Working Paper no. 3/05

HydroKraft:

– Mapping the innovation journey in accordance with the research protocol of CondEcol

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CondEcol

ISBN 82-90391-46-3

ISSN: 1500-5460

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FOREWORD

ProSus is a strategic university programme established by the Norwegian Research Council at the Centre for Development and the Environment (SUM), University of Oslo, Norway.

The goal of ProSus is to provide knowledge and information in support of a better realization of national targets for sustainable development. The work in the current financing period is concentrated on three main tasks:

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William M. Lafferty
Professor of political science
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THE CONDECOL PROJECT

This report is published as part of the research project CondEcol – Exploring the Conditions for Adapting Existing Techno-Industrial Processes to Ecological Premises. The aim of the CondEcol project is to develop strategic management and governance perspectives for realizing product and process innovation with a high potential for improved eco-efficiency.

The CondEcol project is structured as a multi-disciplinary study of the conditions for moving existing production and consumption patterns in the direction of sustainable development. Changes are to be achieved through knowledge-sharing and partnership with industry; goals that directly reflect the focus of the programme providing extra funding for the project – RAMBU ("Conditions, Governance and Policy Instruments for a Sustainable Development") within the Research Council of Norway. Working closely with two industrial partners, Norsk Hydro and Renewable Energy Corporation (REC), the project explores three high-profile cases of technology and product development as a basis for identifying factors that may hinder or promote innovation and diffusion of new technologies with high eco-efficiency.

An important challenge in changing production and consumption patterns is to look for solutions that reduce the environmental strain per consumed unit (eco-efficiency), and to decouple economic growth from environmental impacts. Public authorities and private enterprises have placed these ideas on the agenda, and pragmatic discourse in academia is already underway. However, there is still limited understanding of how and to what extent eco-efficiency gains at the level of specific products or production processes can be converted into eco-effective gains for society at large.

By joining a network approach with the conceptual tools of industrial ecology, economics, strategic management, and integrated governance – and by anchoring the approach in specific case studies of past and current innovation journeys – the CondEcol project aims to develop a new and comprehensive framework for identifying and communicating effective instruments for promoting sustainable production and consumption patterns. The fact that the cases in question involve major attempts by industrial actors to introduce more eco-efficient technologies, and that the cases reflect the actors own experience of the obstacles encountered, makes the CondEcol-project different. Insights from the social sciences regarding sustainable development have only recently come to bear on strategic decision-making in business, so the output of the project should have relevance for promoting more sustainable processes internally in firms as well as in the market and society as a whole.

CondEcol is an integral part of ProSus' ongoing research and dissemination activities. It is also directly tied into the SUSLINK-project, an integrated, multi-level effort focusing on European, national, local and household aspects of sustainable production and consumption in the energy and transport sectors.

Oslo, December, 2005

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Director of ProSus

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1 INTRODUCTION[1]

On the 23rd April 1998 Egil Myklebust, President and CEO of Norsk Hydro, held a press conference in which plans for a "CO_2-free" and environmentally friendly gas power plant was announced. Work on the project, which came to be called HydroKraft, had been in progress within Hydro since the early summer of 1997. The launching of the project coincided with Hydro's annual general meeting and the centrist government's[2] proposal for a White Paper on follow-up plans for Norway's climate change goals. The Norwegian newspaper *Aftenposten* commented as follows[3]:

> "Industry giant Hydro's announcement of a gas power plant with minimal emissions of the greenhouse gas CO_2 was regarded as a coup of the climate debate".

The reference here was to the White Paper no. 29 (1997-98): Norwegian Implementation of the Kyoto Protocol[4]. Here, too, proposals for expanding the CO_2 tax were proposed. This was followed up by the Storting, and from 1999 a CO_2 tax of NOK 100 per tonne was introduced (cf. Parliamentary Bill no. 54 (1997-98): Green Taxes)[5]. This was a political decision which could have had a negative impact on Norsk Hydro's business prospects and financial standing[6]. Norsk Hydro would then have been forced into taking measures.

Norsk Hydro had the operational responsibility for the Grane oilfield, which was due to start operations in 2003. Grane is situated in the Sleipner area[7] in the North Sea and has approximately 100 million cubic metres of recoverable oil, but it also has a considerable requirement for pressure support in order to be commercially exploitable. CO_2, water and natural gas are all suitable for pressure support, but previously it had been difficult to get access to sufficient amounts of CO_2. For the Grane oilfield the estimated annual requirement was for five million tonnes of CO_2[8]; almost 10 per cent of Norway's total annual emissions of greenhouse gasses. However, a HydroKraft gas power plant could prove to be a reliable and stable producer of CO_2 for pressure support on Grane.

As an industrial conglomerate with substantial land-based enterprises, Norsk Hydro was also extremely concerned with the energy balance in Norway. The company was very concerned about the rising electricity prices and, in particular, that energy was not being further developed. There was a fear that this would in time create difficulties for the industrial land-based production in Norway. At the same time there were more than enough gas fields on the Shelf. And while there were good transport and processing capacities, there

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1 This mapping was initiated in 1993 and finalized in fall 2004.
2 The centrist coalition government (Bondevik's first government) was in power from 17th October 1997 - 17th March 2000.
3 *Aftenposten* (morning edition) 24th April 1999: "Hydro went behind our backs" (Auke Lont, former director of Naturkraft, is quoted in the title of the article).
4 White Paper no. 29 (1997-98): Norwegian Implementation of the Kyoto Protocol. Oslo: Ministry of the Environment. (Available at: http://www.odin.dep.no/md/norsk/publ/stmeld/022005-040004/dok-bn.html).
5 Parliamentary Bill no. 54 (1997-98): Green Taxes Oslo: Ministry of Finance. (Available at: http://www.odin.dep.no/fin/norsk/publ/stprp/006005-030019/dok-bn.html)
6 The same decision, however, made it possible for some sectors to be exempted from paying this tax. This applied to companies within the process industry (compensation for taxes on input factors used as reducing agents and raw materials), the fishing fleet and air transport (compensation for additional costs relating to the CO2 tax). The exemption for gas utilised in transportation was upheld. At the same time the CO2 tax on petrol and emissions from petroleum activity on the Norwegian Continental Shelf was continued at the same level as previously.
7 See Chapter 9.3 "Appendix" for map segment.
8 There would have been a similar requirement on Gullfaks. This is equivalent to the amount of CO2 that comes from approximately 2 billion cubic metres of gas. In comparison the total annual emission of CO2 equivalents in Norway is approximately 60 billion tonnes.

were not enough sales contracts with the Continent[9]. Given this situation, Hydro believed that the surplus unprocessed gas could be used for the project without any consequences for gas sales in general.

HydroKraft was a project that generated great enthusiasm and admiration internally in Norsk Hydro. All three operational divisions in the industrial conglomerate, i.e. oil and gas, light metal, and Agri, were involved. Oil and gas sought alternative pressure support by means of CO_2. Light metal, and primary aluminium plants in particular, sought new supplies of electricity, while the Agri segment of Hydro was able to transfer its experience and competence from ammonia production and reforming of natural gas for hydrogen production.

Hydrogen was defined as the energy carrier of the future. This was also recognised by Norsk Hydro, but at that point in time there were few good solutions forthcoming as to how this could be processed in sufficient volumes. The Kyoto Protocol for controlling greenhouse gas emissions, including CO_2, was signed the previous year and was actively supported by the Norwegian government. The HydroKraft project could thus realise national environmental policy goals as well as secure the sale of gas deposits and the development of cornerstone companies in Norway.

The project received support from the Storting and some of the environmental movements, the environmental foundation Bellona in particular. At the same time the launching of the HydroKraft project resulted in work on the gas power plant planned by Naturkraft stagnating. Although Norsk Hydro was part-owner of Naturkraft, it had not informed the company about its "rival" concept.

The technological solution chosen by HydroKraft was based on available technology and involved the removal of CO_2 *before* combustion in a gas turbine; a so-called "pre-combustion" process. In the first phase of the process carbon is removed from the natural gas and converted to CO by bonding the carbon to the oxygen from steam and air. The next phase in the process is a reaction between CO and steam in which the calorific value in CO is transferred to hydrogen while CO reacts with the oxygen in CO_2. The actual patent relating to the HydroKraft project describes the method for producing a mixture of hydrogen, nitrogen and water which can be combusted in a commercially available turbine to produce electricity. In the HydroKraft project the hydrogen was to be combusted to produce heat for electricity production, but it could also be utilised for other applications such as propellant in fuel cells.

Production of hydrogen from natural gas as Norsk Hydro had proposed is, with today's known technology, the variant of hydrogen production with the lowest energy cost per MMBTU[10]. Although feasible technologies for production by means of both wind and sun are available, hydrogen production combined with fossil fuel, is by far the most cost–effective production method with current technology – particularly so if true value is associated with the handling of CO_2. This could provide a basis for future reflections on "jumping the curve" and the chance to realise radical, eco-efficient innovations as they are more generally problematised in the CondEcol project. It also means that CO_2 disposal will be an important theme in the future, both in the debate on hydrogen and climate, as well as in the work on proposing a more sustainable development.

The time frame for the project was dictated by the start-up of the Grane field in 2003. The project was therefore designed to be fully operative in the course of five years. This in itself was a challenge. However, the solution was based on the knowledge that fossil energy carriers were dominant and would be the cornerstone of energy supply for the next 20 years at least, perhaps as long as 50 years[11]. Also, the HydroKraft project could pave the way for more sustainable use of coal. The Americans and Chinese in

9 This was while the Norwegian Gas Negotiation Committee (GFU) still existed.
10 One million British thermal units.
11 See for example the International Energy Agency 's World Energy Outlook for comprehensive information about the global energy situation and different scenarios. World Energy Outlook is published every other year. The 2000 edition is available for free at: http://spider.iea.org/public/freepdfs/2000/studies/weo2000.pdf. (Accessed on 4th March 2004).

particular, both having large amounts of coal, are keen to make coal appealing in the long term, for reasons of security policy and national economy. As is the case with hydrogen production from natural gas, production of hydrogen from coal, results in major challenges with respect to CO_2 emissions – environmentally, technically and structurally speaking.

Great hopes were pinned to the HydroKraft project, especially since it appeared to be a technologically feasible project to be carried out under the auspices of one of Norway's largest companies. Nevertheless, the plans have not yet been realised. The Grane field now uses natural gas for pressure support. The energy balance in Norway has worsened. In this report we shall discuss why the project was never realised.

1.1 Report structure

In this report we will first present the central characteristics of the HydroKraft project and how these can represent a more eco-efficient technological innovation. Then, with reference to the CondEcol methodology's research protocol (summarised in Appendix 1), we will specify in more detail the technical aspects of the project, with reference to the Eco-design Wheel (presented in Appendix 2). We will then in Section 4 chart more closely the main factors that influenced Norsk Hydro's decision to develop and market HydroKraft as a more eco-efficient alternative. This will be followed by a survey of the key actors that have influenced the product development so far. We will then point out important decisions and critical stages along the innovation journey for the HydroKraft project. We will conclude by casting a forward glance and document what plans exist for further production and marketing of the HydroKraft patent.

This empirical documentation is a part of the CondEcol project's first phase, and will form the basis of more general appraisals of which factors influence the course of development of more eco-efficient innovations.

2 WHAT ARE THE MOST IMPORTANT CHARACTERISTICS OF HYDROKRAFT AS A MORE ECO-EFFICIENT ALTERNATIVE?

The most important characteristic of HydroKraft as a more eco-efficient alternative to existing processes is that, with fossil fuel as a starting point, CO_2 is separated from hydrogen before combustion; so-called "pre-combustion"[12]. The purity of the CO_2 that is captured is such that it can be utilised for pressure support purposes and/or injection on the Shelf, and will therefore not have any direct impact on global warming. Together with nitrogen and vapour the hydrogen makes up a mixture, also referred to as fuel gas, which facilitates combustion in existing turbines. But the hydrogen can also be used "as is" in a future hydrogen society. When it was launched in 1998, the HydroKraft project was planned with natural gas as the input factor, but it is also possible to utilise coal or other fossil fuels while at the same time being able to handle the amounts of CO_2 that this application entails.

