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Scenarios for Industrial Transformation:

Perspectives on the CondEcol Case Studies

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Report

ProSus
Program for Research and
Documentation for a Sustainable Society
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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:

> Conducting systematic evaluations of Norway's implementation of international commitments on sustainable development. Evaluations are based on three types of standards: external criteria – targets and values from international agreements and programmes; internal criteria – national goals and action plans; and comparative criteria – performance by other countries in relevant policy areas. The relationship between the demands of sustainability and existing democratic procedures is a key interpretive theme.
>
> A documentation and evaluation of policy implementation that provides a basis for strategic research on barriers and possibilities. ProSus employs an integrated research model (SusLink) that focuses on the relationship within and between different arenas of governance. Research is focused on the supranational, national, and local levels of governance, as well as households and business and industry.
>
> An information strategy based upon open and interactive means of communication to quickly and effectively disseminate research conclusions to central actors within the field of sustainable development. The goal is to highlight alternative strategies of governance and instruments for more sustainable societies locally, nationally and globally.

In addition to books and articles in scientific journals, ProSus also publishes reports and working papers in order to disseminate the research results in an effective manner to key actors and decision-makers within the field of sustainable development. For a full overview of projects and publications, please visit the SUM website: http://www.sum.uio.no/

William M. Lafferty
Programme Director

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, October 1, 2006

William M. Lafferty	Audun Ruud
Director of ProSus	Project co-ordinator

CONTENT

1 INTRODUCTION AND ANALYTICAL APPROACH

Innovation journeys are often highly unpredictable and uncontrollable, such as a journey along an uncharted river (Van de Ven et al 1999). This holds even more for radical innovations: innovations that build upon a basis of knowledge and competences not yet strongly aligned with business, markets, technologies and products; and for which the market is still uncertain in terms of applications, market linkages, and users. Yet, understanding how the innovation journey unfolds may provide clues for successful manoeuvring. Moreover, understanding the landscape through which the river flows may also enhance insight regarding the direction and velocity of the river and its water. Hence, it is possible to develop strategic management tools to increase the chance of successful development and introduction of new technologies. The purpose of this report is to contribute to that.

By reviewing innovation journeys that are underway, and by assessing the way these journeys are embedded in a wider context of political, social, economic, and technological landscape changes, we explore several paths these journeys may take by utilising a sociotechnical scenario method that specifically takes into account the interaction between technological and societal change. The focus is on three innovative energy technologies developed by Norwegian firms. The technologies are still in the development phase with a range of actors involved.

The current report is part of a larger project – the CondEcol-project – which explores the introduction of new radical energy technologies. Based on mappings of specific innovation journeys to illustrate cases of innovation in specific firms, the goal of the project is to understand the factors and actors influencing the innovation process – as well as to develop management/governance tools for better long-term planning of the introduction and success of radical new energy technologies (Lafferty et al 2001).

The three CondEcol case studies are:

- The introduction of the patented technology 'Shecco', a heat-pump technology based on CO_2 as the conductive agent in applications such as mobile air conditioning (MAC), residential air conditioning (RAC), hot water production, and combined hot water and air conditioning. Shecco is an abbreviation of Sustainable Heating and Cooling with Natural CO_2.
- Production of photovoltaic wafers for the global photo-voltaic (PV) market.
- The introduction of a gas-fired electricity production process/unit ("HydroKraft"), with CO_2 sequestration and hydrogen separation processes for use of hydrogen as turbine fuel or for fuel cells.

Figures 1 to 3 provide an overview of the conceptual framework that underlies our analysis and serves as the basis for the scenario methodology. The innovations under study in this report are viewed as new practices within existing sociotechnical systems, or in other words niches emerging within existing regimes (see Figure 1). The examined innovations compete first and foremost with established technological configurations within the transport regime and electricity regime that serve specific established functions – sociotechnical systems – within society. These socio-technical systems are actively created and maintained by several social groups, such as producers, suppliers, users, public authorities, knowledge institutions, etc. Their activities reproduce the elements and linkages in sociotechnical systems and are coordinated and aligned with each other. By providing orientation and co-ordination to the activities of relevant actor groups, sociotechnical regimes account for the 'dynamic stability' of sociotechnical systems. This means that innovation still occurs but is of an incremental nature, based on established 'technical trajectories' and path dependencies.

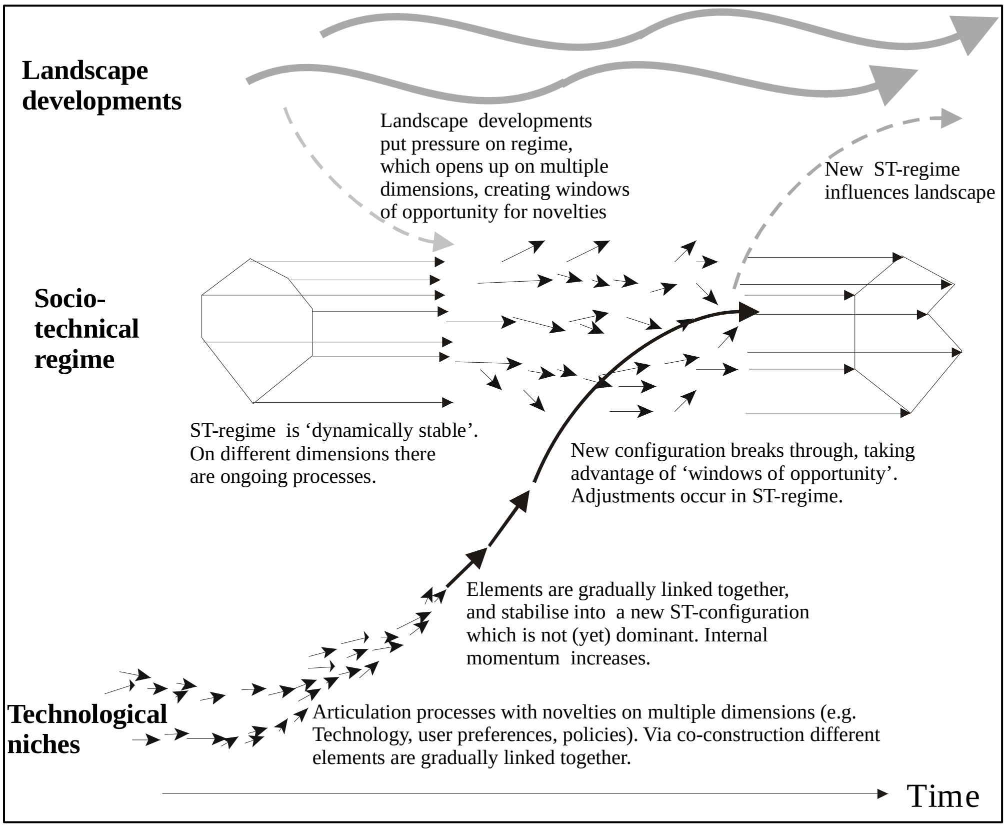


Figure 1: Multi-level perspective on changes in production-consumption systems (Geels 2002).

