Life-cycle assessment of carbon dioxide capture for enhanced oil recovery

Edgar G. HERTWICH [a,b], Martin AABERG [b,c], Bhawna SINGH [a,b], Anders H. STRØMMAN [a,b]

[a] Industrial Ecology Programme and [b] Department of Energy and Process Engineering, Norwegian University of Technology (NTNU), 7491 Trondheim, Norway, www.ntnu.no/indecol, edgar.hertwich@ntnu.no

[b] Present address: DNV, Veritasveien 1, 1322 Høvik, Norway

Abstract The development and deployment of Carbon dioxide Capture and Storage (CCS) technology is a cornerstone of the Norwegian government's climate strategy. A number of projects are currently evaluated/planned along the Norwegian West Coast, one at Tjeldbergodden. CO_2 from this project will be utilized in part for enhanced oil recovery in the Halten oil field, in the Norwegian Sea. We study a potential design of such a system. A combined cycle power plant with a gross power output of 832 MW is combined with CO_2 capture plant based on a post-combustion capture using amines as a solvent. The captured CO_2 is used for enhanced oil recovery (EOR). We employ a hybrid LCA method to assess the environmental impacts of the system. The study focuses on the modifications and operations of the platform during EOR. We allocate the impacts connected to the capture of the CO_2 to electricity production, and the impacts connected to the transport and storage of CO_2 to the oil produced. Our study shows a substantial reduction of the greenhouse gas emissions from power production by 80% to 75g/kWh. It also indicates a reduction of the emissions associated with oil production per unit oil produced, mostly due to the increased oil production. Reductions are especially significant if the additional power demand due to EOR leads to power supply from the land.

Keywords: Carbon dioxide capture and storage (CCS), enhanced oil recovery, off-shore power supply, life-cycle analysis

1 INTRODUCTION

Life-cycle assessment (LCA) is a method to evaluate the environmental impacts of product systems, from the cradle to the grave (3). Emissions and resource use from the resource extraction, production, distribution, use and disposal phases are included in the life-cycle inventory. The contribution of these emissions and resource uses to specific environmental impacts (e.g. global warming, human toxicity, biotic resource extraction) is evaluated in the impact assessment. LCA has been developed independently in a number of applications and disciplines, including chemical engineering and energy analysis. The assessment of alternative energy technologies has been one of the most important application areas, and initial assessments have focused on the cumulative (fossil) energy demand, including embodied or "grey" energy. An important motivation in the 1970s was to consistently compare fossil and renewable energy technologies in terms of the energy services they deliver for a given amount of fossil fuels. LCA has since been extended to address a wide range of environmental concerns. It has been standardized by ISO (15).

CO_2 capture and storage (CCS) is an end-of-pipe technology for fossil fuel fired power plants, boilers, and industrial processes which produce large amounts of CO_2 (14). Many analysts see CCS as a necessary and important element in a strategy to limit global warming and stabilize atmospheric temperature to level below 2^oC above the pre-industrial level (24). There are various different technological options for CO_2 capture, including chemical and membrane absorption from the exhaust stream or a synthesis gas, or combustion with pure oxygen. At this point, post-combustion absorption by an amine-based solvent is the most mature technology, but other technologies are still viable contenders (14).

To illustrate the LCA of energy technologies, we investigated a specific CO_2 value chain using a hybrid LCA approach. The value chain consists of a natural gas combined cycle power plant with post-combustion capture, pipeline transport and injection in a North Sea oil field for enhanced oil recovery. There have been several LCAs of CCS. Enhanced oil recovery (EOR) has been investigated as a storage option for CO_2. These studies very often quite general. In this paper, we investigate enhanced oil recovery in more detail by modeling the processes on a specific platform, both with and without EOR. Due to the CO_2 injection in the oil field, a change in the electricity supply of the platforms is required, and we investigate both running gas turbines on diesel and providing the platform with power from the power plant through an offshore cable. We only model global warming and acidification impacts, because there is too little information available on emissions causing human or ecological toxicity.

2 Life Cycle Assessment of Energy Systems

2.1 Life Cycle Assessment methodology

2.1.1 *General*

Developed from a number of roots in chemical engineering and energy analysis, Life-Cycle Assessment (LCA) is a method to account for the environmental impacts associated with a product or service. The name life-cycle indicates that all stages in a product's life, from resource extraction to ultimate disposal, are taken into account. One precursor of this cradle-to-grave evaluation was the comparative environmental assessment of energy technologies (6,7,11,30). Energy analysis initially focused only on embodied or grey energy. Present day LCA methodology was developed in the 1990s (8,12) and has become standardized through ISO.

LCA aims to provide a complete picture of the environmental impacts of a product, service or system. We usually talk about a product system. Several distinct analytical steps are required to achieve this aim:

1. Quantification of activities and flows associated with a product system: We need to find out what resources are required, how much of each resource, what production, transport, use, maintenance and disposal processes are part of the product system, and how much of each process is utilized per unit output. This requires a model of the economic system. There are two traditions, one of building process models which capture some technical detail of the mass and energy flows of specific processes (6), and the other of using economic input-output analysis to describe all processes in an economy (7).
2. Quantification of the emissions, resource use and other environmental or social interventions associated with the activities that are part of the product system. The sum of these interventions forms the Life-Cycle Inventory.
3. Evaluation of the environmental impacts caused by the different interventions.