2.1 HydroKraft with natural gas as input factor

A conventional gas power plant (with combined cycle gas turbine (CCGT)) has an efficiency[13] of 57-58 per cent. Gas turbines represent approximately 37-39 per cent of this figure, while the remainder is made up by steam turbines. Hydro had hoped that HydroKraft would attain an efficiency of approximately 50 per cent, but ended up with a figure of 44-46 per cent. This was a lower rate than conventional gas power plants, and was therefore less eco-efficient because higher efficiency yields less gas consumption per kWh. In addition, the actual injection of CO_2 for pressure support requires expenditure of energy. On Grane the pressure of CO_2 had to be 200 bars. Norsk Hydro had estimated that this would require a further 2 per cent net energy. HydroKraft, however, made possible an efficient removal of CO_2 before combustion; a factor that significantly improved the eco-efficiency. The percentage of CO_2 removed can vary. HydroKraft considered 90 per cent removal of CO_2 as reasonable from a purely cost-beneficial point of view. The same amount of CO_2 from gas combustion is produced regardless of efficiency, but the big advantage in the HydroKraft project lies in the fact that the greenhouse gas comes out in concentrated form and can therefore be deposited, rather than contribute to additional greenhouse gas emissions. In this case the CO_2 is thereby attributed a value because it can be utilised for pressure support in existing oilfields.

The big gain is therefore that the CO_2 can be utilised separately. Natural gas goes in, and two products come out. The one product is, as already mentioned, CO_2, which can for example be used for pressure support to increase extraction of commercially exploitable oil deposits. The other product is hydrogen which, in this case, is converted to heat for electricity production, but which can also be utilised in fuel cell applications in a hydrogen society of the future.

Already in 1998, Bjørn Arne Sund was an important advocate in Norway for the hydrogen approach to the future of energy supply. For 70 years the production of CO_2 and hydrogen based on gas or coal has been commercially exploited, for example in the production of hydrogen for ammonia, NH_3. The HydroKraft

12 Prior to combustion the concentration of CO2 is 18 per cent, whereas after combustion it is only 3-4 per cent. The production of hydrogen based on natural gas will therefore be more effective in a so-called "pre-combustion" process compared to a "post-combustion" process.

13 I.e. the amount of energy that is converted into electricity.

project makes use of this experience by means of steam reforming. In a reformer CO_2 is captured from natural gas before combustion. The actual HydroKraft patent describes the method for producing a mixture of hydrogen, nitrogen and water which can be combusted in a commercially available turbine to produce electricity. In a way the patent serves as a *bridge-builder* between two already existing technologies: the current production of electricity based on natural gas, and a future utilisation of hydrogen as an energy carrier in a more sustainable society.

2.1.1 HydroKraft can also be utilised with coal as input factor.

Carbon can also be captured before the combustion process by means of coal combustion, just as was planned in the original HydroKraft project. According to Andenæs, nothing that has occurred since 1998 suggests that Hydro's thinking at that time was wrong. Nonetheless, given the higher volume of CO_2 in the combustion gas from coal, compared to natural gas, it would be more feasible to use so-called amine processes to remove CO_2 after combustion; so-called "post-combustion". However, this could result in emissions causing acid rain.

Natural gas combustion discharges CO_2 emissions of 3.5-4 per cent, while coal discharges 13-15 per cent CO_2. All the same, the HydroKraft patent emerged during a coal conference in China in 2003. China's vast coal reserves are situated so far from the trade routes that the transportation costs would be too expensive. It was therefore decided to refine the coal in situ. This is attained by converting coal to syngas[14], which in turn can be used in a wide range of industrial applications. The reason for the decision to utilise gasification is because there is a wish to deal with emissions of sulphur, which pose a serious local environmental problem due to coal burning in China. The use of syngas for energy production makes HydroKraft appealing, to such an extent that a project based on syngas has been launched in China. However, this will most likely emit untreated CO_2[15].

2.2 Summary

Put in popular scientific terms, the HydroKraft patent can be described as a slightly modified reformer. Reforming is a process which, under a given pressure and temperature, breaks whatever is put in down into individual components. Natural gas (CH_4) can be introduced, thereby creating a chemical state in which the carbon is led off one way and the hydrogen another. The reformer that was planned in the HydroKraft project was approximately 10 metres in diameter, 15-20 metres high and operated under approximately 40 atmospheres of pressure at approximately 900 degrees Celsius. With the reformer proposed in the HydroKraft project one could "open the taps" a little, so that the gas produced after the CO_2 was removed, could be combusted in a turbine. The HydroKraft patent represents the connection between this process and the existing turbines.

With explicit reference to conventional gas power plants, and with reference to the climate change issue, the HydroKraft technology can therefore be characterised as more eco-efficient in comparison to conventional technology. This is because the purity and state of CO_2 is such that depositing it in existing oilfields is made possible. When it comes to energy efficiency, the situation is less favourable because, compared with a conventional gas power plant, less electricity is produced from the combustion of natural

14 A syngas is a gas that is created from saturated hydrocarbons (methane, ethane, propane, etc) and that is run through a partial oxidisation process from which carbon and hydrogen are recovered. Syngas is a very basic form of energy which can be "diverted" in many directions; everything from ore to petrochemical use. The hydrogen is however in free form, something which could pose a challenge combustion-wise.

15 General Electric presented the project idea at a conference on 3rd-4th April 2003 in Beijing which was attended by Norsk Hydro. The conference was arranged by the Chinese American Chamber of Commerce.

gas. Nevertheless, the lower energy efficiency can be compensated for in ecological terms by way of CO_2 capture. Moreover, the HydroKraft project renders possible the realisation of the visions created for a hydrogen-based society of the future.

The HydroKraft patent itself is a process, in which one has to dimension two elements correctly so that they match, and in which the one element – the gas turbine – is found and "kept constant" and the other element – the reformer – is adjusted in order to be able to work together with existing turbine technology. It is important to remember here that, given the relatively short time frame for the project due to activities at the Grane field, the view at Hydro was that the turbine was not to be tampered with. At the same time there were considerable technical challenges associated with choosing a project design that could actually yield the expected effects, both with respect to the production of electricity and to CO_2 for pressure support, while CO_2 and nitrogen emissions were still controlled within safe limits.

3 HOW CAN HYDROKRAFT BE CHARACTERISED IN RELATION TO THE FIRST SEVEN SPOKES IN THE ECO-DESIGN WHEEL?

The CO_2 that is captured should, according to the plan, have been used for pressure support on the Grane oilfield. The alternative would have been to replace it with natural gas. Hydro calculated that in order to exploit the entire Grane oilfield, 15-16 billion cubic metres of natural gas for injection would be needed at a cost of approximately NOK 15-16 billion. A substantial part of this would have been returned, but that would have taken 20-30 years, and by then only 70 per cent would be recyclable. Thus, the cost of pressure support, according to Hydro's calculations, would be about the same for CO_2 as for natural gas. The choice of CO_2 as propellant would however yield a significant ecological gain while at the same time appearing, from certain assumptions about the "value" of CO_2 emissions, to be economically and technologically feasible.

Behind this technical design lie various dimensions that support these possibilities, but that at the same time have influenced the development of HydroKraft right up to the present day situation. A closer look at certain spokes in the Eco-design Wheel as presented in Appendix 2 can be decisive for identifying key actors and significant factors that at different stages in the innovation journey have influenced development. This could then link mapping of technical conditions associated with certain spokes in the Eco-design Wheel to the manufacture and supply of input factors, production, distribution, utilisation and use, and re-use or depositing of the finished product.

Here we are faced with a technology in which Spoke 8 *New Concept development* (described in Section 2 above) is clearly the most important spoke in terms of describing the technology. Having said that, interesting technological and non-technological factors and networks can also be linked to some of the other spokes presented in the Eco-design Wheel (see Appendix 2).

3.1 Spoke 1: Selection of Low-Impact Materials

The HydroKraft project was initiated because of the need for pressure support on the Grane oilfield, and was subject to the time limits dictated by the planned start-up for Grane. At the same time the project was also linked to the on shore transportation of natural gas to the Kårstø gas treatment plant. Natural gas as input factor was considered to be the prevailing reference to which technology was adapted[16].

3.2 Spoke 2: Reduction of Material Usage

On this spoke we can not see that there are factors that are relevant in terms of reduction of material usage. It was proposed that turbine technology that was available and tested should be used, and hence there was not much room for reducing material usage. The amount of material was not critical, though Andenæs emphasises that the combustion temperature was significant for material wastage from so-called "material dusting". This can also be linked to Spoke 3.

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16 As already pointed out, it is also possible to utilise other input factors. Natural gas, however, has a low carbon content in comparison to coal.

3.3 Spoke 3: Optimisation of Production Techniques

In conventional gas or coal power plants electricity is the only product, and one justifies the investments in relation to the expected selling price compared to the development, investment and operational costs involved in the production of electricity. Though in a European context, with tighter financial structures, there are opportunities for utilising waste heat from production for external applications, for example for heating. This was not possible in the HydroKraft project[17]. A possible application within fish farming was considered, but a much more important product was CO_2.

It is important to realise that CO_2 was considered a value and a source of revenue rather than an expenditure or a problem, as was the case in the climate debate. At any rate, the relevant questions were: how to produce CO_2, at what price, and what commercial value could be attained? As shown in Figure 1, Andenæs seems to recall that it was decided that the minimum price had to be about 17-18 øre (NOK 0.17-0.18) per cubic metre of CO_2. This would then equal balance, since this was the price they had had to pay for natural gas in 1998[18]. The figure shows how the estimated minimum price for CO_2 was calculated as a function of the price of natural gas to the market, divided by the comparative weight of natural gas and carbon dioxide:

Price of natural gas 1998 [(delivery price to Emden: 55 øre) – (transport: 12 øre)] = **43 øre**

Weight:
Natural gas (NG): (methane CH_4 = 16 + some other gasses) => ≈ 18
Carbondioxide: CO_2 = 44

➔ quotient: $\frac{CO2 = 44}{NG \approx 18} = 2{,}44$

Calculated value of CO_2: $\frac{43øre}{2{,}44} \approx 17{,}6øre$

Calculation presented by Andenæsat project meeting held on 26th May 2004

Figure 1: Estimated minimum value of CO_2 required to ensure profitability of the HydroKraft project. (1 øre = NOK 0,01)

When Egil Myklebust announced the HydroKraft project on 23rd April 1998, he expressed a hope of creating a more or less 100 per cent CO_2-free production of hydrogen. He made reference to the front-end of the ammonia process. This can produce a gas with a hydrogen content of up to 94 per cent. This was significantly more than what could be produced with turbine technology available at that time. This "alarmed" the engineers at Hydro.

Aker Technology's HIOx research project[19] closely resembles such a process, but HIOx cannot be realised without developing a totally new turbine. This would probably take 10-15 years – something the activities at the Grane oilfield did not permit. And even if this had been technologically manageable there was, according to Andenæs, no interest among the turbine manufacturers to modify turbines for this purpose. The market was considered to be all too limited. It is also important to emphasise that, as far as HIOx was concerned, the issue was not hydrogen production, but rather a straightforward gas power plant.

17 Kårstø was already constructed, and the physical infrastructure was taken for granted.
18 In 2004 this price would most likely have been considerably higher because the price of natural gas delivered to Emden in 2003-2004 was approximately 75 øre plus approximately 15 øre for transportation.
19 Initiated in 1997 with support from, among others, KLIMATEK. The goal was to burn natural gas in a closed system, with separation of CO2. A HIOx gas power plant would, in addition to electricity, have CO2, argon and nitrogen as by-products. For more information see for example: http://www.entek.chalmers.se/~anly/symp/01halvorsen.pdf . (Accessed on 24th October 2003).

In en eco-efficiency context, the HydroKraft project was something different and more interesting. Due to the time restrictions however, existing turbine technology had to be the choice. In the combustion of gas with high hydrogen content the temperature stress on the turbine blades becomes extremely high[20], while the chance of backfire increases. Whereas the original plan resembled a modified ammonia production plant – something Myklebust also referred to - the engineers at Hydro took a look at methanol, in which Norsk Hydro also possessed wide technical competence.

With methanol it was found that one could use a slightly different reformer technology than that which was used for the manufacture of ammonia in fertiliser production. Reformer technology for manufacturing methanol based on natural gas would yield approximately 45 per cent hydrogen, the remainder consisting of nitrogen and vapour. This was a technology which the project group felt more comfortable with, and which was better suited to the technology the turbine manufacturers could come up with. Besides, this was a hydrogen concentration that was easier to handle safely in the production of electricity, without danger of explosion. In any case, the question then became how to find out which reformers could match the turbines currently available on the market.

3.3.1 Selection of reformer technology

Norsk Hydro had to select a technology that could solve this particular problem, and Fjellhaug and Andenæs discovered that the technology from coal processing and bottom ash processing from oil refineries represented the most interesting alternatives for the HydroKraft project. This technology uses air to separate oxygen and nitrogen before the oxygen is allowed to enter the turbine's combustion chamber. The technology was well tested, something which was confirmed at a conference in Milan and by a visit to Buggenum in the Netherlands in 1998.