The micro-level in Figure 1 is formed by technological niches, the locus for radical innovations ('variation'). As their performance is initially low, they emerge in 'protected spaces', which shield them from mainstream market selection. Niches thus act as 'incubation rooms' for radical novelties. Niches are important, because they provide locations for learning processes about the technology, user preferences, regulations, infrastructure, functionalities, etc (Kemp et al 1998; Geels 2002; Hofman et al 2004). The macro-level is formed by the socio-technical landscape which refers to aspects of the wider environment (e.g. globalisation, environmental problems, cultural changes). The metaphor 'landscape' is used because of the literal connotation of relative 'hardness' and to include material aspects of society, e.g. the material and spatial arrangements of cities, factories, highways, and electricity infrastructures. The landscape provides 'gradients' for action but are beyond the direct influence of individual actors (Rip and Kemp 1998; Geels 2002).

The relation between the three concepts can be understood as a nested hierarchy or multi-level perspective. Regimes are embedded within landscapes and niches within regimes. Radical innovations may break through and become part of system innovations through the interplay of dynamics at multiple levels. In a first phase, novelties emerge in niches in the context of existing regimes and landscapes with their specific problems, rules and capabilities. New technologies often face a 'mismatch' with the established economic, social and/or political dimensions (Freeman and Perez 1988) and tend to remain stuck in niches. In niches, actors improvise, engage in experiments to work out the best design and find out what users want. In the second phase the novelty is used in small market niches often based on new or additional functionalities the novelty brings. This provides space for further improvement of the novelty as more is learned about configurations under which the technology works. The third phase is characterised by a breakthrough of the new technology, wide diffusion and competition with the established regime. On the one hand, there are internal drivers for breakthrough; for instance, actors who have a significant stake in the new technology may push for further expansion, or price/performance dimensions gradually improve. On the other hand, breakthrough depends on external circumstances, i.e. 'ongoing processes' at the levels of regime and landscape, which create 'windows of opportunity'. There may be changes at the landscape level, which put pressure on the regime. Further, there may be internal technical problems in the regime, which cannot be met with the available technology. Finally, there may be negative externalities, which are problematised by 'outsiders', e.g. societal pressure groups (e.g. environmental NGO's), outside scientific professionals, or outside firms. Or there may be tensions within the existing regime, because of changing user preferences or stricter regulations. The key point of the multi-level perspective is that system innovations occur as the outcome of linkages between developments at multiple levels (Geels 2002).

Based on a further specification of the dynamic stability of existing sociotechnical regimes by Hofman (2005), Figure 2 aims to show how existing systems of production and consumption form a configuration that works through alignment of several elements around established dominant practices and the convergence of technologies around a dominant technological and organisational form. Institutions play a principal role, and they are based on a mix of regulative, normative, and cognitive dimensions. Examples of regulative institutions are rules for access to the electricity grid and the rules through which consumers pay for electricity transport. Mechanisms of normative institutions are processes of formal and informal network and actor group formation such as those networks that take a central role in deciding the direction of public R&D, where certain actors are considered appropriate to take part in the decision-making process, and others not. Cognitive dimensions of institutions relate to the acceptance of existing technological methods. Certain habits and routines are based on a dominant mental model. For example central generation of electricity and distribution to households is considered natural and believed to be more efficient than stand-alone systems. The logic of this is that it reduces transaction costs very significantly, as each actor takes on a specific role in the system. Interactions between a variety of actors have become institutionalised.

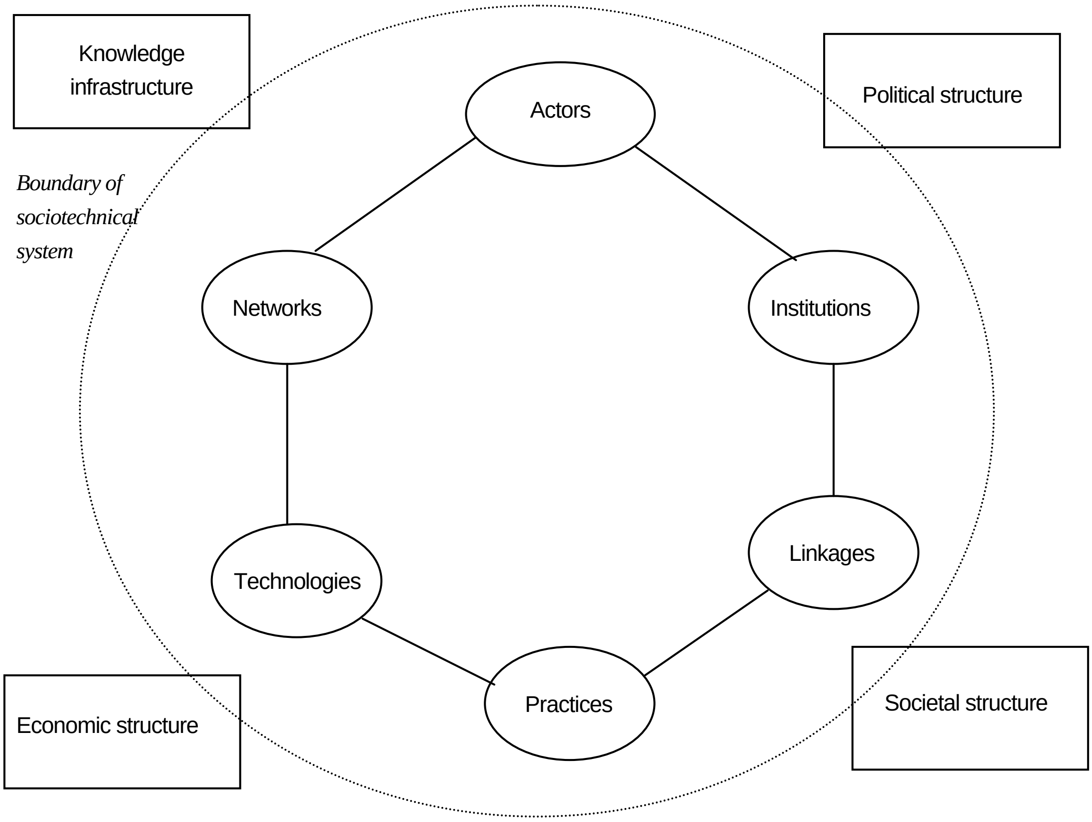


Figure 2: Analysis of innovations from a systems perspective (adapted from Hofman 2005)