> Impact assessment aggregates interventions which cause similar impacts in impact categories. Category indicator results express the level of pressure or damage in a specific category. It should be noted that there are two different approaches to impact assessment: (a) The environmental themes approach aggregates impacts by environmental mechanism, for example climate change, acidification, human toxicity etc. (b) The damage function approach aggregates impacts by endpoint, e.g. human health and ecosystems, sometimes to a single indicator (e.g. monetary value of damages caused) (33).

These quantitative assessment steps are complemented by a goal and scope definition step, which includes the study design, and an interpretation step in which conclusions are drawn.

2.1.2 *Hybrid LCA*

During the 1990s, inventory analysis was usually based on assessing processes in physical terms and using cut-off criteria to identify processes which could be excluded from the modeling because of their small contribution (8,12). It turns out that the sum of small contributions is significant (20). Hybrid life-cycle assessment hence models a foreground system in physical terms and smaller contributions as purchases from a background economy. This effort builds on the earlier modeling practice in energy analysis (7,11). Hybrid LCA is thus able to cover virtually all activities and focuses the effort to model detail on where it matters. Our group has developed a procedure which takes advantage of the analytical capabilities of input-output analysis to identify important steps through structural path analysis (25). This study is one of the first applications of this procedure and the associated software.

2.2 LCA of energy systems

A wide range of studies has been performed on energy systems. Since fossil fuel use causes the largest anthropogenic material flows and energy is essential in the production of every product, assessments of energy are the basis for any LCA. Table 1 provides some exemplary LCI data for electricity production.

Table 1: Basic Life cycle inventory data for electricity from different power plants, per TJ electricity. Data from Frischknecht et al.(10). The fossil fuel and nuclear power data is for the average German power plant.

	CO_2 (kg)	SO_2 (kg)	NO_x (kg)	CH_4 (kg)	Land use (m^2)	Highly radioactive waste (m^3)
Gas-fired power plant	245831	58.3	408	374	2133	3.13E-06
Lignite power plant	365150	2660	500	29.5	1977	1.48E-05
Nuclear power plant	3690	25	9.68	10.7	27384	1.26E-03
Run of river hydropower	913	2.13	3.25	2.05	1316	6.17E-07
Storage hydropower	976	2.4	2.77	2.36	1368	9.79E-07
3kWp Rooftop PV (m-Si)	29217	194	69.7	64.6	4744	8.71E-05
Windpower	13394	58.3	30.2	41.5	2384	8.49E-06
Oil power plant	225170	2320	495	301	6134	1.41E-05
Hard coal power plant	277155	409	249	1230	1791	2.19E-05

2.3 LCA of CCS

Few LCAs of CCS have been conducted, giving insight into environmental costs and benefits. The studies differ in terms of the technologies assessed, the detail in processes modeled, the completeness of the life-cycle inventory, and the emissions included in the assessment. Table 2 presents an overview of existing studies.

Table 2: Aspects covered by 'CCS system assessments'- Literature review

	Fuel					Power cycle		Carbon Capture			Transport			Storage						LCA				Emissions	
	NG	C	PC	SG	BM	SC	CC	PoC	PrC	Oxy	P	S	R-R	G	ER	A	O	M	Ot	MEB	FG	F	Hy	CO_2	Ot
Summerfield et al, 1995	x		x	x		x	x	x	x		x	x		x			x		x	x				x	x
Waku et al., 1995	x			x			x	x	x		x	x		x			x			x				x	
Aycaguer et al., 2001															x						x			x	x
Rao et al., 2002		x				x		x												x	x			x	
Lombardi, 2003	x			x			x	x	x	x												x		x	x
Benetto et al., 2004		x			x			x														x		x	x
Suebsiri et al., 2006															x						x			x	
Khoo et al., 2006			x			x		x							x		x					x		x	x
Khoo et al., 2006		x				x									x							x		x	x
Viebahn et al, 2007	x		x	x		x	x	x	x	x	x			x							x			x	x

Fuel	Power cycle	Carbon capture	Transport	Storage	LCA
NG Natural gas C Coal PC Pulverised coal SG Syngas BM Biomass	SC Simple Cycle CC Combined cycle	Po C Post combustion Pr C Pre combustion Oxy Oxyfuel combustion	P Pipeline S Shipping R-R Rail and road	G Geological ER Enhanced recovery A Aquifier O Ocean M Mineral carbonation Ot Others	MEB Mass & Energy balance FG Foreground LCA F Full LCA Hy Hybrid LCA