So what occurs in a reformer during conversion to CO_2? Syngas is produced. Syngas consists primarily of CO and hydrogen, and is made up of saturated hydrocarbons (methane, ethane, propane, etc). The syngas passes through a converter, where the oxygen from water reacts with the CO to produce CO_2 *without* permitting the hydrogen to get hold of the oxygen. It is a one-way process which, under certain conditions, goes the "right" way so that oxygen is extracted from water, bonded to CO to make CO_2, and at the same time more hydrogen is created. Once CO is converted to CO_2, it goes through a normal amine scrubbing process in order to grab the CO_2, which is then extracted in a heating/cooling cycle. This is done in an ordinary wash tower of the type found in all ammonia production plants and refineries. An amine solution bonds with the CO_2 and thereby functions as an agent, taking out the CO_2 and then repeating the process. In the HydroKraft project it was decided to aim for a 90 per cent removal of CO_2. How much is captured is determined in the scrubbing process. This depends on how large liquid surface is made available for contact with the gas. This has to do with dimensioning of the wash tower (number of trays, flow, etc) and the temperature. A small tower will remove less CO_2, while the amine solution's ability to bind to the gas is contingent on the temperature level.

Once the CO_2 has been captured, one is left with a gas mixture, a fuel gas, which contains 45 per cent hydrogen, 40 per cent nitrogen and steam. This gas is combusted in a normal combustion chamber (or combustor) in a gas turbine. Together with the steam, the nitrogen is used to regulate the temperature. This is where the HydroKraft patent comes in: a method for producing a fuel gas that actually can be combusted in existing turbine technology. When selecting which reformer technology to use, it was important to Hydro that nitrogen should be used as the moderator in the process. Many companies possess technology that

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20 The blades are cooled down with CO2 (most effective), water (next most effective) or nitrogen (least effective). The most usual is to use available CO2 or water .

utilises air in such a way that oxygen and nitrogen is separated before the oxygen is allowed to pass into the combustion chamber. This is found for example in the entire petrochemical industry, but Hydro was interested in finding manufacturers who used air (≈O_2N_2) as air. We shall return to the selection of hardware supplier in Section 5.1. We shall now take a closer look at the selection of turbine technology.

3.3.2 Selection of turbine technology

Turbines are enormous mechanical devices that spin around at exceptionally high speeds. All gadgetry that spins round at high speeds will normally fall apart. One should therefore show great respect when making modifications. Among turbine manufacturers there is an evolutionary path that is followed. They never come up with completely new models, but rather with small modifications to models that have, for the most part, been in use for years. The turbines that HydroKraft needed were approximately 2 metres in diameter, with a velocity of over 13,000 revolutions per minute. This would provide a peripheral velocity[21] of more than the speed of sound. However, in front of the actual turbine is a combustor (combustion chamber) where fuel gas is combusted. The challenge in the HydroKraft project lay in the fact that hydrogen was the only ignitable/combustible component in fuel gas. This is in contrast to normal gas power plants, where both the carbon (C) and the hydrogen (H_2)[22] are combusted to produce electricity. In order to combust, hydrogen needs to react with oxygen. But in hydrogen combustion it is extremely important that oxygen and hydrogen are not put together <u>before</u> combustion, because if they do, the mixture would immediately ignite.

Much of the motivation behind the development of gas turbines over the past decades has been so-called pre-blending or pre-mixing, i.e. the optimal mixing of natural gas with air before it is combusted in the combustor. General Electric (GE) has, however, taken a slightly different technological path where air and the ignitable material first meet inside the turbine before combustion. Siemens' turbine mixes directly before combustion and would also have worked[23]. This was the only feasible route to take if hydrogen were to be used as fuel, and it had a bearing on the choice of turbine technology.

The emission of CO_2 from gas power plants was one of the ecological aspects of the HydroKraft project, but large sections of the environmental movement were also concerned about the nitrogen emissions[24], particular forms of which could cause local pollution problems. In the combustion process in the HydroKraft project nitrogen has the job of moderator. After combustion, the nitrogen is released into the atmosphere in pure form. It comes from the nitrogen in the air, passes through the gas power plant and exits as nitrogen (not NO_x). According to Andenæs, however, NO_x was a problem that Hydro was very aware of. Specific demands were made of the technology manufacturers, and the starting point for the process design was that NO_x emissions should be kept to below 10 ppm. One can produce as much or as little NO_x as required in an ordinary combustion process. Little is produced when the combustion temperature is low, but in such a case a lot of CO is produced, and vice versa. It was therefore necessary to find a balance that was reasonable and desirable. All combustion that occurs at maximum cost effectiveness creates NO_x emissions, but when Hydro arrived at the fuel gas mentioned above, they also did it to comply with the most stringent emission limits that existed for NO_x. Hydro based the design process on compliance with the emission limits of 20-25 ppm[25], and went as low as 10 ppm because they knew that this was a growing environmental policy concern

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21 The speed at the blade tips.
22 C=39 per cent, H2=61 per cent
23 Pre-blending would work under special conditions, but then the gas would have to be driven in at such a speed that the speed with which it was driven was at least as high as the combustion speed, otherwise the flame front would recoil and the equipment would be totally destroyed. In HydroKraft it is not possible to attain the necessary high speed.
24 Ref. hearing held by Norwegian Water Resources and Energy Directorate (NVE)
25 Ppm = particles per million

on the part of the authorities[26]. This is the background for why the process was designed with a little lower efficiency so as to avoid high emissions of NO_x, something which was an important goal in the then ongoing negotiations relating to the Gothenburg Protocol, eventually signed in 1999.

3.4 Spoke 4: Optimisation of the Distribution System

Optimisation of the distribution system is relevant in the HydroKraft context. Distribution of both CO_2 and electricity is achieved. There already existed a relatively well developed distribution system for electricity, but this was not the case for CO_2. According to Andenæs, Hydro had not used many resources on alternative transport systems for HydroKraft, and the HydroKraft plan was to transport the CO_2 to Grane in pipes. The gas would be collected at Kårstø, where new gas already came for processing.

Statoil had used many resources on the transportation of CO_2, though that was by boat. Hydro is a large operator in the commercial handling of CO_2 in Europe, and knows a lot about distribution but, if asked, the people at Hydro Agri (now Yara) will by and large say that one should show great respect when transporting and containing CO_2. Serious problems could arise if a sudden decrease of pressure should occur on a boat or in a tank. This would create dry ice, which would be difficult to melt back. The people at Hydro were therefore sceptical to transporting large amounts of CO_2 by boat.

The transport systems to Europe are also a factor that restricts how much of the natural gas in the North Sea can be utilised. Therefore by doing something with the gas in Norway, the transport systems would not be overloaded. HydroKraft could use the unprocessed gas at Kårstø, and thereby avoid reducing the valuable winter capacity of the export system to the Continent.

As for the distribution of electricity, connection to and modification of existing transmission grid systems would involve a relatively small investment, estimated to be around NOK 157 million in 1998. This adaptation was not considered to be a problem technology-wise. Originally the plan was to distribute the electricity via the transmission grid system, but Hydro was only concerned with supplying electricity at a price that was applicable to the industrial sector. Hydro was not interested in building power plants to meet general demands and therefore was not prepared to finance the project. Looking back, one has of course seen that the price in the consumer market has risen but, being an aluminium manufacturer, Hydro wanted the power to be made available for industrial purposes in Norway at competitive prices, in other words well below 20 øre (NOK 0,2) per kWh.

3.5 Spoke 5: Reduction of impact during use

The reduced environmental impact from HydroKraft is linked to reduced emissions of CO_2, but this is not linked to the patent itself. The patent does, however, enable production of CO_2 as a separate product. The patent itself does not, therefore, entail any ecological improvement, but it does allow for management of a climate problem that arises from the use of fossil energy in gas power plants.

3.6 Spoke 6: Optimisation of Initial Lifetime

The lifespan of this system is the same as for an equivalent conventional gas power plant.

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26 By comparison, in October 2000 Naturkraft was granted an emission permit for its planned gas power plants at Kårstø and Kollsnes for 10 ppm NOx at start-up and 5 ppm from 2005. Note that this permit was granted after the HydroKraft project planning. Source: Emission permits published on web site for SFT (Norwegian Pollution Control Authority): http://www.sft.no/arbeidsomr/luft/gasskraft/. (Accessed on 22nd March 2004).

3.7 Spoke 7: Optimisation of end-of-life system

There are no differences between the presented technology and the technology used in conventional gas power plant on this spoke.

4 WHAT WERE THE MAIN REASONS FOR NORSK HYDRO'S DECISION TO DEVELOP AND MARKET HYDROKRAFT AS A MORE ECO-EFFICIENT ALTERNATIVE?

As suggested in the introduction, there were many reasons why Hydro started up with the HydroKraft project. Although the need for pressure support on the Grane oilfield was the triggering factor, Hydro was also concerned with the energy balance in Norway because the company needed competitive electricity for processing activities. Also, large-scale production of hydrogen was seen to be an element in the energy balance of the future. The project also fit in with Hydro's philosophy on environment and sustainable development, associated with the handling of greenhouse gas emissions. All these elements involved technological and commercial considerations for all of Hydro's subsidiary business activities. Combined, this incited enthusiasm internally for the project, which in itself became an important reason for its further development.

4.1 The connection to Grane, 1997-98

The discussions held around the end of 1997 and beginning of 1998 on pressure support for the Grane oilfield were the decisive cause, and commercial motive, for the HydroKraft project. The Grane oilfield lies extremely close to Production Licence 001 on Balder. As the number suggests, this was the first licence awarded on the Norwegian Continental Shelf, awarded to Esso[27] as early as in 1965. Esso drilled a number of dry wells under the licence, and parts of the license were returned to the Norwegian government at the end of the 1980's without any commercially exploitable oil finds having been made. A new exploration licence was awarded to Norsk Hydro as operator, with Esso as one of the partners. The partnership found commercially exploitable deposits. The field was originally called Hermod, but was subsequently given the name Grane, and partially extended into the Production Licence 001 area[28].

What is particular about Grane is that it is a completely "dead" field. It contains an estimated 100 million cubic metres of recoverable oil, but no pressure with which to force the oil out. Generally, in such cases, one has two alternatives: either sink a pump that pumps the oil up, or inject something (normally water or gas) to create pressure. Hydro had made studies of the technology for injecting CO_2, but the actual application remained untested. The problem was procuring a sufficiently large source of CO_2. Calculations indicated an annual requirement for approximately 5 million tonnes of CO_2, of which recycling would reduce the supply demand. This could be obtained anyway, by means of reforming natural gas.

4.2 Hydro's requirement for cheap energy

The project also coincided with Hydro's requirement for access to electric power in Norway. Hydro is an energy company, and approximately 10 per cent of the total power production in Norway is used in Hydro's industrial activities. Hydro was very concerned about whether HydroKraft could make cheap production of

[27] ExxonMobil in Norway includes several companies – i.a. Esso Norge AS, ExxonMobil Exploration and Production Norway AS, and ExxonMobil Production Norway Inc. – all of which are affiliates of ExxonMobil Corporation in the USA.
28 Licence 169, Block 25/11. More information about the licence is available from the Norwegian Petroleum Directorate's fact pages: http://www.npd.no/engelsk/cwi/pbl/en/index.htm. (Accessed on 2nd March 2004).

electric power possible for use in aluminium plants situated in Norway. Given the electricity prices which Hydro's competitors had access to, it would have to cost well below 20 øre (NOK 0,20) per kWh. Based on the gas prices in 1998, Hydro calculated that it would have cost approximately 15 øre (NOK 0,15) *more* per kWh (in other words almost twice as much) to get electricity from a potential HydroKraft project compared with an ordinary gas power plant. For a private consumer this would not be a deterrent factor, but for an energy-intensive industry in tough international competition this could be crucial for its ability to compete.

4.3 Hydro's enthusiasm for the project

Hydro's management was enthusiastic about the project because it had ramifications for technologies and commercial interests in all of Hydro's subsidiary areas of activity. At that point in time, Myklebust was also chairman of WBCSD (World Business Council for Sustainable Development), which had a clear profile of "the business case for sustainable development".

President and CEO Myklebust represented an industrial conglomerate in which Hydro's strategies and business interests could be drawn together to create scale economy advantages and mutual benefit across divisional boundaries. This was still dominant at that time. To a large extent, therefore, Hydro's conglomerate strategy also comprised a search for business synergies between different business activities. This situation arose at a time when streamlining and demergers were being increasingly realised in comparable companies. The consequence of this, according to Andenæs, was that when the HydroKraft project came up with a solution that involved all areas, it proved attractive. As late as the summer of 1999, half a year after the HydroKraft project stopped working specifically with Grane in mind, Andenæs was in America testing turbine technology. Andenæs reported to Bjørn Arne Sund, who in turn had to submit daily reports to Hydro's management on the progress of the project.

4.4 Manufacturing hydrogen

Rolf Marstrander clearly states that already at this stage in Hydro's thinking in the light of HydroKraft technology, it was important to be able to shift to a new S-curve based on hydrogen. Andenæs underlines this, but nevertheless Hydro saw that this could make hydrogen available, something which was considered extremely interesting when it came to proposing alternative energy carriers. This also fit well with the reasoning expressed in Hydro's strategic work on sustainable development.