The analysis focuses on the way the emergence and establishment of the CondEcol innovation cases as new practices involve changes in elements in the sociotechnical system and their interactions. The challenge for these innovations and for radical innovations in general, is firstly that their deployment demands much higher transaction costs relative to incumbent technologies and secondly that they initially have to compete with technologies that have a better economic performance for the traditional functions within the existing system. The rationale and legitimacy for developing these innovations is based on the new technology providing distinct functionalities relative to the incumbent technologies and the expectation that the innovation is on a trajectory that will deliver better economic performance in the future. At least three processes are therefore crucial to the success of these innovations: The first is the increased importance of the new and/or, additional functionalities that the new innovation can deliver. The second is reduced legitimacy of the existing system, in the sense that further improvement and optimisation here is discredited as the solution to the new functionalities or problems that the system faces. The third is the adaptation or build-up of a configuration of the different elements depicted in Figure 2 that facilitates the further improvement of the technology and lowers transaction costs for its deployment. Apart from analysing how the new practices are shaped by, and also shape, the internal organisation and coordination of different elements in the system, this also involves a more outward focus on the way that such a system is embedded in broader societal structures. This embeddedness, visualised by the four rectangles in Figure 2, involves:

- the way knowledge is generated, directed, distributed and used;
- the way the system is regulated and legitimated in a political sense;
- the way the system serves its function in the economic system; and,

- the way the system provides a societal function and maintains its legitimacy.

Thus, the multi-level perspective is extended with a fourth level; societal structures – as illustrated in Figure 3.

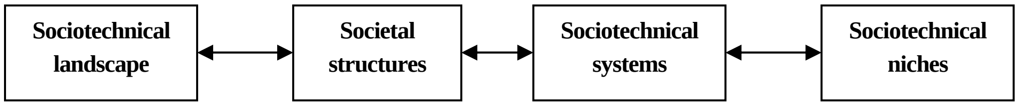


Figure 3: Extended multi-level perspective on changes in production-consumption systems

These broader societal structures have become geared to existing systems of production and consumption, but also adapt continuously to external changes, ranging from disruptive events such as oil price shocks, extreme climate events, and wars, and to more gradual changes such as the process of European integration, the rise of China as an economic force, the pervasive impact from ICT technologies, and the development of international treaties such as for climate change. The function of the scenarios is first to assess landscape developments and sketch the way these may impact broader societal structures and regimes, and second to provide insight in the way ongoing innovations and niche development processes may hook on to these processes.

This perspective is especially relevant for the cases under investigation in the CondEcol project which derive part of their viability from their contribution to reducing the climate change problem. Thus, their emergence is related to changes in political institutional arrangements, e.g. the Kyoto Protocol, and energy saving and renewable energy policies, and to increasing societal attention and organisation to environmental and climate change concerns. The three innovation journeys will thus be analysed with reference to the four evolving broader societal structures but also in terms of the way they adapt to and integrate within the existing system. Figure 2 also points to how various elements of sociotechnical systems become aligned as certain practices gain dominance, are facilitated by established networks, linkages and institutions, and further optimised through convergent actor strategies.

The following section shortly describes the three CondEcol case studies based upon more extensive case studies provided elsewhere (Larsen and Ruud 2005ab; Ruud and Larsen 2005). The main purpose is to derive some basic insight on what the main drivers for the innovations are, both internal and external to the firms, and what have been the main directions the innovations have taken. This is followed by section three in which a number of tools for exploring long-term technological change are reviewed. It is concluded that these methods exhibit weaknesses in exploring the way innovations become embedded in and co-evolve with institutional and societal change. A subsequent section introduces sociotechnical scenarios as a tool specifically designed to solve this weakness. Section five then illustrates this tool by applying it to the three innovation journeys previously introduced. The report ends with a concluding section.

2 THE THREE CONDECOL CASE STUDIES IN CONTEXT

This section provides an assessment of the three CondEcol case studies as processes of co-evolution of technological and institutional change. More specifically the aim is to explain the emergence of these innovations and different factors and actors that played a role in this either by promoting or hampering the innovations. Broadly speaking these may be divided into economic, technological, political, and social factors, related to the four societal substructures previously introduced. The section also involves an assessment of the perceived sociotechnical configuration that the innovations represent: the nature of the institutional set-up (knowledge base and flows; information flows and interactions between actors; and roles of different actors) in which the innovation is expected to work.

Innovation	Regime	Divergence	Nature of change due to new practice
ScanWafer PV	Electricity	High – new technological organisational form	Fundamental technological change involving radical changes in mode of production and coordination
Shecco technology	Transport/Air conditioning	Low- component substitution	New technological component added to the system (car) requiring alteration in other components and change in safety standards
HydroKraft	Electricity	Medium-key technological change	Modification in key technology with additional components added to the system