Summerfield et al. (29) concluded that the majority of the atmospheric emissions come from fuel processing and transport rather than from the power generation process themselves. Waku et al. (32) found that emission control potential for LNG C/C and IGCC were in the range of 61-69% and 65-76%, respectively. Aycaguer et al. (2) suggested that the EOR process was not only a major CO_2 user but could also provide a significant means to store it underground. Rao et al. (26) concluded that the CO_2 control system generates several new waste products, principally ammonia gas and hazardous reclaimer bottoms. On the other hand, the CO_2 capture system also reduces emissions of particulate matter and acid gases such as SO_2, HCl and NO_2. Lombardi (22) concluded that IGCC plant gave highest score for green house effect; and the majority of emissions were from maintenance/operation phases. The assessment of other impacts included in Eco-indicator 95 method concluded that the reduction in greenhouse effect is not accompanied by transfer of pollution from one category to another. Benetto et al. (4) showed that biomass co-combustion is always environmentally better than the sole CO_2 capture and/or biomass combustion. Suebsiri et al. (28) concluded that the emissions of CO_2-based EOR operation are only two-third of the life cycle emissions of conventional oil production. Khoo et al. (18) concluded that the most promising environmental benefit stems from enhanced coal bed methane production (ECBM) combined with chemical absorption followed by EOR with chemical absorption. Khoo et al. (17) concluded that enhanced resource recovery methods, both with potential to sequester CO_2, results in significant environmental benefits. Viebahn et al. (31) showed that CCS technologies emit per kWh more than generally assumed in clean-coal concepts and much more if compared with renewable electricity. Nevertheless, CCS could lead to significant absolute reduction of GHG-emissions within the electricity supply system.

3 Systems Description

3.1 The foreground system

The foreground system consists of a power plant with CCS, the fuel supply, and the CO_2 utilization infrastructure including oil production (Fig. 1). We will describe this in some more detail.

1. **Natural gas production and transport**: Heidrun field produces 7.7 million standard m^3 of oil and 2230 million standard m^3 of natural gas per year. It requires

368 GWh of power which is produced by dual fuel gas/diesel turbines. The gas is compressed and transported to Tjeldbergodden through the Halten pipeline. Inventory data for the emissions and fuel consumption for the production, power production and compression were obtained from Statoil.

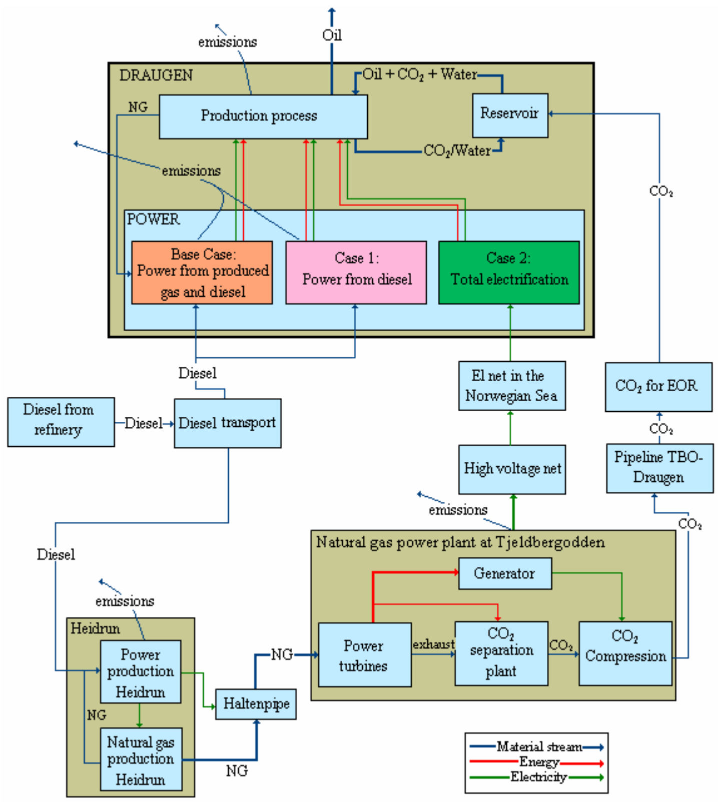


Figure 1: Process flow chart of the foreground system of the LCA: Natural gas production at Heidrun, power production and carbon capture at Tjeldbergodden (TBO), and carbon storage and enhanced oil recovery at Draugen.

2. **The power plant and CO_2 capture facility**: A combined cycle power plant with a gross power output of 832 MW is modeled to be running at full load. The lifetime is assumed to be 30 years. Materials for the construction of the power plant were obtained from Fluor (9) and Sintef (19). Data for capital and operational expenditure were used to model environmental impacts not connected to energy and materials. The separation plant employs amine based post combustion technology to capture CO_2 from the turbine exhaust. The plant is designed to capture 90% of the CO_2 emissions. The separation plant is co-located with the power plant which supplies the energy to the separation processes. Medium

pressure steam is tapped from the steam turbine to drive the amine regeneration process. The plant inventory is based on Solli (27). The CO_2 is compressed to 150 bar and sent through a 150km, 12" chromium steel pipeline to Draugen. The inventory of the pipeline was modeled based on the material inputs and capital/operation expenditure.

3. **Enhanced oil production**: The Draugen field has been in operation since 1993. Water injection was started in 1999. At the end of 2005, 52.3% of the original oil in place (OOIP) had been produced, and the total recovery was estimated 65% without EOR. The EOR potential was estimated to be 8.6% or 18MSm^3 of oil. 35Mt of CO_2 would be injected and stored in the reservoir (13,21). The CO_2 injection was modeled to begin in 2010 and would result in a breakthrough of CO_2 already in 2011. A total injection of 64Mt is hence required. Fig. 2 provides a profile of the oil production, water production and CO_2 production from the field. The modeling and life-cycle inventory of the platform are described in more detail in the next section.