The hydrogen can be found in two applications. It can be used as a raw material, for example in the production of ammonia, or it can be used as an energy carrier in power plants, combustion engines or fuel cells. Hence, excellent combination possibilities exist. The front-end process in HydroKraft, which makes CO_2 and hydrogen, can be made as large as desirable, and one can choose to have either one or five turbines at the other end. One can choose to store some of the hydrogen or combust it to produce electricity.

4.5 Climate and the Kyoto Protocol of 1997, and NO_x and the Gothenburg Protocol.

Some of the background for HydroKraft can also be attributed to Hydro's increasing awareness of global and local environmental challenges associated in particular with emissions of greenhouse gasses and NO_x.

Climate change challenges were made particularly visible due to the Kyoto Protocol in 1997, in which Norway committed itself not to increase greenhouse gas emissions, measured in so-called CO_2 equivalents, by more than one per cent of the emission level for 1990[29]. The situation was discussed at a large, closed, Hydro conference held in Bordeaux in the summer of 1997. The whole greenhouse gas issue led Hydro to consider its thinking and conceptions about the company's exposure with respect to CO_2 and nitrous oxide[30]. Ammonia is used in the manufacture of nitric acid, which in turn is used in the production of artificial fertiliser. Manufacture of ammonia consists of the carbon in natural gas being bonded to the oxygen from the air and released, while nitric acid production results in nitrous oxide emissions. There were also climate policy challenges associated with the other business areas in Norsk Hydro, including primary aluminium. The work on entering into a voluntary climate treaty for Norwegian primary aluminium production for the period 2000-2005 should also be mentioned here. This also led to significant reductions in greenhouse gas emissions by way of point feeding technology being adopted in the cells.

Hydro thought that, in general, not enough attention was being paid to the climate issue by the technology community. Throughout 1997, Hydro itself had looked very closely at where industrial activity stood in relation to a possible new climate regime. A number of seminars were arranged, and Hydro researchers worldwide were consulted. Hydro's total greenhouse gas emissions were at this point in time approximately 27-28 million tonnes of CO_2 equivalents per year. At a rate of NOK 100 per tonne, this meant an annual cost of NOK 2.8 billion. The value of NOK 2.8 billion in 7-10 years time will be approximately NOK 15-20 billion with a discount rate of 10 per cent in real terms. With a stock market capitalisation of approximately NOK 60 billion, this represented a risk of approximately 30 per cent of the company's value. It was quite obvious that the greenhouse gas problem posed a threat to the group.

The negotiations relating to the Gothenburg Protocol, signed in 1999, were well underway, and the issue of NO_x emissions in particular could create challenges for the HydroKraft project. The Gothenburg Protocol is the most current binding agreement under the Convention on Long-Range Transboundary Air Pollution[31], and is an advanced agreement under which various gasses that cause acidification, eutrophication and ground-level ozone are treated collectively. The protocol therefore also treats sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and non-methane volatile organic compounds (NMVOC). Norway's commitments are extensive. Between 1999 (the reference year) and 2010, Norway must reduce emissions of sulphur dioxide by 58 per cent, NO_x by 29 per cent, and NMVOC by 35 per cent. Ammonia emissions must be kept at the same level as in 1990[32]. Hydro has significant emissions of all of these gasses, and negotiating the agreement was an important part of the evaluations made with respect to controlling potential NO_x emissions from HydroKraft.

4.6 Conclusion

As we have emphasised, many reasons for Norsk Hydro's decision to develop and market HydroKraft as a more eco-efficient alternative can be documented. The decision can also be viewed in the light of the Naturkraft project, in which Hydro itself had been active in initiating. The Grane oilfield created a time frame that opened the way for significant sales of CO_2. At the same time, access to future cheap electric power was unresolved, and with a gas power plant the process industry could be assured competitive terms in line with international competitors. President and CEO Egil Myklebust soon began to take a great interest

29 For more information see for example State of the Environment Norway's web pages on climate: http://www.miljostatus.no/templates/themepage____2143.aspx. (Accessed on 22nd March 2004).
30 Nitrous oxide (N_2O) is one of the gasses incorporated in the Kyoto Protocol. In Norway nitrous oxide constitutes approximately 9 per cent of total greenhouse gas emissions. Fertilizer production makes up approximately 34 per cent of nitrous oxide emissions in Norway (as per 2000). Source: State of the Environment Norway: http://www.miljostatus.no/templates/PageWithRightListing.aspx?id=2308). (Accessed on 29th October 2003).
31 Geneva Convention, signed in 1979.
32 For more information on the Gothenburg Protocol see: http://www.miljostatus.no/templates/themepage____2366.aspx or: http://www.sft.no/publikasjoner/luft/1735/ta1735.pdf (Both accessed on 3rd March 2004).

in the project, and the media profile was high. The HydroKraft project also fit in extremely well with other initiatives for promoting the hydrogen society. It could also be linked to the Kyoto agreement of 1997 and the need to find alternative energy carriers. Given the implementation of the Kyoto agreement, Norsk Hydro's greenhouse gas emissions could represent significant financial commitments and subsequently reduced competitiveness. At the same time, the company was also bound by other national environmental obligations such as the reduction of NO_x emissions. All in all, the HydroKraft project could have fulfilled many of these obligations, and the conditions were right for realising an innovation with considerable ecological potential. Things, however, were not to turn out as expected. Why did they not turn out as hoped for?

5 WHICH KEY ACTORS AND SPECIFIC CONDITIONS HAVE SO FAR IMPACTED THE DEVELOPMENT OF THE HYDROKRAFT PROJECT?

We have established a technical insight into what the HydroKraft project represents. Furthermore, we have documented the main reasons for why the project was promoted. The next question is which key actors and specific conditions have so far impacted the development of the HydroKraft project.

We have arranged this section so that it correlates with our research protocol (Appendix 1). First we shall make some references to various conditions associated with technology and production. Here it is particularly important to mention the role of General Electric (GE). Esso will also be mentioned. Prior to this we include a brief mention of Statoil. Thereafter we shall make a few brief comments on the market conditions which, in this connection, have limited significance. Only a few references will be made to financing. Slightly more can be linked to regulatory bodies, but it is primarily within the cultural and social organisation that we find the relevant key actors. We include here both references to research and prevailing knowledge, as well as the specific role played by Bellona and other environmental organisations. It is also natural here to dwell a moment on Naturkraft. Finally, we shall review the role of ABB's President and CEO at the time, Kjell Almskog. In our sumation we will conclude that the important key actors and impacting conditions can be linked to internal circumstances in Norsk Hydro as it stood in 1998. As we also point out in our conclusion, major changes have since taken place. The Agri division was spun off and established as an independent company, Yara[33]. The light metal division consolidated its international orientation, and any national opportunities that resulted from the interaction between Hydro's various business areas have since diminished.

5.1 Technology and manufacture

The technology design and project development was initiated by Gunnar Kongshaug and Werner Soyez in Hydro's Agri division. Sigurd Andenæs, Henrik Fjellhaug and Bjørn Arne Sund from the central research sector expanded on the whole concept and established a feasible strategy. Ole Rønning[34] was made responsible for leading the department that was to translate ideas into practice. Eivind Reiten, the current President and CEO, formerly the boss for light metals, was chairman of the steering committee of HydroKraft.

In the planning phase of HydroKraft, Sigurd Andenæs and Henrik Fjellhaug[35] travelled around to find out what kinds of technology were available from the different suppliers. Some of the companies visited were ABB, Siemens, Mitsubishi and GE. On the reformer front, visits were made to Halldor Topsøe and Kellogg.

ABB had a relatively high profile, due partly to Kjell Almskog because of the contract with Naturkraft for delivery of turbines for the planned gas power plants, but also because the company had a number of other turbines which they were eager to show off. However, ABB's large turbines were based on pre-

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33 For more details on Yara see: http://www.yara.com/no/index.html.

34 Ole Rønning came to Hydro from the position as head of the Control Division of the Norwegian Pollution Control Authority (SFT) in Grenland. He advanced rapidly up the ranks of Hydro and is now president of Naturkraft.

35 According to Andenæs, Henrik Fjelhaug, originally a mechanical engineer, has for the past 20 years been recognised as one of the leading authorities on this in Norway.

blending, and with hydrogen combustion this would have self-ignited and destroyed the turbine. Hydro's Bjørn Arne Sund was ridiculed by Kjell Almskog following a presentation in Oslo in May, 1998. According to Almskog, it was impossible to use the technology that had been chosen for HydroKraft and, as far as ABB was concerned, the project was assessed not to be very realistic.

However, an Icelander by the name of Eliasson in ABB contended that ABB's technology was far more versatile than Almskog was claiming. ABB had developed some smaller turbines that, technically speaking, were capable of handling the fuel gas that Hydro intended to use. What is interesting to note here is that this was not the turbine that Almskog had attempted to sell in Norway. Either way, an awful lot of turbines would have been necessary in this case. According to Andenæs, Hydro would have had to fill up the whole plant floor at Karmøy with turbines if it had chosen ABB's solutions.

Mitsubishi was very interested in HydroKraft, but considered the technical challenges in shifting their turbines, which were based on syngas, over to HydroKraft to be unrealistic, given that the HydroKraft project had to be operative by 2003. If the project had had a horizon of 2006-2008, it would have been another matter[36].

Siemens was another company with the technology to do the job, but it had technical and financial problems at that time. It had launched a number of products at the beginning of the 1990's which had resulted in very large claims for compensation. Andenæs and Fjellhaug looked at a gas power plant outside Buggenum in the Netherlands which was based on coal and that was a type of turbine technology that Hydro was interested in. Siemens had however used two years to start the plant up, and it was not very large. The company also had a plant in Portolano, Spain, that was supported by the EU. According to the original plans, the plant should already have been in operation for a year at the time Hydro showed its interest, but Hydro was told that the power plant was still not ready. Because of poor delivery ability, Hydro abandoned plans of a possible technological collaboration with Siemens.

General Electric (GE) holds the "world record" in combusting gas with high hydrogen content, and the technology was based on the premise that hydrogen and oxygen should not meet before they were inside the combustion chamber. This was in contrast to the technology which ABB had offered Naturkraft. Norsk Hydro's project group quickly seized on GE's interest, and a study tour to the company's headquarters in Schenectady in upstate New York was made. The discussions with GE's representatives were very productive.

5.1.1 General Electric

It was the turbine aspect of the HydroKraft project in particular where Hydro lacked its own technology base. GE had a high level of competence and was a leader in the fields directly relevant to HydroKraft. It was therefore considered important to nurture a close relationship with these world leaders. Through the internal conference in Milan in 1998, Andenæs and Fjellhaug gained access to the world of applications of energy within coal gasification, refineries, etc., and to technologies that had been developed and could prove useful in connection with HydroKraft. This led the project group into direct dialogue with GE in New York, and Hydro ordered a test from GE in which it was agreed that the hydrogen content for the fuel gas, of approximately 45 per cent, would be the optimal amount in the HydroKraft project, if it were to be based on GE's turbines. GE spent nine months collecting enough hydrogen to run the test, which was carried out in June 1999. Everything went well.

36 Perhaps Mitsubishi would have been interesting in connection with Gullfaks, but it is difficult to say whether they would have proved better than GE.

GE had a significant impact on the whole of Hydro's thinking in this matter. Douglas Todd in particular was a central point of contact at GE for Andenæs and Fjellhaug.

5.1.2 Statoil

During the summer/autumn of 1998, Statoil and Hydro arranged a design competition for energy production and CO_2 for Grane. How much energy could be produced? Statoil had a rival technology for producing CO_2, with conventional gas power plants and purification of exhaust gas as its starting point. Fluor Daniels had completed a design assignment for Statoil and had come up with a three-block solution[37]. It produced slightly less power because HydroKraft uses slightly more fuel due to its lower efficiency.

Statoil challenged the same designers to propose a solution for capturing CO_2 from the exhaust gas. Andenæs still recalls the enormous dimensions they came up with. They would need six towers, each larger than Oslo City Hall, and loads of trays inside to purify the exhaust gas. When they presented their estimated costs, Statoil withdrew. The whole project was therefore shelved and Norsk Hydro concentrated on its pre-combustion technology, that is to say reforming and separating CO_2 before combustion.

In line with the current paradigm, Hydro and Statoil were to develop rival solutions. In hindsight, Sigurd Andenæs wonders whether the two companies should rather have collaborated on developing a new concept. According to him, "competition on the Norwegian Shelf" should have been replaced by "global competition".