Table 1: Short synopsis of the three CondEcol innovation cases

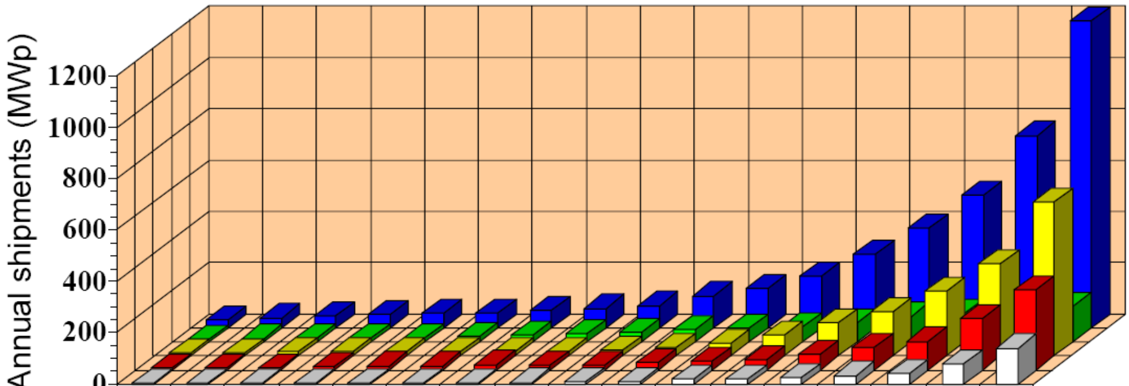
2.1 Solar energy and ScanWafer

The first CondEcol case study involves the production of photovoltaic wafers. Moulded from silicon, these wafers serve as input for the production of solar cells, modules and panels. There are several competing technologies for the production of solar cells, such as mono- or multi-crystalline wafers which are basically extensions of semiconductor production techniques of the micro-electronics industry, and thin-film technologies where thin layers of semiconductor material are put on a supporting substrate (Green 2000). ScanWafer was established in 1994 and started to produce multi-crystalline photovoltaic wafers in 1997. The company has been able to establish itself and become successful based on a strong knowledge network related to technologies. Further it has created a strong market network related to the various steps of manufacturing of silicon to multi-crystalline wafers for solar cells, modules and panels, enabled by the personal experiences, capacities, and networks of the founder of ScanWafer, Alf Bjørseth (Ruud and Larsen 2005). Also the availability of metallurgic silicon, cheap power, and access to cooling water were important local factors that facilitated the start-up in Norway (Ruud and Larsen 2005: 13). ScanWafer became the leading global manufacturer of multicrystalline wafers in 2005 (Photon International 2005). Its technological network involves exclusive deals and cooperation with producers of equipment central to the wafer production process, such as with firms involved in:

- Development of melting furnace for multi-crystalline silicon into blocks.
- Development of ceramic crucibles in which silicon ingots are manufactured (molds).

- Development of wire saw technology for slicing ingots into wafers. (Brekke et al 2005)

The company has been able to gain a competitive edge because it has access to the main raw material, pure silicon, and because: it applies very efficient and state of the art production processes, produces high quality wafers, and has been riding the wave of strong increases in demand for solar cells worldwide and in some particular markets, especially Japan and Germany. The main uncertainties involve; the way in which markets will unfold (e.g. specific applications and products etc), the question of how long multi-crystalline will remain dominant and which technology might attack this dominance (i.e. should the company further invest in multi-crystalline technology, invest in multiple technologies, or shift to another technology?). Another uncertainty concerns how the technology will best reap the advantages of investment and R&D subsidies available, and maintain the strong networks it has (i.e. is Norway the best choice for further wafer production in view of the role PV has in energy technology development in Norway?).



	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Rest of World	3	4	4,7	5	4,6	4,4	5,6	6,35	9,75	9,4	18,7	20,5	23,42	32,6	40,7	80	140
Europe	6,7	7,9	10,2	13,4	16,4	16,55	21,7	20,1	18,8	30,4	33,5	40	60,66	86,38	112,1	200	314
Japan	12,8	14,2	16,8	19,9	18,8	16,7	16,5	16,4	21,2	35	49	80	128,6	171,2	254,5	360	602
United States	11,1	14,1	14,8	17,1	18,1	22,44	25,64	34,75	38,85	51	53,7	60,8	74,97	100	112,9	110	139
Total	33,6	40,2	46,5	55,4	57,9	60,09	69,44	77,6	88,6	125,8	154,9	201,3	287,7	390,2	520,2	750	1195

Figure 4: Global PV module shipments for 1988-2004 (Sinke 2005, based on P. Maycock (ed.), PV news).

If we apply the systems perspective we come to the following assessment of the innovation journey: The establishment of ScanWafer was enabled by ongoing processes of knowledge and market formation at the global level regarding photovoltaic technologies and applications. At the moment of its establishment the market for PV was just shifting from mainly off-grid, stand-alone applications to grid-connected applications. Especially the integration of photovoltaic cells in rooftops started to take off. In addition specific stimulation programmes were developed in Germany and Japan at the end of the 1990s. These countries became major markets for photovoltaic cells and wafers triggered by the interplay of landscape developments (increasing importance of the climate problem, and in Japan particularly because of the aim to reduce dependency on fossil fuels) and developments in domestic societal structures. In Germany the inclusion of the Green Party in government played an important role, in Japan a long-term vision was developed by the Ministry of Industry in collaboration with industrial parties (particularly electronics conglomerates) for the development, application and diffusion of PV. These were the front-running countries in terms of incentives and objectives for solar energy where the largest markets for solar cells and wafers emerged. But also in other European countries and the US incentives and markets for PV increased. Figure 4 gives an overview of global PV module shipments for the period 1988-2004 and shows an annual growth rate of around 25 % for the whole period and with significantly higher rates in later years. Moreover, growth rates for Japan have been significantly higher than for Europe, while the rest of the World has gained in market significance. Recently the European Commission developed a long-term vision for PV development, but unlike Japan, there is no broad political and industrial commitment to the realisation of this vision.

With regard to network formation ScanWafer has been able to establish partnerships with front running companies for specific production aspects of multicrystalline wafer production. Of strategic importance is their access to pure silicon through their majority acquisition of Advanced Silicon Material in 2002, a company that used to deliver high purity silicon to the electronics industry. Availability of pure silicon is a major constraint to the expansion of global wafer and solar cell production. With regard to the existing market and applied knowledge ScanWafer is therefore well positioned. For the longer term the question is what type of solar cell will become dominant. Related to this is also the question regarding the nature of the applications of solar cells, and possible paths of integration of solar cells with other products.