4. **Power supply**: Due to the CO_2 breakthrough and the increased power requirement of the CO_2 injection, the produced gas can no longer be used to supply the power on the platform. Two alternative power supplies were modeled: Option 1 is the use of diesel in gas turbines. Option 2 is the supply of electricity from the land to the platform through a sea cable. Six oil installation would be connected to the grid through a set of sea cables (23). The life-cycle inventory of this electrification was modeled based on capital expenditure, and a fraction was allocated to Draugen based on its share in the power demand.

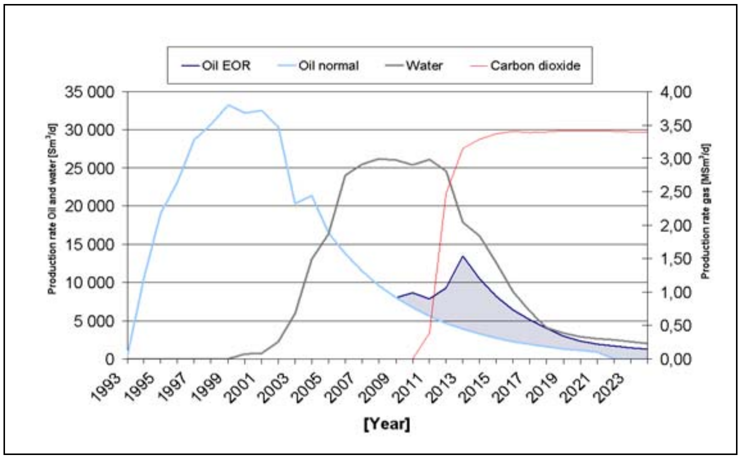


Figure 2: Production profile of Draugen, 1993 – 2024

3.2 Modeling the platform modifications for EOR

The introduction of CO_2 handling and its use for enhanced oil recovery require substantial changes to the operations on platform. Injection compressors, pumps and new wells are required. The injected CO_2 will soon result in a break-through. This means that it will come up again through the oil well, mixed with the produced gas. This gas hence becomes unsuitable for the use in gas turbines. Separating the CO_2 and the gas would be too expensive, so it is assumed that both will be reinjected on the platform. The power supply hence needs to change. In addition, the process equipment needs to be corrosion resistant to the carbonic acid that forms. In order to quantify the material flows and energy needs and to describe the modifications required in some detail, we have modeled the platform in HYSYS. We compare a base case and an EOR case.

Following elements were modeled in the *base case*:

1. The power generation for electric power and injection pumps.
2. The oil train, which includes two separators and a vapor outlet, a scrubber and a booster compressor for the gas.
3. A gas compressor train which receives gas from the two separators of the oil train and recycled lift gas. It includes three compressor scrubbers, as well as a set of compressors and air exchangers.
4. A condensate train, which has a highly simplified presentation of the condensate

treatment processes.

In addition, a gas turbine, water injection and oil loading were modeled. To validate the HYSYS model the production rates were tuned to match the average production of 2003. The results from HYSYS model were then compared to similar data stated in the 2003 air emissions report (1). There was a reasonable agreement of the results.

The *base case* HYSYS model has been utilized to calculate energy consumption and emissions from Draugen from 2010 – 2021. The production profiles shown in Fig. 2 were used as a basis for the simulation. Diesel consumption was adjusted to compensate for the reduction in produced gas. The amount of injected water was set equal to the volume of the produced fluids.

For the *EOR case*, a large part of the original production system must be modified. A modified production process more appropriate for the EOR operation was created using HYSYS. The EOR configuration is derived from the current production system with the following major modifications made to the system:

1. The compressor train is substituted. The new compressor train is based on the ENCAP-CO_2 standard for CO_2 compression (5). The compressor train comprises three compression stages and a final pump stage for dense phase compression.
2. The current condensate train is completely removed.
3. A CO_2 injection system is added.
4. To simplify the model it has been assumed that lift-gas is not needed during EOR operations.

The HYSYS model has been utilized to calculate energy consumption and emissions from EOR operations at Draugen. It was assumed that some water injection continues in a water-alternating-gas injection strategy. The WAG operation is simulated as injection of water equivalent to one Tornado turbine (4.3MW) in constant operation. Part of the operation before the CO_2 breakthrough is based on the model of the base-case. Once CO_2 breaks through, it is assumed that there is no flaring possible due to the high CO_2 concentration in the produced gas.

The energy consumption in the two cases is comparable, on the order of 200-250 GWh/y. In the EOR case, however, the oil production is significantly higher, so that the energy consumption per unit oil produced is only half as large as in the base case. Table 3 shows the emissions for base case and EOR case.