Statoil has gradually built up a high level of competence in the depositing of CO_2 on the ocean floor, and also has a depositing project running on Sleipner, SACS[38]. Given the choice of pre-combustion technology, however, experiences from Sleipner would contribute little to the selection of technologies for HydroKraft. Sleipner is a pure case of depositing, but it could nevertheless contribute to disseminating knowledge and acceptance of the opinion that handling CO_2 is both technologically and practically possible.

5.1.3 Esso

Balder[39] is located in Production Licence 001, while Grane is located approximately 20 per cent in 001 and approximately 80 per cent in 169. The licences date back to around 1965. Esso was a partner in Grane[40] at the time when Hydro was working on the HydroKraft project and in 2003, had 25.6 per cent of the shares in Grane. After spending billions of NOK on exploration over many years, the original licence expired and, with the exception of Balder and other proven deposits, it was returned to the Norwegian government. Returned areas were reallocated to a group with Hydro as operator at the end of the 1980's.

The geological structure in the area known as Production Licence 001 was difficult. Every time Esso drilled, none of the wells turned out as expected, and Esso had to make alterations to all of its models. Esso probably felt that the authorities, as Andenæs puts it, "grabbed the field from right under their noses". When the work on HydroKraft was well under way, Norsk Hydro realised that Esso did not want the project, although this was not explicitly expressed while the work was going on. Exxon, represented by company boss Lee Reynolds, had stated that CO_2 "is no winning issue for the oil industry" and, with regard to an

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37 A standard power plant is approximately 400 MW. Statoil set up three such blocks (or units) each consisting of a gas turbine with a capacity of 260 MW and a steam turbine with a capacity of 140 MW. Three such blocks provide therefore 1200 MW. In comparison, HydroKraft had a capacity of 1300 MW, but used more gas. Statoils three-block solution used roughly 1.6 billion cubic metres per year, whereas HydroKraft used approximately 2 billion cubic metres per year.

38 Saline Aquifier CO2 Storage (SACS). More information at: http://www.ieagreen.org.uk/sacshome.htm. (Accessed on 16th June 2004).

39 See Appendix ??, Section 10.1 for area map.

40 Together with ConocoPhillips and Petoro, among others. Statoil has also been involved, in varying degrees over the past few years. See: http://www.npd.no/engelsk/cwi/pbl/en/index.htm for overview.

application on Grane, the company was basically negative. Perhaps Esso would have been more positive today. Given the new approach to the climate problem and USA's awareness of depositing, a pilot project for depositing of CO_2 in Norwegian waters could have fit better with Esso's strategic evaluations.

Andenæs believes it is important that, if industrial partners are to achieve anything, they must participate in the process, be enthusiastic and be committed. There is no point in presenting something which is fundamentally full of pitfalls and that have to be negotiated along the way. Exxon had nothing positive to say about CO_2 and they were very cautious about how they played their role. Nonetheless, it is reasonable to suggest that, if Esso's attitude to using CO_2 for pressure support on Grane had been more supportive, perhaps a lot of things would have been different with respect to realising the HydroKraft project.

5.2 The market

There has been no opinion voiced suggesting that market actors had any significant impact on the development work.. Having said this, failure to lower the price of electricity from HydroKraft to a level more acceptable in a competitive industrial situation, i.e. below 20 øre, was a distinctly negative experience. The lack of an internal market, which one tried to create, also proved to be one of the main reasons why HydroKraft could not be realised with respect to Grane.

5.3 Financing

The project had a budget of between NOK 30-40 million[41]. It was financed mainly by Norsk Hydro, but a total of NOK 6 million was provided by the KLIMATEK programme[42], under the auspices of the Research Council of Norway (NFR) in 1998 and 1999. This was not, however, financially crucial to the execution of the project. The contribution from NFR did however entail other positive aspects, which will be commented on later.

5.4 Regulatory bodies

In conversations with Andenæs and Marstrander, the impression given is that no individual actors within the policy instrument system have been important – and here we refer specifically to the Norwegian Ministry of Petroleum and Energy (OED). Neither the Ministry of the Environment (MD) nor the Ministry of Trade and Industry (NHD) were involved in the project. Furthermore, the White Paper on the Domestic Utilisation of Natural Gas[43] had no influence on HydroKraft's thinking either.

It is clear, however, that both the Kyoto Protocol and the negotiations relating to the Gothenburg Protocol have had indirect influence. The Gothenburg agreement was not completed until 1999, but Hydro was concerned with reducing NO_x emissions. GE was aware of the US Environmental Protection Agency's (US EPA) emission limits and was therefore also very eager to find a technological solution to limit NO_x emissions in a completely different way to that which Hydro had originally planned. In fact NO_x emissions

41 According to KLIMATEK's web site (http://www.program.forskningsradet.no/klimatek/fs/vis.html?kategoriid=2&id=147 (accessed on 13th May 2004)), the project had a budget of NOK 28 million, but cost a bit more due to additional expenses in the final phase).

42 KLIMATEK (Norwegian National Technology Programme to promote technology for reducing greenhouse gas emissions) was a result of an initiative by the Ministries of the Environment, Oil and Energy, and Trade and Industry in connection with White Paper no. 41 (1994-95): Norwegian policy to mitigate climate changes and reduce emissions of nitrogen oxides (NOx) More information available at: http://www.program.forskningsradet.no/klimatek/om/ (accessed on 31st October 2003).

43 White Paper no. 9 (2002-2003): On domestic use of natural gas. Oslo: Ministry of Oil and Energy . Available at: http://odin.dep.no/oed/norsk/publ/stmeld/026001-040005/dok-bn.html. (Accessed on 17th June 2004). (English translation available at: http://odin.dep.no/filarkiv/169416/Stmnr9E.pdf. Accessed on 8th January 2005).

became a central point of reference in the concept development process, and it was decided to aim for a level that was way below the official requirements. The eco-efficiency was consolidated, but this was done at the expense of the cost-effectiveness of the project.

5.4.1 Price mechanism / uncertainty surrounding the Kyoto Protocol's implementation in Norway.

The two possible sources of revenue that Hydro envisaged were either to place a value on CO_2 in a market or send it to Grane. Regarding Grane, Andenæs seems to recall that, after ordinary rounds of negotiations, Hydro reached the figure of 17.5 (NOK 0,175) per cubic metre[44] of CO_2 as an acceptable price to pay for this form of pressure support. This was the equivalent price for ordinary gas divided by specific gravity. Furthermore, Hydro calculated that in 1998 it would need NOK 256 per tonne of CO_2 to justify climate-related investments. They discussed what kinds of expenses they would have to operate with if they had to pay for quotas, etc. This was a very difficult question to answer because it would depend on the demand.

In the Stoltenberg administration's White Paper on Norwegian climate policy[45], to which Minister of the Environment Børge Brende sent an amendment[46], one ended up with a system based on a large portion of free quotas, in addition to the fact that "something" had to be bought in order to create a balance in the market. According to Andenæs, the problem with this is that under such circumstances the market is not allowed to do its job. If one creates market-based mechanisms, then the market must be allowed to find a balance between volume and price. Brende proposed that the quotas should for the most part be allocated for free. Why? Well, according to Andenæs, because there really should not be a price to ensure that one can continue to produce at the level of the day. Andenæs further argues that it is politically important *not* to be able to invent a policy instrument that actually works. Instead one ought to invent a policy instrument that gives the impression of working, but which in fact has no effect[47].

5.5 Cultural and social organisation

Cultural and social organisation had great significance for the development of the HydroKraft project. This could partially be linked to ongoing research and the prevailing competence and knowledge; curriculum. This should also be linked to political actors such as Bellona and other environmental organisations. We have also chosen to include Naturkraft in this connection, because a political rivalry arose, that became significant for Hydro's internal priorities. ABB has already been mentioned under technology and production, but we mention them again in this connection because their president and CEO, Kjell Almskog, was instrumental in influencing the social and political perception of what the HydroKraft project represented.

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44 There is approximately 0.6 kg CO2 (in liquid form) per litre. In gas form there is approximately 1.5 grammes CO2 per litre.
45 White Paper no. 54: Norwegian Climate Policy. (Summary in English available at: http://odin.dep.no/md/engelsk/publ/stmeld/022001-040012/hov001-bn.html. Accessed on 8th January 2005).
46 White Paper no. 15 (2001-2002): Amendment to the White Paper 54 (2000-2001): Norwegian Climate Policy. Summary in English available at: http://odin.dep.no/md/engelsk/publ/stmeld/022051-040013/dok-bn.html. Accessed on 8th January 2005).
47 According to Rolf Marstrander there is also a factor here which has not really come across. The gas price of NOK 256 which Andenæs alludes to is a gas price that was the market price in 1998, but there exists a number of gas streams that have to be finished. Andenæs points out that this was before GFU (Norwegian Gas Negotiation Committee) was disbanded and at one point in time the gas price was determined after the awarding of contracts. There was in truth no market to approach. By using gas to create energy in Norway, one could sell gas which one did not envision getting any revenue from for another 80 years. But the revenue in 80 years time is worth nothing in today's down-discounted world. So that if one managed to rally support in a regime for using gas for gas power plants, the owners, Hydro and Statoil, would consider it to be free fuel. In the worst case one could envisage the gas costing money to pump back down for storage. But that applies to the gas that is injected out. For the most part there is not very much gas injected for storage. Most of the gas that is injected is for pressure support purposes. There was a natural motivation for building the gas power plant at Kollsnes, and that was because it was practically free. It was a different case with Kårstø.

5.5.1 Research (NFR/KLIMATEK)

Although Andenæs wished that they had had more money, the KLIMATEK research programme did have a particular impact on the HydroKraft project[48]. Hydro was in general very pleased with the programme as long as they received a few million from it for relevant R&D work[49]. However, it was not so much the money that was so important, but that fact that KLIMATEK forged research alliances[50]. Otherwise much of the R&D work in Hydro was done internally, using the resources of Hydro Technology and Projects (HTP)[51]. HTP is more of an engineering company than a research unit but, it still played an important role in the HydroKraft project.

The KLIMATEK programme provided financial support, some R&D networks were established, but Norsk Hydro in fact had little contact with NFR. Andenæs gave a HydroKraft presentation for NFR in the end of February 2000. Erik Normann from NFR was, according to Andenæs himself, notoriously negative, and asked whether Hydro regarded the Research Council as a hair in their soup, etc. This, however, did not reflect Hydro's opinions. What Hydro believed was that introducing HydroKraft to the climate debate gave legitimacy to the activities, and the political debates, that were going on in the country regarding different solutions to exploiting natural gas and electricity production from gas power plants.

While Normann was negative, Andenæs himself also expressed a negative attitude to many of the priorities made by NFR, particularly the former Industry and Energy Division (IE). As he comments: "We think that the research done in Norway in this area is totally meaningless – particularly that done on HiOx. It is more a case of restrictive research with no clear commercial solution - at least when it comes to gas power plants.

5.5.2 Prevailing competence and curriculum

When it comes to the prevailing competence and the general curriculum for the choices of technology and their applications, these are less relevant here than is the case in other case studies in the CondEcol project, such as Shecco[52]. Reformer and turbine technology is available from commercial actors in the market, from GE and from process manufacturers, application providers, etc. The conceptual aspect of gas power plants lies with the actors. Having said this, one should not discount the possibility of someone within an institution or rival company, casting the issue in an unfavourable light that does not correspond to the reality of the situation. However, the lack of technological competence with regard to reformers and turbines has not proved a hindrance to any future realisation of the HydroKraft project.

If gas power plants are to be built and CO_2 used for *pressure support* in the volumes discussed, then the lack of curriculum could prove to be a hindrance although, rather than be technically founded, this will more likely be a consequence of the politicised public debate on what this would entail in practice. If CO_2 is used for pressure support, then Andenæs believes that the research institutions will have little to contribute with. Pressure support is very reservoir-dependent and varies from field to field and from formation to formation. Knowledge on this is more likely to be found with the operators of the individual gasfields and oilfields. In the longer term, if more parties were involved in this, then one could perhaps envision a generic knowledge

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48 For more information on KLIMATEK see: http://www.program.forskningsradet.no/klimatek/ (Accessed on 31st October 2003).
49 Hydro received NOK 4 million in 1998 and NOK 2 million in 1999 from the KLIMATEK programme.
50 Brief commentary on HydroKraft at: http://www.program.forskningsradet.no/klimatek/fs/vis.html?kategoriid=2&id=147 (accessed on 31st October 2003).
51A bit more on Hydro Technology and Projects at:
http://www.hydrooilandenergy.com/en/our_activities/new_projects/htp/hydro_technology_projects.html (accessed on 31st October 2003).
52 Energy-efficient cooling and heating technology ("heat pump") with CO2 as working fluid. For more information see: www.shecco.com (Accessed on 10th May 2004).

base in the form of some kind of database that was administered by the research institutions, though this would go far beyond the terms that actually influenced the development of the HydroKraft project.