2.2 CO_2 as a medium for heating and cooling through Shecco technology

The second CondEcol case study involves the development of heat exchangers with CO_2 as a medium. This journey started in academic circles in Norway, where a professor in refrigeration engineering invented ways to effectively use carbon dioxide as a medium, triggered by the phasing out of CFCs as cooling medium in the Montreal protocol. The research was financially supported by Norsk Hydro who were interested in an application of the technology for air-conditioning systems in cars, mobile air conditioning (MAC). The first patent was awarded in 1993 under the established trademark Shecco (Larsen and Ruud 2005a). Thus, the rising concern regarding the impact of CFC’s on the ozone layer was the first landscape development that put pressure on established practices for cooling, while later on in the development of the innovation growing concerns regarding climate change, became an important driver. However, the first market application did not occur in cars but in households. “*The first commercial breakthrough came in the year 2000. In 1990, the Denso Corporation, a leading Japanese manufacturer of air conditioning systems for cars, began work on the development of new, more energy-efficient heat pumps for tap water to the Japanese in Tokyo. The attention of the company was drawn to SINTEF's successful experiments on the use of CO_2 heat pumps. The result was the Eco Cute, a small, neat and efficient water heater and a license agreement between Hydro and Denso on heat pumps for tap water in Japanese homes was signed*” (Information at Shecco website, www.shecco.com). Market application for tap water heating has induced several learning effects, although not all are equally relevant for the application of the technology in MAC for cars, due to the specific requirements, such as small size, low weight and high resistance to vibrations (Brekke et al 2005). Such a pattern of niche cumulation is however illustrative for most radical innovations. Learning processes take place in specific market niches where the new functionalities are best exploited and/or entry barriers to the respective regimes are lower.

With regard to the MAC application in cars the journey has mainly involved positioning of the technology through the formation of alliances and networks, and through positioning the technology as a realistic option for GHG abatement and CFC and HFC phasing out, with specific focus as CO_2 technology as an alternative for HFC-134a technology in MAC. An important factor in the process was the formation of an EC-directive involving sharpened emission standards for MAC. This shows how landscape pressures are distinctly translated into different institutional structures. While the proposed EC directive implies a stepwise phasing out of HFC-134a and allows alternatives such as HFC-152a and CO_2 technology, the US MAC lobby, supported by the US EPA, do not favour regulations and staged a research project aiming at improvement of existing HFC-134a technology (which will also make a transition to HFC-152a more feasible in the future). As the global car industry strives for a one standard system, the impact of diverging paths can be enormous as is shown by the ongoing process of phasing out of CFC-12, which has already been banned for new cars. Table 2, taken from the IPCC report on safeguarding the ozone layer and the global climate system (IPPC/TEAP 2005: 58), shows how the number of cars with mobile air conditioning based on CFC-12 technology is continuously dropping, and how HFC-134a technology is rapidly expanding.

Table 2: MAC fleet evolution and refrigerant choice from 1990 to 2003 (Source: IPPC/TEAP 2005: 58)

Year	AC vehicle fleet (million)	
	CFC-12	HFC-134a
1990	212	-
1991	220	-
1992	229	0,7
1993	229	10
1994	222	27
1995	215	49
1996	206	74
1997	197	100
1998	186	128
1999	175	161
2000	163	198
2001	149	238
2002	134	285
2003	119	338

A ban on HFC-134a is proposed by the EC directive for new cars by 2017, and a ban on new car models with HFC-134a by 2011, with a phasing out process before that. This implies that the prospects for alternative concepts for mobile air conditioning, such as CO_2 based technology are promising. To reach the situation where CO_2 technology was considered as a serious option, a development period of around 15 years took place. In this period Norsk Hydro significantly invested in R&D to improve the concept, developed networks with various R&D centres and car makers, and collaborated in various research projects funded by industry and governments. The innovation process itself has been one of manoeuvring to create the right network partners and conditions, and to prevent other parties from hijacking the principles under the concept. Moreover, it has been a highly politicized process, with the regulatory focus on global warming potential of various cooling media as one of the main issues.

2.3 HydroKraft for hydrogen production and CO_2 removal from gas

The third CondEcol case study involves the development of carbon neutral gas based power plants through the separation and storage of carbon dioxide. The HydroKraft concept was based on removal of CO_2 before combustion with the injection of the CO_2 in the Grane oil field as pressure support to enable exploitation of the so-called dead oil field. The pre-combustion technology produces hydrogen as a product in addition to CO_2 that can be used either for electricity production or as a raw material for the production of for example ammonia (Larsen and Ruud 2005b). The amount of CO_2 extracted and hydrogen produced could be specified, allowing combustion in gas turbines for production of electricity. Plans for HydroKraft were announced in 1998 in anticipation of action required for the realisation of Norway’s obligations under the Kyoto-protocol. It was expected that the HydroKraft gas power plant could provide pressure support for the exploitation of the Grane oil field starting in 2003.

The project failed to materialise and was blown off after a couple of years due to economic factors, and due to the presumed technical challenges of using CO_2 for pressure support in the Grane oil field. The other partner in the oil field, Esso, did not perceive this technological option as realistic in such a huge project. Instead, exploitation of the Grane oil field was commenced with natural gas as pressure support. An additional hampering factor was the calculated price for produced electricity. This was assumed to be sold to aluminium smelters of Norsk Hydro. However, the price was expected to set significantly lower than the commercial spot electricity market price. The project could not maximize the revenues from sale of electricity from the combustion of hydrogen in gas turbines. Consequently, the expected rate of return of the HydroKraft project was significantly reduced.

The project had several features that fitted a long term strategy towards a more sustainable electricity system, such as carbon capture, hydrogen production, and a specific application for carbon dioxide as pressure support. These features, however, were not yet well articulated and integrated in terms of networks and various converging actor strategies. The vision of Norsk Hydro was thus not shared by major actors relevant for making the project a success. Norsk Hydro expected HydroKraft to be integrated within the existing regime for electricity production and strategies for CO_2 reduction. However, our assessment is that several institutional changes, mainly within broader societal structures, were lacking for the project to be successfully implemented. One was the broader acceptance of CO_2 storage as a legitimate and feasible option for the climate change problem. The second was the acceptance of gas-fired power stations as a reasonably cost-effective and clean way to produce electricity, particularly with CO_2 capture, and thus also for generating electricity for households. The third was the process of CO_2 pricing, for instance through the initiated carbon emission trading scheme in Europe. The fourth was the lack of a shared vision regarding the role hydrogen can play in the electricity system. This was further influenced by a lacking niche constituency due to limited experiences, projects and applications for hydrogen. The fifth was a political climate that was not conducive for the type of project proposed by Norsk Hydro. Part of the failure of the project can thus be attributed to unfortunate timing, and partly to the failure of positioning the project into broader processes of change. The main reasons for the dismissing of the project, however, are probably found in the junction between financial factors and technical challenges.