Table 3: HYSYS simulation results for the platform emissions

	base case					EOR case				
Year	**NO_X [t]**	**SO_2 [t]**	**CO_2 [kt]**	**CO [t]**	**CH_4 [t]**	**NO_X [t]**	**SO_2 [t]**	**CO_2 [kt]**	**CO [t]**	**CH_4 [t]**
2010	678	8	202	12	45	582	8	172	12	38
2011	666	8	197	10	45	581	8	172	12	38
2012	656	8	195	12	43	1 146	201	248	50	0.05
2013	609	8	180	12	40	1 362	238	286	60	0.03
2014	593	8	175	12	39	1 331	233	279	58	0.02
2015	611	25	171	16	33	1 306	228	272	57	<0.01
2016	705	55	182	23	27	1 279	224	263	56	<0.01
2017	785	80	191	29	22	1 251	219	256	55	<0.01
2018	851	101	198	34	18	1 234	216	251	54	<0.01
2019	892	118	204	39	14	1 216	213	246	53	<0.01
2020	952	133	209	42	11	1 205	211	244	53	<0.01
2021	931	145	197	378	7	1 197	209	242	52	<0.01
2022						1 191	208	241	52	<0.01
2023						1 185	207	239	52	<0.01
2024						1 179	206	238	52	<0.01
Sum	**8 928**	**697**	**2 301**	**276**	**343**	**17 243**	**2 831**	**3 648**	**727**	**75**

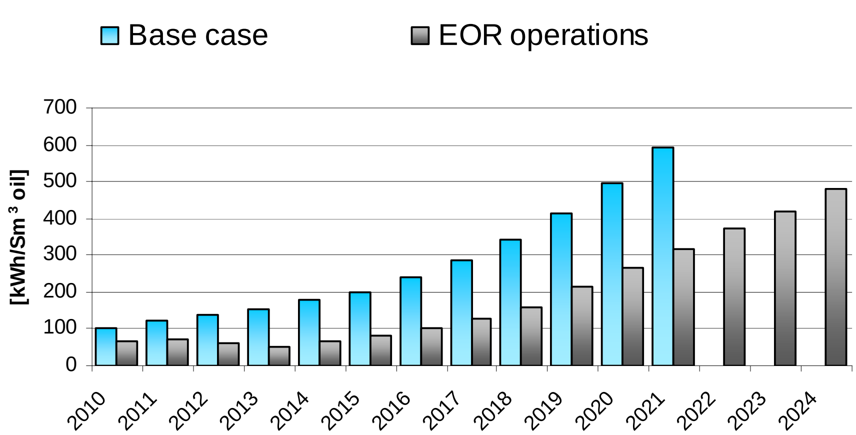
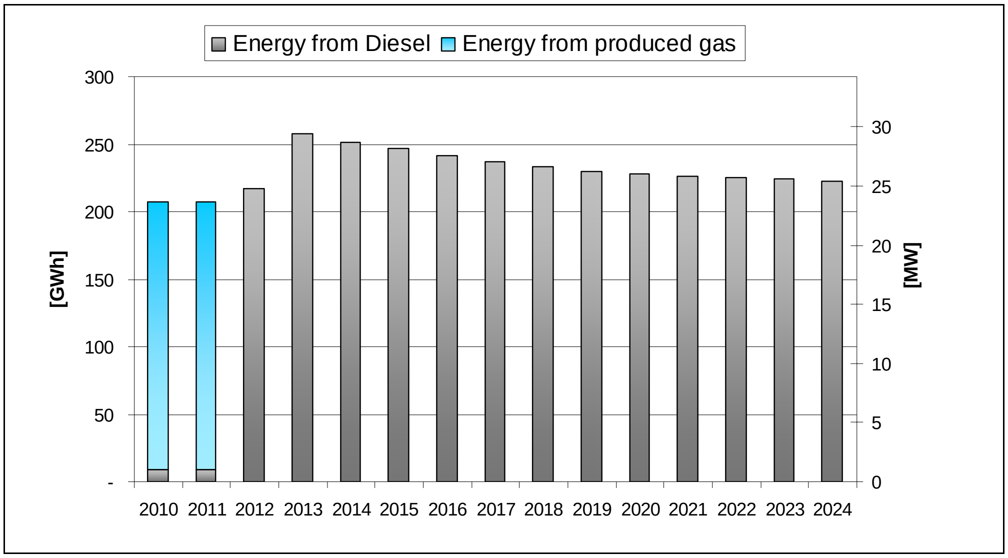


Figure 3: Power consumption per standard m^3 oil produced at Draugen.



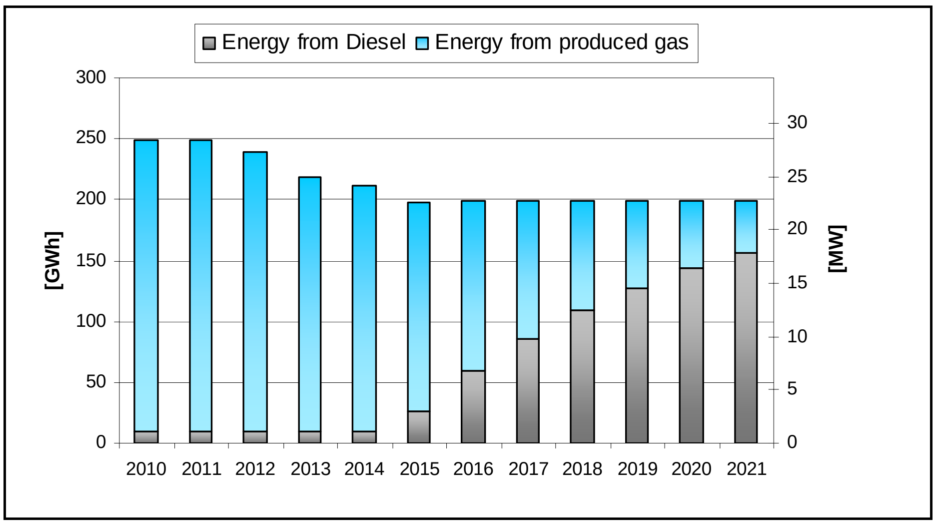


Figure 4: Energy source for off-shore power production in the EOR (top) and base case.