When it comes to *depositing*, Andenæs says that the knowledge requirements are completely different. In this case the communities of competence and research institutions should come up with some good prototypes. If the ministry approaches the Norwegian University of Science and Technology (NTNU), it will not receive any good answers, because few researchers there are involved in depositing. It is strange that the institutions do not have the ability to come up with an action-oriented project. The only work being done on depositing is being carried out by Statoil on Sleipner. Experiences from Sleipner will however have little influence on HydroKraft simply because Sleipner is purely a case of depositing.

5.5.3 Bellona

At a conference organised by Bellona in the autumn of 1998, Andenæs presented HydroKraft and a representative from Aker presented HiOx. Andenæs was left with the impression that little interest on the part of Bellona was expressed at that time, even though Frederic Hauge had been positive at the time of the project's launch[53]. Also, around 2001, Hydro and Andenæs on a number of occasions had the impression that Frederic Hauge and Bellona were becoming increasingly positive towards the project. However, in November 2003 Bellona went on the offensive, arguing (among other things) for the use of CO_2 for pressure support in tail-end production on Gullfaks, Tampen and Ekofisk. This ought to be done instead of preparing to open new oilfields in Lofoten and the Barents Sea[54]. Interestingly enough, however, no reference to a gas power plant was made in Bellona's letter to Einar Steensnæs, Minister for Petroleum and Energy. Instead, a case was made for establishing a "CO_2 infrastructure" in the North Sea area which would entail, among other things, collecting CO_2 from a number of different sources[55]. According to Andenæs, this was a very unrealistic alternative as long as it remained very energy-demanding and expensive to get such an infrastructure to work.

5.5.4 Other environmental organisations

According to the media reports and consultative rounds carried out in connection with the project, most of the environmental organisations were negative towards HydroKraft, chiefly on grounds of principle; the project would lead to increased energy consumption, and because the CO_2 was to be used to extract more oil, this would lead to additional CO_2 emissions from combustion. It is also interesting to note that, at many of the consultative rounds, concern was expressed for emissions of NO_x. Some examples of the statements made by the environmental organisations are listed below:

- According to *Aftenposten* (26th August 1998), Action Against Gas-Fired Power Plants said yes to HydroKraft at Karmøy. Lars Haltbrekken from Action Against Gas-Fired Power Plants was pleased that this probably put a stop to Naturkraft's conventional gas power plant.

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53 "Hydro came to the rescue of the Government's gas power opponents with its project, in which 90 per cent of the CO2 emissions were to be deposited in an oilfield in the North Sea instead of releasing and thereby contributing to a further increase in Norwegian emissions of greenhouse gasses. This proposal earned Hydro a solid environmental bonus. Bellona's Frederic Hauge is one of those who commended the company and the project. (*Aftenposten*, morning edition, 24th April 1999: "Hydro went behind our backs").

54 This contribution came while the Storting was handling oil exploration in Lofoten and the Barents Sea.

55 Letter to the Minister of Oil and Energy Einar Steensnæs dated 24th November 2003: "CO2-infrastrukltur – En forutsetning for bedre utnyttelse av våre petroleumsressurser og innfrielse av klimaforpliktelsene" ("CO2 infrastructure: a premise for better utilisation of our petroleum resources and for meeting our climate obligations"). (Accessed on 3rd March 2004 at: http://www.bellona.no/data/f/0/31/85/0_9811_0/Steensn per centE6sbrev.PDF).

- According to the consultation statement on "HydroKraft, Report on Proposals to Programme for Environmental Impact Assessment" and contributions published in *Haugesunds Avis* (30th November 1998), the Friends of the Earth Norway were negative towards the project[56].
- Friends of the Earth Norway in Rogaland said they were positive towards Hydro beginning with almost CO_2-free technology, but they were still negative towards the plans for expansion. They were against increasing energy production and were critical of the use of CO_2 for pumping up more oil which in turn would lead to CO_2 emissions. Furthermore, Friends of the Earth Norway in Rogaland were critical towards NO_x emissions[57].
- The Norwegian Association of Hunters and Anglers (NJFF) did not wish to declare its position on gas power plants, but was very concerned about NO_x emissions[58].
- Nature and Youth (NU) "sets strict demands for expanding Hydro's so-called CO_2-free gas power plants". NU wanted to see; energy consumption in Norway reduced, energy from HydroKraft replacing as much polluting energy production as possible, and NO_x emissions be reduced to a minimum. NU appeared to be moderately positive, and concluded by stating that HydroKraft could contribute to reducing greenhouse gas emissions, but demanded strict regulations for the concession so that the power plant did not increase CO_2 emissions nor hinder commitments to energy efficiency initiatives (ENØK) and new renewable energy sources[59].
- In a joint consultation statement Friends of the Earth Norway and The Future in our Hands declared their opposition to expanding gas power plants, the reasons for which were set out in the organisations' main energy policy standpoints. "Hydro's power plants will not in themselves contribute to a sustainable energy system – not nationally, regionally nor internationally"[60].

The majority of the environmental organisations who have submitted consultation statements were in other words opposed to the plans. It is however interesting to note that most of the arguments against the project referred to $NO_{x,}$ and matters of principle, such as a norm that increased energy consumption was negative. *It is possible that the aspect of limited NO_x emissions from HydroKraft was under-communicated on the part of Hydro.*

It is also interesting that the organisations that made statements on the case were far more positive towards the HydroKraft gas power plant, than towards Naturkraft's gas power plant.

5.5.5 Naturkraft

The relationship between Naturkraft and Auke Lont became complicated when the HydroKraft project was launched on 23rd April 1998. According to Andenæs, Hydro chose to promote this concept totally independently of Naturkraft, while at the same time owning (and still owning) a third of that company. Statoil and Statkraft also owned a third each.[61]. Lont has commented on several occasions that the launching

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56 Friends of the Earth Norway, Karmøy local branch: "Høringsuttalese; HydroKraft, Melding med forslag til konsekvens-utredningsprogram av november 1998" Consultative datement dated 27th January 1999. Obtained from NVE's archives.
57 Friends of the Earth, Rogaland: "Vedrørende Norsk Hydros planlagte gasskraftverk på Karmøy". Consultative statement dated 1st February 1999. Obtained from NVE's archives.
58 Norwegian Association of Hunters and Anglers: "Melding om gasskraftverk på Karmøy – Høringsuttalese". Consultative statement dated 2nd February 1999. Obtained from NVE’s archives.
59 Nature and Youth: "Høring til Norsk Hydro: Melding om gasskraftverk på Karmøy". Consultative statement dated 15th February 1999. Obtained from NVE’s archives.
60 Friends Of The Earth Norway and The Future in our Hands: **"**Forhåndsmelding fra Norsk Hydro om bygging av gasskraftverk på Karmøy**".** Consultative statement dated 15th February 1999. Obtained from NVE’s archives.
61 More details on Naturkraft are available at: http://www.naturkraft.no/ (Accessed on 22nd March 2004).

of HydroKraft in 1998 made him feel as if he'd been "stabbed in the back"[62]. When Hydro wanted to go with an alternative technological solution than the one selected in the Naturkraft project, he felt pushed aside.

Naturkraft was set up because both Statoil and Hydro felt that they should do something to produce gas energy in Norway and that it was okay to bring Statkraft in. Naturkraft had spent several years working on the construction of two conventional power plants: one at Kårstø and one at Kollsnes. There was an agreement that to the extent that the three companies planned activities together, they would establish projects and contracts for supplying energy based on gas in this country. When Hydro chose to go it alone, with a particular emphasis on climate and the environment, Lont felt that he had been stabbed in the back.

The climate/environmental dimension was important. According to Andenæs, Hydro had always seen the issue of environment as a sensitive matter for the company's activities. This became apparent during the work done by the Green Tax Commission[63], with proposals for a broader tax regime and the subsequent report on the structure of industry[64] in which Eivind Reiten emphasised the adverse aspects of general environmental taxes. This was linked both to social conditions as well as to the innovative capacity to establish economic activities such as Norwegian aluminium works. For Hydro's part this problem area was a question of finding technologies that either removed greenhouse gasses, or of finding ways to handle them that were cheaper than those one envisioned could be generated from environmental taxes or other forms of direct taxation on manufacturing. This was also a relevant point of reference in Hydro's proposal for a voluntary climate agreement in the Norwegian aluminium industry, and the same point of reference was the motivation for proposing the HydroKraft project, despite different priorities in Naturkraft. According to Andenæs, this was also related to the realisation that Naturkraft was not the place where new technology for fulfilling the demands and possibilities that lay in the Grane oilfield should be developed.

5.5.6 ABB and Kjell Almskog

ABB was the favoured turbine manufacturer for the installations that Naturkraft planned at Kollsnes and Kårstø. This was partly why ABB did not pay much attention to all that was happening on the gas power front, especially when it was related to a turbine technology that ABB did not want to supply in Norway. At this point in time the tenders were still current and valid, and were under assessment and evaluation by the owners. ABB therefore had a heavy commercial interest in the gas power plants that were launched by Naturkraft. Kjell Almskog's negative statements about the HydroKraft project in general, and to Bjørn Arne Sund (as presented in Section 5.1), must also be interpreted in this context.

5.6 Summary

In the case of HydroKraft, as in the case of Shecco[65], the most central actors who influenced the innovation journey were to be found internally in Hydro, as well as in the company's industrial network. The project clearly shows how Norsk Hydro possessed considerable competence in several convergent fields of expertise and could set up large in-house projects. The know-how, financing and project management was all drawn from within the company's own ranks. It is very interesting to observe how the greenhouse gas challenge and the need for energy in the aluminium division, together with technological know-how in Agri and the need for pressure support in an oilfield that was operated by Hydro Oil and Gas, all became

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62 *Aftenposten*, morning edition, 24th April 1999: "Hydro went behind our backs".
63 NOU 9 (1996): Green taxes – policies for a better environment and high employment.
64 NOU 23 (1996): Competition, competence and environment. Main industrial policy strategies.
65 See for example: Ruud, Audun and Olav Mosvold Larsen (2003): "How can Eco-design be used as a guiding tool towards the diffusion of sustainable product innovations? Some empirical findings from the CondEcol project**"**. Conference paper presented at the 11th Greening of Industry Network Conference, San Francisco, 12th-15th October 2003**.**

integrated into one project, especially with respect to what was then Agri. Everyone pulled their weight, but who pulled the most, probably depends on the person judging.

GE emerged as the only actor outside of Hydro that had a decisive impact on the innovation journey. GE had expertise in a particular type of process which Hydro lacked, and carried out the tests that were necessary for evaluating the project's realisation and profitability. It also seems that GE was the only turbine manufacturer who would actually have been able to deliver the product within the given deadlines. The driving forces in the industrial network and the motives behind the criticism from ABB and Kjell Almskog are important points of reference to keep in mind with respect to the final phase of the CondEcol project[66] (Lafferty, Marstrander and Ruud 2003).

Profitability was the issue that defeated the project. The disappointment internally was huge when it became clear that it would not be possible to push electricity prices to "well below 20 øre per kWh" which, according to Hydro, would have been necessary to sustain and run a profitable industrial activity in Norway, particularly in the case of light metals. Having said this, it is not unlikely that if Esso had been more positive, this might have been of significance for the realisation of the project.

The general public (and the environmental organisations) would probably not have proved too great an obstacle because Naturkraft's plans for a "polluting" power plant probably would have been shelved if HydroKraft had been realised. At the same time, the authorities were very positive towards the project and would most probably have granted permission for the building of HydroKraft. The question could however be asked if the government could have been more pro-active and sent out signals about special framework conditions, so that the price of energy from the plant could have been reduced even more. Andenæs believes that the "green certificates" could have been an alternative here. In retrospect many, including Bellona, have pointed out that the kind of knowledge and experience that a project like HydroKraft could have generated, would have been valuable in terms of environmental and industrial policy, from both a national and a global perspective.

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66 For more information see: Lafferty, William, Rolf Marstrander and Audun Ruud (2003): "Exploring the Conditions for Adapting Existing Techno-industrial Processes to Ecological Premises – CondEcol". Conference Paper submitted to the 11th GIN conference in San Francisco 11th-15th October 2003.

6 WHAT HAVE BEEN THE CENTRAL DECISIONS AND CRITICAL MOMENTS IN THE DEVELOPMENT OF HYDROKRAFT SO FAR?

We focus here on 23rd April 1998, when Myklebust announced the project, as referred to in the introduction, though clearly a lot of work had already been invested and a lot remained to be done. Let us draw attention to some critical moments that have been significant for the project:

1. **Summer 1997**
   - International Hydro meeting in Bourdeaux where climate challenges were discussed. Mainly Agri was represented. Trygve Refvem is a central point of reference here.
   - Gunnar Kongshaug elaborated his thoughts on a gas power plant based on the combustion of hydrogen. Kongshaug can be regarded as the initiator of the HydroKraft project.
   - The decision to commit to HydroKraft was solely Hydro's. The development of the innovation was also quite separate from Naturkraft's plans.