After this short introduction and assessment of the three innovation journeys, the following section will focus on future paths that the journeys may take. The first section focuses on the use of scenario methods for long-term technological change, and this is followed by a sketch of a strategic management tool for the further exploration of innovation journeys.

3 SCENARIO-METHODS FOR LONG-TERM TECHNOLOGICAL CHANGE AND RELEVANCE FOR STRATEGIC MANAGEMENT

This section assesses appropriate scenario methods for long-term technological change. The aim is to develop strategies to further expand the innovations in question. Here, there is a difference between a business (private) and a public orientation: the firms involved are traditionally more oriented towards the micro-level. However, efforts are increasingly undertaken towards higher levels in order to assess threats and opportunities relevant to their innovation. Through such an extended visioning, efforts may be taken to identify ways in which they can sensibly navigate between challenges at different levels. Public actors are more macro oriented and view the innovations as part of a set of promising options to realise public goals. Scenarios can then serve as a tool to gain insight into how various options may play a role in realising these public goals (while also giving insight in how these public goals may shift). For business, important functions of scenarios are to make managers aware of uncertainties, and to gain understanding regarding the way different futures might impact a firm's activities.

3.1 Main methods

The main methods currently in use for the long term exploration of more fundamental change processes can be classified and characterised as follows:

- **Forecasting** extends current trends to predict how the future will unfold and is often based on a combination of quantitative (models) and qualitative (storyline) elements (van Asselt et al 1998);
- In **foresight** current trends are assessed in order to explore how they may lead to possible futures. It is a process of gaining fuller understanding of the forces shaping the long-term future, and of threats and opportunities that may impact they way the future will unfold (van der Meulen 1999; Wehrmeyer et al 2002);
- In **backcasting**, a certain, normative, future state of sustainability is taken as point of departure, and a process of backcasting leads to several possible development paths allowing combinations of technological, social and cultural change (Green and Vergragt, 2002). Backcasting does not extrapolate current trends and developments but takes a possible future image as a starting point for analysis and subsequently reasons backwards to the present situation;
- The essential activity of the **technological roadmapping** process is the evaluation of various technological opportunities and their potential benefits and the development of a comprehensive vision and agenda for further research (EPRI 1999);
- **Breakthrough oriented methods.** These are methods specifically oriented at the breakthrough of 'radical' innovations, and the way this process can be managed (Noori et al 1999; Jolivet et al 2002). It involves a process of visioning the way a 'radical' innovation may become embedded in society, and anticipating the way the future may unfold and the actions to be taken from the innovators perspective (McDermott, C.M., G.Colarelli O'Connor 2002).

Appendix 1 presents a number of recent scenario projects that illustrates these different methods. These projects represent the state-of-the-art methods regarding long term technological change. A short characterization is provided in terms of the type of scenario, the nature of the method, and its scale and function. For each scenario project we discern the focal issue of the scenario and its time-scale (e.g. global emissions scenarios to 2100, or the Dutch energy system up to 2050).

3.2 Evaluation of different scenario methods

The purpose of our evaluation is in the first place to gain insight in the way that scenario methods explore the uptake of radical innovations and their interaction with existing sociotechnical systems, and secondly to gain insight in the way the methods can be utilised as a strategic management tool. Based on a detailed review provided elsewhere (Hofman 2004) we come to the following conclusions:

3.2.1 Forecasting methods

Forecasting methods, especially those in combination with narratives, pay some attention to the co-evolution of technology and society at an aggregate level, and allow for the uptake of radical technologies as they are assumed to follow certain learning curves. However, limited attention is given to the multi-level processes that *underly* the co-evolution of technology and society, i.e. learning processes and interaction processes at the level of actors, the way they initiate and navigate changes in institutional settings, regulatory policies, infrastructure developments, and changing user preferences. Overall, these methods therefore tend to produce scenarios that have a mostly linear character based on extrapolations of the present, while divergence in the scenarios often takes place by contrasting business as usual scenarios with those where specific policies are introduced. Dominant users are policy actors that use the scenarios to gain insight into the way public policies may affect the scenario outcomes.

3.2.2 Foresight methods

Foresight methods pay attention to potential outcomes of processes of co-evolution of technology and society and the uptake of radical technology. The likelihood of these outcomes are assessed by looking at driving forces and the way these may unfold. Techniques that are used to assess the most promising technologies involve the mapping and monitoring of technologies through bibliometrics and patent data; trend-analyses with experience curves and s-curves (for shorter term technological predictions); and judgemental methodologies such as delphi surveys and expert panels (for longer term focus on potential promising technologies). To understand the way various technologies may penetrate society, different scenarios or storylines are constructed based on two dominant driving forces in combination with opposite ways they may unfold, effectively leading to four different scenarios. While these scenarios are of a less linear nature than those produced through forecasting, limitations lie in their macro-orientation and the lack of attention given to learning processes and co-evolution that takes place through interactions at the micro and meso levels. Overall, these methods are useful in producing alternative futures that differ widely, but provide limited insight in the way these futures may unfold through interactions and learning processes at different levels and between a variety of actors. These scenarios are used by a range of actors to understand implications of various scenarios for their strategies. In the business sector Shell has played a leading role in the development and use of scenarios. Shell (1995) sees scenarios as having the following functions: (1) to help the company and its managers prepare for discontinuities and sudden change; (2) to help create a common culture, or language, through which the future can be imagined; and (3) to challenge the mental maps which are held, in order to help envision and create new possibilities.

3.2.3 Backcasting methods

Backcasting methods have a strong focus on the co-evolution of technology and society. They start from normative futures based on the premise of both technological and societal change, for example an imagined sustainable energy system fifty years from now. In the paths backcasted towards this future state, changes in actor networks, shifts such as those from a product to a service economy (implying also cultural changes) are considered necessary. Interactivity is also key to these methods, with stakeholders participating in the development of scenarios, such as to create some shared vision regarding the future. The basic idea is to link long-term goals with shorter decision-making, gaining an understanding of how current decisions make these long-term goals more or less likely. The method has been employed in several projects, such as the sustainable technology development programme in the Netherlands, mainly to guide public policy.

