysis to estimate economy-wide discharges. Environmental Science and Technology, 29(9):A420–A426, 1995.

[24] Lenzen M. A generalized input-output multiplier calculus for australia. Economic Systems Research, 13(1):65–92, 2001.

[25] Pan X, Kraines S. Environmental input-output models for life cycle analysis. Environmental and Resource Economics, 20:61–72, 2001.

[26] Matthews H. S, Small M. J. Extending the boundaries of life-cycle assessment through environmental economic input-output models. Journal of Industrial Ecology, 4(3):7–10, 2001.

[27] Norris G. Life cycle emission distributions within the economy: Implications for life cycle impact assessment. Risk Analysis, 22(5):919–930, 2002.

[28] Miller R. E, Blair P. D. Input-output analysis: Foundations and extensions. Prentice-Hall, Englewood Cliffs, NJ, 1985.

[29] Ciaschini M, ed. Input-output analysis : Current developments. Chapman and Hall, London, 1988.

[30] Peterson W. Advances in input-output analysis : Technology, planning, and development. Oxford University Press, New York, 1991.

[31] UN. Handbook of input-output table compilation and analysis - Studies in methods. Series F, volume 74. United Nations, Department of Economic and Social Affairs, Statistics, New York, 1999.

[32] Heijungs R, Suh S. The computational structure of life cycle assessment. Kluwer Academic Publishers, Dordrecht, 2002.

[33] Jansen P. K, ten Raa T. The choice of model in the construction of input-output coefficients matrices. International Economic Review, 31

(1):213–227, 1990.

[34] Maehle N. Input-output data and analysis in Norway 1970-1990. Statistics Norway, Oslo, 1993.

[35] Delft T. IDEMAT 2001. Faculty of Design, Engineering and Production. Delft University of Technology, Delft, 2001.

[36] PReConsultants. SimaPro5. PRE Consultants, Leiden, 2001.

[37] Guinee J. B. Handbook on life cycle assessment : Operational guide to the ISO standards. Series: Eco-efficiency in industry and science. Kluwer, Dordrecht, 2002.

[38] Norsk-Hydro. Large scale hydrogen production. Norsk Hydro Porsgrunn Research Centre, Porsgrunn, 2001.

[39] Vold M. LCA of norwegian oil and gas exctraction. Stiftelsen Ostfoldforskning, Fredrikstad, 2001.

[40] SYNTETX. Catalco process catalysts. Technical report, Cleveland England, 2000.

[41] Fossum M, Stromman A. Combustion of gas mixtures, report no. TR F5240. Sintef Energy Research, Trondheim, 2000.

[42] Hertwich E. G, Erlandsen K, Sorensen K, Aasness J, Hubacek K. Pollution embodied in Norway's import and export and its relevance for the environmental profile of households. In E.G Hertwich ed.: Life-cycle Approaches to Sustainable Consumption, no. IR-02-073. Laxenburg, Austria: International Institute for Applied Systems Analysis, 2002.

[43] de Haes H, Jolliet O, Finnveden G, Goedkoop M, Hauschild M, Hertwich E, Hofstetter P, Klopffer W, Krewitt W, Lindeijer E. W, Mueller-Wenk R, Olson S. I, Pennington D. W, Potting J, Steen B. Life cycle impact assessment: Striving towards best practice. Society of Environmental Toxicology and Chemistry, 2002.

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