2. **Turn of the year 97/98:** The HydroKraft-team approached the research unit at Norsk Hydro. The project was considered important for Agri. The project was still a secret, but gradually a considerable coordination between divisions in Hydro and management was initiated.

3. The plans were made public at the annual general meeting on **23rd April 1998**. This was also the start signal to continue with HydroKraft.

4. Andenæs and Fjellhaug began their "tour" for concept verification already in **April/May 1998**, including visits to GE in Schenectady and the technology fair in Milan.

5. **Summer 1998.** Ole Rønning established his project organisation for concept realisation and commercial implementation, which included detailed engineering.

6. During the **autumn of 1998**, Andenæs and Fjellhaug ran the design verification. Tests from GE were ordered. The test results were not ready before the **summer of 1999**.

7. From **mid-October and through November 1998** insight was obtained on efficiency, cost estimates, etc, from consultants in Copenhagen and Houston and modelling of HydroKraft carried out by Ole Rønning, all of which suggested that the financial prospects for the project were not as good as hoped for. *Hydro's estimates for the total investment in the project were approximately NOK 11 billion.*

8. From the **spring of 1999** Hydro realised that, with respect to the Grane oilfield, it was not realistic to take the HydroKraft project further.

HydroKraft has so far not been realised, and natural gas is now used for pressure support on Grane. However, it is not necessarily cheaper to use natural gas for pressure support, and it is important to remember that the sale of CO_2 was calculated to make up only 20 per cent of the total revenues for the project. The rest was to come from the sale of electricity for Hydro's own industrial operations. Moreover, it was obvious that a high level of knowledge of gas injection from many previous projects existed. It was therefore unnecessary to change or adapt the technology, which meant substantially less uncertainty and risk. A fundamental lack of knowledge of how CO_2 would work on an offshore processing plant also played a role.

The most important reason for the project still not being realised in Norway was that energy prices became too expensive. The natural gas power plant, had at that time a stipulated cost of 20 øre per Kwh, while in HydroKraft it was as much as 25-30 øre. Optimising the technology could have attained a somewhat lower cost, but it would not have been a significantly better economic solution. This being said, it was also possible – according to Andenæs – that the project would have had a different progression if Hydro had been better at involving other actors in the project, for example Esso, Naturkraft, etc. Hydro did not manage to create an environment with many allies.

Stronger commitment on the part of the authorities could also have had a positive effect. Andenæs emphasises that providing subsidies was not a desirable measure from an industrial perspective because this would be considered much too unreliable. Investment aid would have been preferable, but this could have conflicted with EEA regulations. According to Andenæs, it would actually have been better if the authorities had for example bought CO_2, based on an agreement under civil law, at a specified price for a specified number of years.

So what happens next? The new time frames that for example Tampen, Ekofisk and Sleipner represent are very realistic, but once the blowdown decision is taken, it is too late. The HydroKraft patents lie there "waiting to pounce", and are ready for use on very short notice, if desirable.

7 WHAT ARE THE CURRENT PLANS FOR FUTURE PRODUCTION AND MARKETING?

The Grane oilfield is now operative and utilises natural gas for pressure support. This is not the case in the HydroKraft project, but for HydroKraft the innovation journey has not yet been completed. The level of ambition has however been lowered and Hydro itself has no concrete plans to use the HydroKraft patent. Andenæs thinks it is pointless to talk about Norway in isolation; technology is a global matter, with a global scope of application. The question is how to make use of it.

At of fall 2004 the conditions that would make it financially appealing to build such a power plant in Norway are non-existent, but other time frames exist in which the technology could be utilised, particularly in relation to tail-end production, i.e. prolonged extraction on existing fields. Hydro therefore wishes to keep the technology accessible, with rights, so that no-one can stop them in one area or another. In 1998, NOK 256 per tonne of CO2 was required as a supplement in order to get an energy price of 17-18 øre per kWh to be remunerative for the HydroKraft project. As far as Andenæs knows, no-one has as yet developed a cheaper equivalent concept.

7.1 Patent applications

The HydroKraft project is first and foremost interesting wherever gas can be found. Hydro therefore choses to apply for patents in countries where gas deposits and a working legal system prevail. The first application was already submitted in the summer of 1998. The application was relatively loosely formulated and, after the hearing and administrative procedures, the final text was formulated and submitted in the summer of 1999. The first patent awarded to Hydro for HydroKraft was in Turkey in 2001[67], thereafter Australia in 2002[68], and USA in 2003[69]. In Russia the concept is "approved", that is to say that the whole of the technical side is approved, only the administrative work remains before it is in order. Otherwise the patent is under consideration in Norway, EU, the Czech Republic, Estonia, Hungary, Poland, the Slovak Republic, Canada, Mexico, Brazil, Trinidad and Tobago, New Zealand, Israel, China, Indonesia, Japan and Singapore[70].

When Hydro originally took out the patent it was to ensure that they had all the rights to realise what they envisioned for exploitation of the Grane oilfield. When they realised, in 1999, that this time frame was closed, the motivation shifted to securing the rights for HydroKraft. The commercial possibilities are there – also regarding the use of coal – and Hydro wants no-one to be able to spoil their future opportunities.

7.2 Gullfaks and tail-end production. Time frames

Future Norwegian time frames for utilising HydroKraft technology, in which a conceivable value of CO_2 as pressure support is envisioned, hangs together with the blowdown of the oilfields on the Shelf, i.e. so-called tail-end production. Any "new" production will be of little relevance in the future. Fields like Grane, a

67 23rd July 2001 (valid until 2018).
68 6th June 2002 (valid until 2018).
69 14th January 2003 (valid until 2018).
70 Hydro has its own patents office. Andenæs mentions a certain Venke Johansen as a central contact in the patent application process.

reservoir with as much as 100 million tonnes of oil but which totally lacks a drive mechanism and requires 5 million tonnes of CO_2 per year, are few and far between. The Grane oilfield is the last of this size remaining on the Norwegian Continental Shelf.

Production on the Norwegian Continental Shelf and in Norwegian industry takes place in phases. We found some of the big "elephants" as they are known - and produced a lot from them. Soon a decision must be taken as to whether and how the projects should be further developed. Should tail-end production be promoted or should all these big elephants be phased out? The crucial decisions on the British shelf have already been made: they are to be blown down, and water and gas has been used to squeeze out most of what remains. But their fields are not as big as the Norwegian ones. They were also found and developed earlier.

In Norway the most relevant fields for blowdown at some time in the future are Gullfaks, Statfjord, Troll, Snorre and Ekofisk. The method of tail-end production of Gullfaks and Statfjord must be determined in the course of the next few years. In the cases of Snorre and Ekofisk, the decision can wait for another 10 and 20 years respectively. The HydroKraft patent could be interesting here.

We have pointed out the prevailing curriculm, and Andenæs believes that those who carry out research in the field are counteracting appreciation of the opportunities which the HydroKraft patent represents. In the case of CO_2 disposal the scale on which the projects are being operated is much too small. Despite many political promises and specific committees set up to discuss hydrogen, there exist few connections to the HydroKraft patent. In the Hydrogen Commission's report (NOU 2004:11), various national efforts are proposed, emphasising among other things the importance of environmentally friendly production of hydrogen from natural gas. Explicit reference is made to pre-combustion technology and how this could form the basis of large-scale production of electricity with hydrogen as the natural middle product. No explicit reference is however made to the HydroKraft project[71]. This is a paradox, given the industrial structure and oil and gas-based economy we actually have. We can also mention here the fact that neither does there seem to be any politicians or others in the political system who appear interested in exploiting the possibilites that the HydroKraft patent represents. Very few actors have expressed an interest in gas power plants that handle CO_2. Bellona, however, is actively promoting tail-end production on existing oilfields, with CO_2 for pressure support.

7.2.1 What can the Norwegian authorities do?

If technology of the same type as HydroKraft is to be realised in Norway, then the industrial actors would prefer investment aid, claims Andenæs. They have little faith in, and are sceptical to taxes, because these are too unpredictable. If one is to stir up enthusiasm from the industrial actors, this must be done on the investment front, either by means of tax relief or other financial subsidies. Alternatively the authorities, or the relevant administrative body, could go directly in, as part-owner in the project, thereby having direct responsibility and a share of the risk involved in the project development and commercialisation of the innovation which the HydroKraft patent represents. With this alternative one could make a shift from solely thinking in terms of short term returns and minimising abatement costs in NOK per tonne of emissions of greenhouse gas equivalents, to relating this to genuine technology development and the opportunity to promote green innovations, which could also advance a more sustainable development.

71 The report is available at: http://www.odin.dep.no/oed/norsk/publ/utredninger/NOU/026001-020003/dok-bn.html.

7.3 International opportunities – with environmentally friendly coal-based power plants?

There are no national boundaries for the HydroKraft technology. For example, no turbine manufacturer was interested in developing turbines specifically for HydroKraft, or specifically addressing a distinctively Norwegian CO_2 tax. Somewhere or other, however, they may suddenly discover that they need HydroKraft for something. An example of this is the references made to the HydroKraft project at an energy seminar in China in April 2003. Enormous coal gasification power plants are being considered there, but there is cause for concern about the emissions. The Chinese have probably begun to establish at least one such power plant for producing syngas, which could then be refined in all kinds of ways without CO_2 being safely handled.

7.4 The transition to the hydrogen society

Not many references to a future transition to the hydrogen society were made in the first conversations with Andenæs. Yet it is clear that hydrogen can be extracted from both coal and gas. In HydroKraft the hydrogen can be used as a raw material or as an energy carrier. Hence excellent combination possibilities exist. The front-end process that makes CO_2 and hydrogen, can be made as large as required. One can therefore choose whether to have one or five turbines at the other end. One can also choose to store some of the hydrogen, and burn the rest. It provides a good combination of possibilities, thought it is clear that more CO_2 can be obtained from the exhaust gas from coal than from natural gas. When discussing gas power stations it is fundamental that the technology that is used grabs the CO_2 *before* combustion, as with HydroKraft, rather than after combustion, because the concentration of CO_2 in the exhaust gas is too low when burning gas. The HydroKraft technology is suitable for gas power plants. The technology that purifies exhaust gas is pointless in Norway. In connection with the design competition in 1998 mentioned earlier, Hydro looked at this with Statoil, but chose instead a more traditional design without special handling of contaminant emissions.

It is crucial to appreciate the time frames for setting up such gas power plants. When ABB says that it would take between 10-20 years to have the technology developed and ready, this is of no interest whatsoever in relation to the North Sea. In a small country like Norway it is necessary to have an awareness of the intended use of technology. Nevertheless it goes without saying that, in a global perspective, this would be a totally different matter. Then it is feasible that it could be interesting even in 20 years time.

We mentioned earlier the Hydrogen Commission's report. In the report reference is made to the fact that Norway possesses considerable competence within, among other things, the production of hydrogen, and that it is important for Norway to establish itself with respect to the future supply of knowledge, components, products and system solutions. In connection with the commission's work, an expert group on hydrogen in the transport sector was appointed. The expert group indicated that considerable resources were needed for a transition to increased use of hydrogen in the transportation sector, and recommended that active political action be taken in this area. This was also emphasised by the other expert group appointed to look at the production and stationary application of hydrogen. The general recommendation was that an organisation that contributed to the development and implementation of a national commitment to hydrogen should be established. Furthermore, it was pointed out that a goal-oriented commitment to research and development should be made, as well as the importance of carrying out pilot projects. The expert group on transportation mentioned that, in an early phase, state subsidising of hydrogen vehicles should be done by means of investment aid or project financing rather than by means of the taxation system[72].

72 Report prepared by an expert group on hydrogen in the transport sector. Separate Amendment no. 2 to NOU 2004: 11. Oslo: Ministry of Transportation. (Accessed on 17th June 2004). Available at: http://odin.dep.no/oed/norsk/publ/utredninger/NOU/026001-020003/dok-bn.html).

8 CONCLUSION/SUMMARY

HydroKraft was a project that generated great enthusiasm and admiration internally in Norsk Hydro. All three of the commercial operational divisions in the industrial conglomerate, i.e. oil and gas, light metal and Agri, were involved. Oil and gas sought alternative pressure support by means of CO_2. Light metal, and primary aluminium plants in particular, sought new supplies of electricity, while the Agri segment of Hydro was able to transfer experience and competence from ammonia production and reforming of natural gas for hydrogen production. With Agri sold off by Hydro and Yara established, part of Hydro's underpinning as energy developer has, according to Andenæs and Marstrander, been taken away.