3.2.4 Technological roadmapping methods

Technological roadmapping methods have a strong focus on technical aspects, with less focus on how actors, their strategies and interactions may influence the rate and direction of that technological change. It can have manifold purposes, ranging from supporting strategic planning processes in firms to developing visions regarding R&D agendas for public-private R&D programs (Phaal et al 2004). Within firms it is used to integrate business and technology strategies with market opportunities often with time horizons up to 5 or 10 years, while within (semi-)public organisations it is used to develop visions on how technologies may evolve over longer periods of time. In the latter category the interaction with society tends to be limited to how a research agenda is given shape.

3.2.5 Breakthrough methods

Breakthrough methods focus on individual projects, companies and technologies and much less on the way a broader process of sociotechnical change is set into motion. This leads to a strong focus on the micro level, with a bias towards the innovators and consumers as core actors. Moreover, these methods are specifically designed to indicate actions for companies to be taken in the short-term and are less suited to explore long term processes of systems change.

Overall it can be concluded that with regard to informing business strategy on the one hand, more general foresight methods are used (i.e Shell), in order to get a general idea on how markets may evolve and what the underlying driving factors are. Technological roadmapping may serve business strategy in the sense that it provides insight in the way co-evolution may take place between markets, products and technologies. Breakthrough methods are specifically concerned with the introduction of more radical technologies and the way this can be managed. Appendix 2 introduces the most relevant methods in some more detail.

3.3 Conclusion

The overview shows that most of the scenario methods incorporates aspects that are relevant for the introduction and development of radical innovations (see also Appendix 2). This holds in particular for backcasting and breakthrough methods. However, most methods also exhibit some deficiencies when it comes to exploring how these radical innovations are part of multi-level processes of systems change, such as a lack of attention for actors, their decisions, interactions and learning processes, and the way these shape twisting transition paths. One basic deficiency is the lack of a clear conceptual framework regarding the way fundamental technological and system changes occur. In the case of projects based on forecasting, technological change is often conceptualised in a simple way, e.g. as a determining, relatively autonomous, force or through assuming aggregate learning curves. In foresight the pathways in most scenarios seem to be determined by autonomous macro factors, often with a choice for the two most pervasive factors being developed in a matrix with factors developing in two opposite ways, leading to four different scenarios. In technological roadmapping more attention is paid to the different paths that technological change may take, for example through processes of hybridisation or bifurcation, but these developments are largely detached from social developments. While both in forecasting and foresight projects there is a strong focus on drivers (economic, political, demographic, ICT developments, etc.), there is limited attention for the interaction between different levels, such as the way specific actors develop strategies to exploit these driving forces, and the way this may induce imitation by other actors and is reinforced by institutional changes that facilitate the newly emerging practices. In the case of projects based on backcasting normative future states form the starting-point for long-term change, and much less ongoing multi-level dynamics in existing sociotechnical systems. The main deficiency of breakthrough methods is its single-actor and micro-orientation.

The aim is therefore to develop a method that better captures the multi-level dynamics of technological change. This especially involves exploring how new innovations, and the networks of actors involved in them, may penetrate existing sociotechnical systems through alignment with, and reinforcement of, specific dynamics within the systems and with changes set in motion by landscape developments. The following section sketches the contours of such a method – sociotechnical scenarios – based upon the multilevel conceptual framework presented in the introduction.

4 SOCIOTECHNICAL SCENARIOS AS STRATEGIC MANAGEMENT TOOL

This section introduces a scenario method based on the sociotechnical perspective – with potential application for serving different functions for different actors: informing policy strategy, informing business strategy, exploring promising niches, and stretching mental models. Our main purpose here is to utilise the method as a strategic management tool for business. In the sociotechnical scenario method we utilise the conceptual framework presented in the introduction for the construction of scenarios by tracing several patterns and mechanisms which can be discerned in transition processes. Overall some general patterns can be pointed out.

First, transitions always involve changes at multiple levels and interaction between multiple levels. Processes of change will only acquire a transitional nature as they take direction and gain momentum through interlinkages between landscape developments, societal structures, regime changes and niche emergence. There is not one single factor causing a shift in sociotechnical systems but an interplay of a range of factors that leads actors to shift their strategies and to advance novel concepts. Moreover, these transition paths are of a non-linear nature, in the sense that there is not a straightforward solution developing to a specific problem, or a rational goal-oriented process (Geels 2005a), but that frequent changes in problem perceptions and in linkages to solutions occur. A continuous remanoeuvring and repositioning of actor groups and their strategies therefore takes place in response to changing conditions. However, there are moments when a number of conditional factors come together and create a window for more fundamental changes (a tipping point). Important in these processes of change is that they represent a change in the direction and velocity of the system, which is difficult since the system has a lot of mass, machines, infrastructures, etc. in which considerable capital has been invested (Hughes 1983). Apart from these tangible aspects the focus is on intangible aspects, such as the way established mental models or belief systems may come under scrutiny due to several interlinking factors. For example, Hofman (2005) illustrates how the combination of the oil and environmental crisis and the development of the gas turbine led certain actor groups to attack the general wisdom that central electricity generation was superior to decentralised generation.

Second, transition processes involve sequences of changes with the essence of the change being the formation of (qualitatively) new couplings that may exploit various developments at different levels, where an initial change in one dimension triggers wider change as actors react and adapt their decisions and strategies in a significant way. In his analysis of the breakthrough of rock 'n roll in the US music industry, Geels (2005b) points at the way technical changes enable certain social changes which stimulate further technical change, etc. He labels this a "sociotechnical innovation cascade". Thus, further development of a certain innovation involves not only diffusion but also qualitative changes as actor groups learn from and adapt to the emerging innovation. Another type of cascade is the way new initiatives may trigger reactions within business, civil society and so forth. One example is the introduction of green electricity in the Netherlands, which triggered a chain of reactions from competitors, policy makers, and new entrants in the electricity sectors. Another example is the introduction of the zero-emission scheme for cars that was started in California, and led to significant changes in strategies of major car producers, and to reorientation of R&D directions for public and private organisations. Currently a chain of events is unfolding in response to the climate change problem, with the Kyoto protocol entering into force, and where actions of governments and business create change processes that are playing a central role in the emergence of the CondEcol case innovations. More fundamental transformation of existing sociotechnical systems, or transitions to new systems, can occur as the sequence of change triggers a process of chain reactions where waves of change tend to spread more and more and become pervasive throughout society. An example is the introduction of the computer and microchip and the way it has transformed the processes of information provision and transport, and changed behaviour of people and businesses regarding work, trade, leisure, communication, etc. This is also affecting more traditional regimes such as electricity and transportation, for example through the emergence of a 'new economy' and 'network society' that may provide gradients for innovation processes.