3.3 Allocation

The system in Fig. 1 produces a number of products: Electricity, oil, and gas. Co-product allocation is an important issue that has been discussed extensively in the LCA literature. Allocation can be based on a systems expansion, i.e. the comparison with other combinations of systems that produce similar output, allocation based on the value of the output, or allocation based on a physical measure such as mass, energy or exergy. In principle, there is no correct allocation procedure, but some procedures are more suitable for some cases.

The problem in our case is how to allocate the pollution associated with the CO_2

infrastructure: does CCS happen to produce more oil, or is EOR just a way to handle unwanted CO_2 from the electricity production? A similar allocation issue also exists for the costs and financial risk of the CO_2 infrastructure. Bellona (16) has been proposed a solution for resolving the financial risk issues, proposing government-backed firms that would capture the CO_2, transport it to the platform, and sell it to the oil companies. In the spirit of that solution, we propose that the power plant and capture plant should be seen as one unit, with the pollution and energy use associated with capture assigned to the product electricity. The oil production should be seen as a separate unit, with the pollution associated with the CO_2 transport and storage assigned to the additional oil recovered.

4 LCA RESULTS

We present the results for both the electricity production and the oil production. It is important to keep in mind that, for the CCS-EOR system, these two are co-products of a common system. The impacts of the capture facility were allocated to the electricity production, while the impacts from the CO_2 transport and storage were allocated to enhanced oil recovery. The EOR cases include both additional oil and oil that would have been produced without EOR.

4.1 Electricity production

The life-cycle impact assessment results for global warming and acidification are shown in Fig. 5. The power plant produce emissions equivalent to 410 kg CO_2/MWh. 90 % of the CO_2 emissions are captured by the CCS system. CCS requires power and heat, and this lowers the overall efficiency of the plant. The effect of the additional fuel use due to the CCS system is illustrated by white area in the “Power turbines at TBO” bars in Fig. 5. Table 4 indicates that, on a life-cycle basis, the CCS reduces greenhouse gas emissions by 80%, but it substantially increases acidification potential due to the NH_3 emitted from the capture plant.

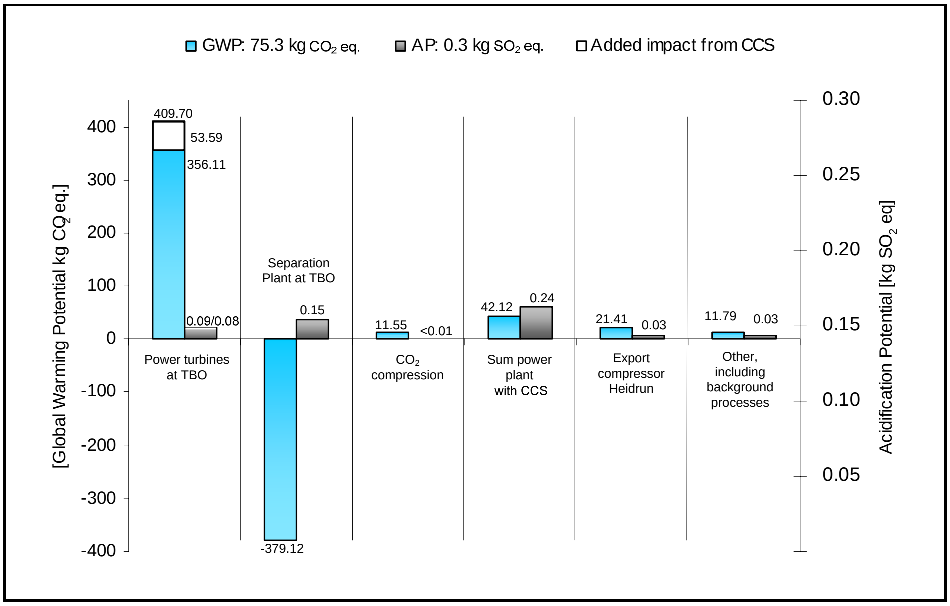


Figure 5: Distribution of impact resulting from production of 1MWh electricity at TBO

Table 4: Life-cycle impacts of electricity from the NGCC power plant at Tjeldbergodden.

	1 MWh with CCS	1 MWh w/o CCS
GWP (kg CO_2e)	75	381
AP (kg SO_2e)	0.30	0.12

Oil production

The results of the life cycle impact assessment for oil production are presented in Table 5. Comparing worst and best cases relative to the amount of oil produced shows that normal operation of Draugen results in the highest climate change emissions. In the other effect category, acidification potential, Case 1 causes a slightly higher impact. Case 2, enhanced oil production and electrification of the platform, shows a superior environmental performance within both impact categories.