Hydrogen was defined as the energy carrier of the future. This was also recognised by Norsk Hydro, but at that point there were few good solutions forthcoming as to how this could be processed in sufficient volumes. The Kyoto Protocol for controlling greenhouse gas emissions, including CO_2, was signed the previous year and was actively supported by Norway. The HydroKraft project could thus realise national environmental policy goals as well as secure sales of gas deposits and the development of cornerstone companies in Norway.

8.1 Did the management's way of handling things break up the innovation journey?

Could the initiative taken by the Hydro management on 23rd April 1998 have "killed" the project? The initiative overshadowed the original idea because it was strongly linked to ammonia-based technology with a rate of exploitation of hydrogen that could not be applied to the petrochemical-based technology chosen. The Hydro management's initiative also led to a diminished perspective of Grane – a decisive point in the case. Let us reflect a little closer on this point.

In the transitional phase when the project was "elevated" from the company's engineers to the top management, the main idea for the gas power plant in fact disappeared. As we have emphasised repeatedly, the idea was not only to establish a gas power plant in line with the plans for Naturkraft, but also to combine this with CO_2 as pressure support for the Grane oilfield. Pressure support combined with hydrogen production was an integrated part of the techno-economical equation, but this was lost in the political handling of the project on the part of Hydro's management.

It is therefore important in retrospect to understand the internal communications within the company, in particular the dialogue between technical personnel and the non-technical representatives who relayed the project to the media. This is important because these actors form the basis for the general public's comprehension of what the project is about and not what kinds of changes and alternatives it represents.

In concrete terms we are talking about how the focus on pressure support for Grane was pushed into the background in favour of global climate change challenges. This reorientation diminished the work on how the HydroKraft project actually was to be realised in purely technological terms. This caused a break-up in the project development or innovation journey, which perhaps, in this case, made all further realisation impossible. The initiative, with stronger focus on global climate issues, also gave rise to a public perception that was to prove difficult to change. At the same time several technical issues remained unresolved. When this occurs without any close linking to fundamental technical premises – as in the case with Grane – it is often the case that more rhetoric and little concrete development is generated.

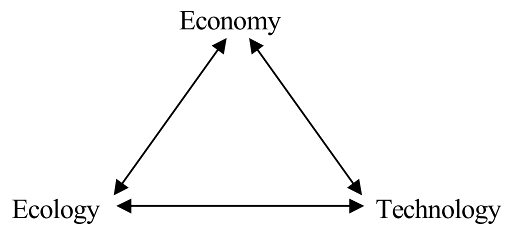


Figure 2: Decision-making triangle for ecological innovations

Marstander believes it likely that previous Hydro managements would have handled this in another way. Such a management would probably have maintained that this was primarily a technological leap, a radical innovation, with more closely specified economical perspectives. This means that, with reference to Figure 2, one would have kept the focus primarily on the techno-economical axis. Then the Hydro management would have left it to the politicians to find this interesting, also in an economical-ecological context, though one would then have underlined that this expanded focus would have had to take place on the basis of the total idea of the project, including the possibilities for utilising a greenhouse gas for pressure support. The HydroKraft project would then easily have undergone a completely different progression. Andenæs agrees with his argument. The traditional dividing line between industry and society is drawn where the Grane project becomes a general matter for society, thereby moving it out of the corporative sphere. The challenge in the HydroKraft project, as Andenæs and co. saw it, was that Grane departed from the techno-economical evaluations that were made and that formed the basis for the whole idea for the project. At the same time the HydroKraft project in Hydro was developed as a project that was politically oriented towards global climate change challenges.

8.2 What needs to be done further if HydroKraft is to be realised?

In Andenæs' opinion the big problem in Norway is that industrial thinking easily becomes corrupted by politico-economical thinking, with no regard for technological limitations or possibilities. The initiator is no longer the techno-economical axis, but the politico-economical analysis in which the matter is reduced to a *decision*. The challenge is that in the techno-economical sphere this decision must also be correctly founded techno-scientifically. This was not the case in April 1998, hence a considerable challenge to realising the HydroKraft project was created, both with regard to handling greenhouse gasses and to producing hydrogen in an environmentally safe manner. Andenæs concludes by expressing the following concern: "It is wrong to direct the criticism at politicians, economists and lawyers. The technologists themselves have, here as in other cases, managed to play themselves out of the game".

If one were to consolidate the techno-economical reference, many would emphasise that there should also exist genuinely interested customers for CO_2 in the future. It is precisely here that the global climate change challenge will have relevance. Given Norway's international commitments to the Kyoto Protocol, new solutions will have to be sought if one is to justify the present business and industrial policy strategies. A sharper focus on the solutions and possibilities that the HydroKraft project represents could also be linked to the debate on tail-end production on Gullfaks, Statfjord and Ekofisk. Increased oil and gas extraction could then be combined with the international environmental commitments to which Norway has already pledged itself. This would thereby be an innovative contribution to a more sustainable development.

Although feasible technologies for production by means of both wind and sun are available, hydrogen production combined with fossil fuel is the production method which with current technology - particularly if true value is associated with handling CO_2 - has the lowest energy cost per MMBTU[73]. This could give grounds for future reflections on "jumping the curve" and the chance to realise radical, eco-efficient innovations as they are more generally problematised in the CondEcol project. It also implies that CO_2 disposal will be an important theme in the future, both in the debate on hydrogen and climate as well as in the work on proposing a more sustainable development.

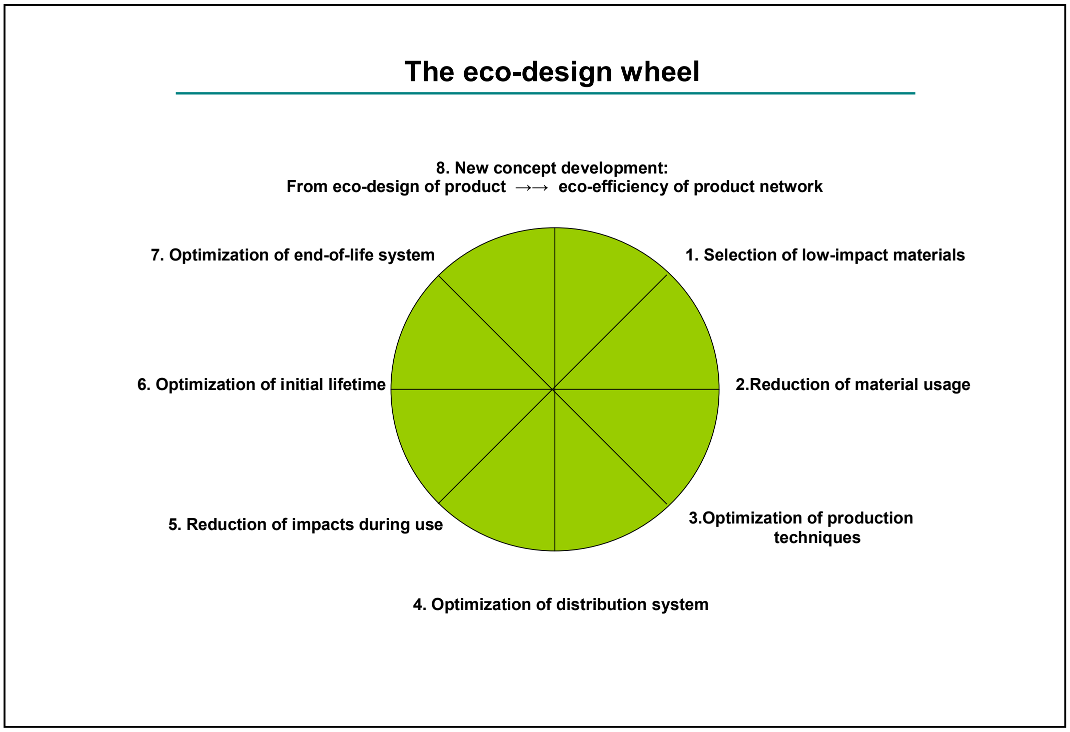
73 One million British thermal units.

9 APPENDICES

9.1 Research Protocol

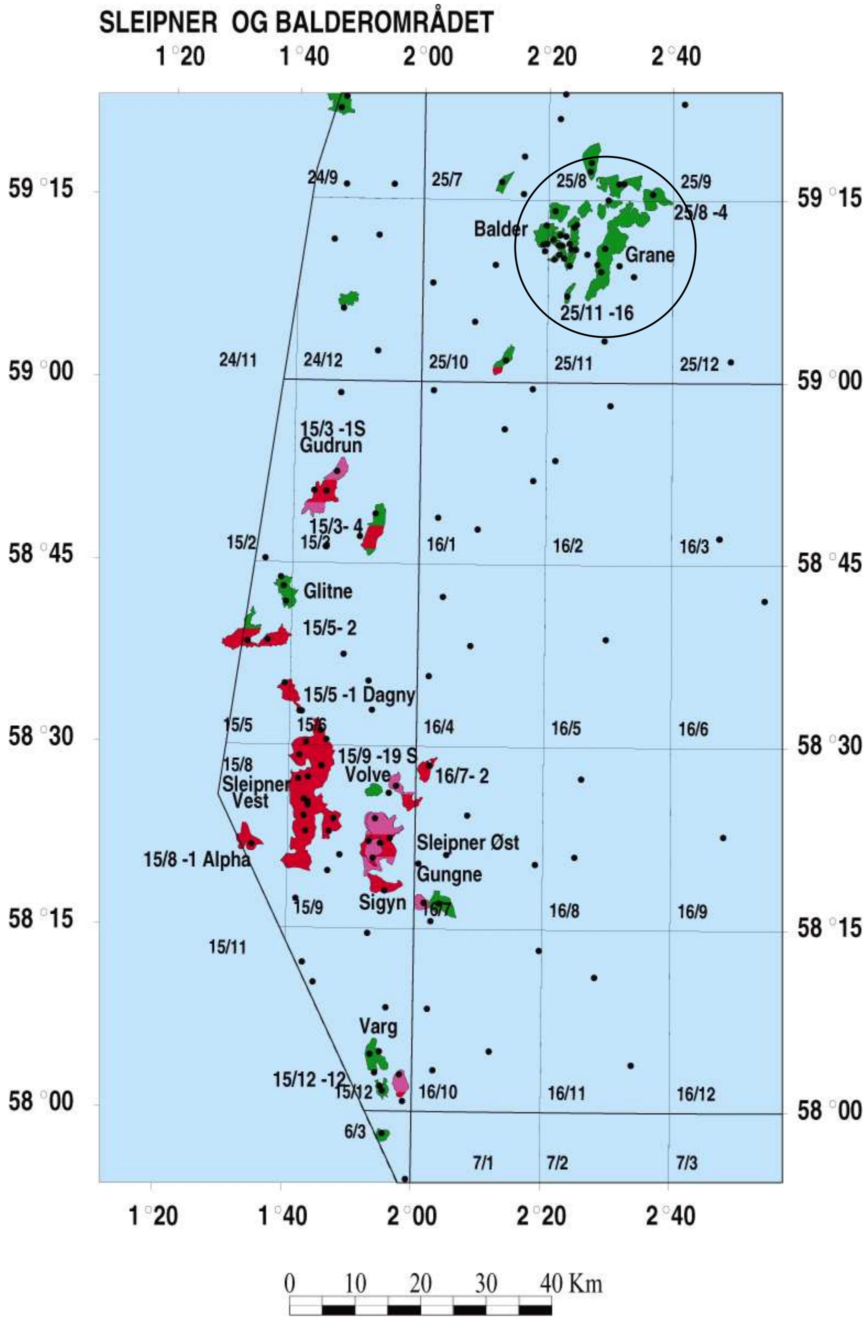
1. What are the most important characteristics of a more eco-efficient alternative to existing products or processes?
2. How can the company characterise the product in relation to the first seven spokes in the Eco-design Wheel?
3. What were the main reasons for the company's decision to develop and market the product as a more eco-efficient alternative?
4. Which key actors have influenced the product development so far?
   a) Technology and manufacture
   b) The market
   c) Financing
   d) Regulatory bodies
   e) Cultural and social organisation
5. What have been the central decisions and critical moments in the development of the product so far?
6. What have been the significant factors, both positive and negative, that have affected the innovation journey so far?
   a) Input factors – specific manufacturer constellations
   b) Technology and manufacture
   c) Internal actors
   d) Financing: internal/external
   e) Market characteristics
   f) External infrastructure
   g) Legal/political framework
   h) Culture and society
   i) Other
7. What are the current plans for future production and marketing?

9.2 The Eco-design wheel



The Eco-design wheel. Strategic opportunities within a eco-design strategy. Presented in the CondEcol-project description (Lafferty, Marstrander og Ruud 2003) based on Brezet og van Hemel (1997:81).

9.3 Map of Sleipner and Balder



Grane is situated west of Stavanger (58° 58'North, 5° 45'East) on the Norwegian Continental shelf.