Table 5: Impacts per functional unit, [1Sm^3 oil]

Case\Impact category	GWP [kg CO_2 eq]	AP [kg SO_2 eq]	Oil production [MSm^3]
Base case, normal operation:	180	0.43	13.1
Case EOR1, Diesel:	128	0.45	31.1
Case EOR2, Electrification:	19	0.06	31.1

The poor performance of the base case is related to a low annual oil production rate, and the fact that the emissions for the operations of the platform are distributed over a small production. There are substantial emissions from diesel combustion for power generation on the platform both in the base case and the EOR1 case. When electrifying the platform, using electricity produced by the power plant at TBO, the emissions are substantially lower.

Tables 6-8 show the distribution of the impacts across the processes in the foreground systems and the pollutants included in each of the two impact categories, for each of the three cases. Emissions from the foreground system are almost exclusively linked to the operation at Draugen. NO_X is the main acidifying stressor but SO_2 emissions are also making a noteworthy impact. SO_2 emissions originate from combustion of diesel in offshore turbines. The sulfur content in diesel is relatively high compared to natural gas. When diesel is used to compensate for the shortfall of natural gas, the acidic emissions increase. In addition, emissions related to diesel transport and production increase.

Table 6: Impact indicators and emissions per Sm^3 oil, base case

	Impact [kg/Sm³ oil]		Emissions [kg/Sm³ oil]					
Process	AP	GWP	NO_X	SO_2	NH_3	CO_2	CO	CH_4
Production process	7.4 %	9.9 %	9.0 %			10.0 %	31.4 %	5.3 %
Offshore power generation	86.2 %	88.1 %	86.0 %	87.5 %	-	88.1 %	51.7 %	75.2 %
Diesel transport/production*	6.5 %	2.0 %	5.0 %	12.5 %	100 %	2.0 %	16.9 %	19.5 %
Total [kg/Sm³ oil]	**0.43**	**180**	**0.72**	**0.06**	**<0.001**	**179**	**0.03**	**0.02**
% of total acidification			83.1 %	16.9 %	0.04 %	-	-	-
% of total global warming			-	-	-	99.7 %	-	0.3 %

Table 7: Impact indicators and emissions per Sm^3 oil, EOR1 case

	Impact [kg/Sm³ oil]		Emissions [kg/Sm³ oil]					
Process	AP	GWP	NO_X	SO_2	NH_3	CO_2	CO	CH_4
EOR production process	0.5 %	3.2 %	-	-	-	3.2 %	0	0
Modifications at Draugen*	3.6 %	3.8 %	3.3 %	3.6 %	76.9 %	3.3 %	28.9 %	71.3 %
Offshore power	85.4 %	88.3 %	86.1 %	84.4 %	-	88.8 %	53.1 %	6.6 %
Diesel Transport/Production*	10.6 %	4.8 %	9.9 %	10.8 %	23.1 %	4.7 %	16.6 %	21.8 %
Other	<0.1 %	<0.1 %	0.7 %	1.2 %	0.03 %	3.2 %	1.5 %	0.3 %
Total [kg/Sm³ oil]	**0.45**	**128**	**0.64**	**0.11**	**<0.001**	**127.4**	**0.04**	**0.04**
% of total acidification			71.1 %	28.6 %	0.3%	-	-	-
% of total global warming			-	-	-	99.4 %	-	0.6 %

* Emissions induced in the background processes are included in the figures on this row.

Table 8: Impact indicators and emissions per Sm^3 oil, EOR2 case with electricity from TBO

	Impact [kg/Sm^3 oil]		Emissions [kg/Sm^3 oil]					
Process	AP	GWP	NO_X	SO_2	NH_3	CO_2	CO	CH_4
EOR production process	3.8 %	21.3 %	7.0 %	-	-	22.1 %	4.4 %	<0.01%
Modifications at Draugen*	27.2 %	25.1 %	32.0 %	77.7 %	4.7 %	23.1 %	65.5 %	82.0 %
Power turbines at TBO†	20.8 %	28.0 %	37.0 %	-	-	29.1 %	-	-
Separation Plant at TBO	32.4 %	-259 %	-	-	94.1 %	-268.7%	-	-
CO_2 compression at TBO**Error! Bookmark not defined.**	0.6 %	0.8 %	1.0 %	-	-	0.8 %	-	-
Export compressor at Heidrun	7.3 %	14.6 %	13.0 %	-	-	15.1 %	11.1 %	2.4 %
Power production at Heidrun	2.6 %	5.1 %	5.0 %	0.5 %	-	5.3 %	4.1 %	0.9 %
Other	5.4 %	4.9 %	5.0 %	21.8 %	1.3 %	4.6 %	14.9 %	14.8 %
Total [kg/Sm^3 oil]	**0.06**	**19.1**	**0.06**	**0.005**	**0.013**	**18.4**	**0.02**	**0.03**
% of total acidification			55.5 %	10.1 %	34.4 %	-	-	-
% of total global warming			-	-	-	96.5 %	-	3.5 %

A comparison of the two EOR cases shows that not only the greenhouse gas emissions are reduced substantially by replacing the offshore turbines by electricity from TBO. This reduction is due to the high emissions of NO_x and SO_2 from using diesel in the gas turbine.

Structural Path Analysis

To indicate further analytical possibilities, we present a structural path analysis of EOR Case 1. The analysis was performed in an early version of the software developed by Strømman and Solli using an algorithm developed by Peters (25). In Figure 6 the foreground processes are presented as nodes, and it is indicated how the total climate change impact is of 128 kg CO_2 eq. is distributed among them. Impact originating directly from a process is illustrated by a curly arrow while emissions induced by the demanded inputs of this particular process are indicated on the inter-connection arrows. An impact induced in the background system by a particular process is illustrated by a single straight arrow into the process' node.

† The capture plant captures 90 % of the CO_2.

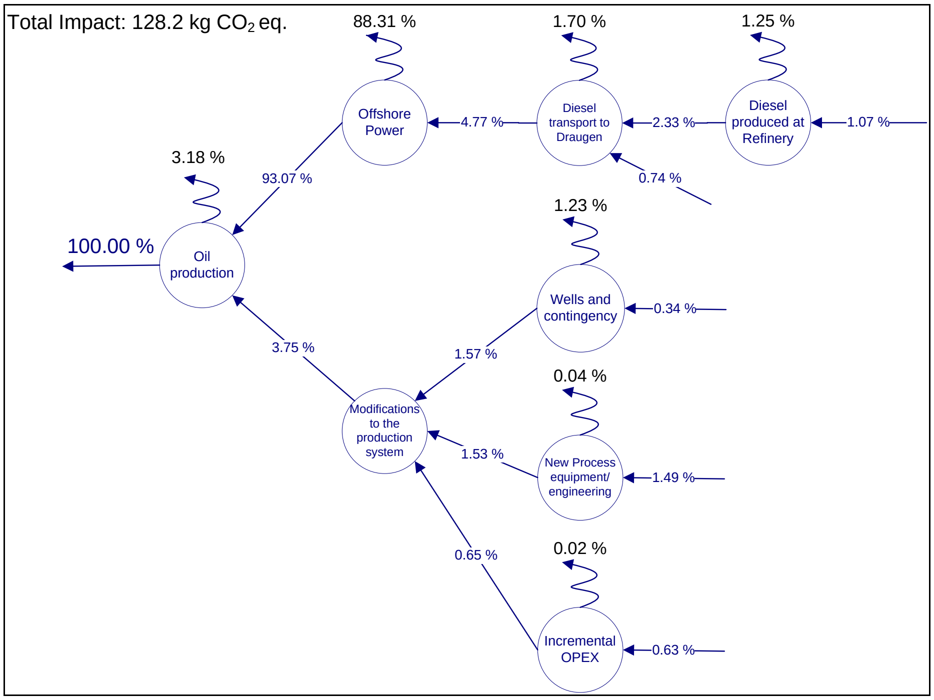


Figure 6: Structural Path Analysis of the GWP results for Case 1, EOR-diesel

As we have seen, offshore power generation is the main source of GWP. The SPA reveals that manufacture and transportation of diesel is the second largest contributor. Combined offshore power generation and diesel procurement cause 93% of the GWP. Modifications to the production system at Draugen account for less than 4% of the GWP. These modifications have been modeled by economic input-output tables. Figure 6 indicate how these modifications contribute directly and how they induce impacts throughout the Norwegian economy.

5. DISCUSSION

It is important to understand that an LCA of a future system involving unproven technologies carries substantial uncertainties. The most important uncertainties in this work are connected to the performance characteristics and impacts associated with the carbon capture plants, the reservoir characteristics which influence the amount of recoverable oil and time at which the CO_2 breaks through, and uncertainties about the design and operations of the CO_2 injection and re-injection at the platform. The use of a process modeling software, HYSYS, to describe the off-shore operations has enabled us to provide a better estimate of required investments, energy consumption, and emissions than we could have obtained from other sources. The use of economic input-output tables to estimate the environmental impacts of investments and operational inputs is both time saving and allows us to focus on the essential processes. At the same time, there are uncertainties connected to input-output analysis and associated emissions data, and uncertainties connected to the costs that were used as a basis for the estimates. Given these uncertainties, the results should be taken as indicative and the significant figures provided in the tables and figures are a reflection of the calculations, not a claim for the precision of the results.

The analysis indicates the proposed power plant with carbon capture would have substantially lower greenhouse has emissions and somewhat higher emissions of acid precursors than a gas fired power plant without CCS. More surprisingly, the enhanced oil recovery using CO2 from the power plant would reduce the greenhouse gas emissions per unit of oil produced. An electrification of the platform would cause substantial benefits in terms of reducing both greenhouse gas and acidifying emissions.

CREDITS

This paper is based on the Aaberg's MSc thesis, supervised by Hertwich and Strømman. Singh provided the literature review and figures, and Hertwich wrote the paper. Jan Addicks and the cleaner production team at Shell Technology Norway provided data and information on the case. Christian Solli and Rahul Anantharaman provided technical support with the calculations.

NOMENCLATURE

AP	Acidification Potential
CCS	Carbon dioxide Capture and Storage
ECMR	Enhanced Coalbed Methane Recovery
EOR	Enhanced Oil Recovery
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NGCC	Natural Gas Combined Cycle power plant

TBO	Tjeldbergodden
bbl	barrels
kt	1000 metric tons
Mt	1 million metric tons
MSm^3	Million standard cubic meters
MW	Megawatt
MWh	Megawatt hours
Sm^3 oil	Standard cubic meter oil (1 Sm^3 oil = 6.29bbl)

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