Third, it is possible to identify some typical pathways that transitions follow. Geels and Schot (2005) developed a taxonomy of five transition pathways based on the analysis of various historical case-studies. Which path develops depends upon factors like the relative importance of niche developments and the relative importance and timing of landscape influences. A recent Tyndall report (Tyndall 2005) uses the different pathways for the development of scenarios towards a carbon-lean future. This is presented in Appendix 3.

Fourth, within these more general pathways, more specific patterns and mechanisms can be pointed out that frequently occur in cases where radical innovations break through. Some of these patterns are (Hofman et al 2004; Elzen and Hofman 2005):

- a process of niche accumulation enabling the breakthrough of radical innovations (such as in the case of PV which travelled through various niches (satellites, stand-alone applications, integration in roof-tops that facilitated improvement and learning processes);
- niche proliferation, i.e. the spread of niches to other domains (= other regimes) or other geographical areas (visible in the case of the Shecco CO_2 technology where its application moved to water heating);
- the so-called 'sailing ship effect' (i.e. the existing regime defends itself against radical innovations by improving performance, like sailing ships that started using more masts and sails when steamships emerged);
- the existing regime comes under pressure as the credibility of its way of provision ('dominant design') for a specific function (energy, mobility, food) in society comes increasingly under scrutiny. This creates space for niches.
- co-evolution of technology and society (sociotechnical cascades).

The patterns and mechanisms can be seen as a tool-box with basic building blocks for the construction of scenarios. It can also be utilised for the development of a strategic management tool for business to explore the way innovation journeys may unfold. One focus is on understanding how landscape factors may impact the regime through the changing interface of the four societal structures. A further focus is to identify how unfolding innovations can co-evolve (and are co-evolving) with those institutional changes. Basically we discern the following steps (Elzen and Hofman 2005):

Step 1: Design choices and contours of the scenarios. These are strongly related to the specific function of the scenario exercise and the type of user.

Step 2: Inventory of potential linkages[1] as promising transition 'seeds for change'[2]. Here the CondEcol case innovations form one set of promising transition seeds.

Step 3: Analysis of dynamics at the different levels. The necessary elements include:

- Landscape trends, key uncertainties
- Societal structures: relevant trends and uncertainties
- Regime characteristics, problems, strategies and trends
- Relevant niches: opportunities and barriers for transition

Step 4: Develop a basic scenario architecture by combining the different levels and making use of various patterns and mechanisms.

Step 5: Make the scenario.

Step 6: Reflect on the scenarios (analyze, interpret scenarios)

Step 7: Develop recommendations

These seven steps describe what we call the the 'core-methodology' of a Sociotechnical scenario (STSc). In order to actually make an STSc, more detailed design choices need to be made and these steps need to be filled in for a specific case. These choices will largely depend upon the function and specific user of the method. In the CondEcol cases the users are incumbent industry and entrepreneurs. The incumbent industry usually focuses on the current technologies and tries to improve these on the basis of various criteria. In a situation where the existing system is under pressure, because of problems and/or upcoming niches, this is not always wise. It is useful for these industries to explore possible alternative future developments to help determine their business and R&D strategies. Thus, a scenario exploration could solve the following functions for them:

- to stretch mental maps, i.e. to create awareness that seemingly small niche alternatives may become a serious option and threaten the current system in which they have vested interests;
- to identify in further detail possible future threats and opportunities under different assumptions as a basis for their strategy;
- to help define the R&D agenda.

Entrepreneurs are often initially working against the odds, facing an incumbent system that seems impossible to penetrate. A scenario exploration could help them discover how the alternative that they are working on could account for possible 'weak spots' in the current system and identify 'promising linkage opportunities' for their novelties under possible future circumstances.

[1] A linkage can be any type of 'qualitative' new relationship between different elements, e.g. a landscape pressure linking up to a niche and/or a regime technology, to a new type of user behaviour, etc.
[2] I.e. the novel (S-T) combinations that could start a small initial change of the 'course of development' of a regime but, when consistently followed through, in the long run could lead to a transition (possibly by (re-) combining with other 'seeds for change').

5 THREE INNOVATION JOURNEYS EXTENDED

This section indicates the way paths may unfold in which strategies from public actors and firms interact and start to reinforce each other in a way that the innovations can develop towards more encompassing sociotechnical systems. The paths are based on interactions between the levels of the landscape, regime and niche and take into account the way such paths relate to the earlier identified four broader societal structures. These four broader societal structures refer to the nature of knowledge generation (the knowledge infrastructure), political goals and policies within the political structure, industrial organisation and patterns of exchange between firms and sectors within the economic structure, and civil society at large. Initially, the analysis will identify how developments in the four broader societal structures may act as opportunity or threat for the unfolding path. The scenario then explores how the path may further co-evolve with changes in these societal structures, how these may further take root within existing regimes, and how some level of synchronisation may occur between the various change processes.

We follow the steps for the construction of the scenarios mentioned in the previous section. Steps one and two concern design choices and promising linkages. Design choice is related to the type of user and function of the scenarios. In our case the prospective users are firms involved in the specific innovations and actors such as policy makers with interest in the further development and diffusion of these innovations. The main function is to gain insight in opportunities for the respective innovations to align with changes in regimes and societal structures. Thus, the promising linkages are formed by the specific CondEcol cases of innovation that serve as niches that through linking up with the multiple levels may start to break through. The following section elaborates steps three and four. This involves an analysis of dynamics at the different levels, followed by sketches of scenarios for the three innovations. Developing full scenarios would take the form of a number of contrasting scenarios related to each case innovation, but that is beyond the scope of this report. Here the aim is to indicate the type of multi-level linkages that could provide opportunities for further development and diffusion of the innovations in the CondEcol cases.

5.1 Analysis of dynamics at the different levels (Step 3)

The necessary elements include:

Landscape factors & societal structures: trends, key uncertainties

The key here is to interpret landscape factors to the extent that these may change institutional frameworks in a way that actors' positions and strategies will change significantly. The institutional frameworks are the four broader structures in which sociotechnical systems are embedded, see Figure 2. In other words the focus is on how landscape factors may change the rules of the game in societal structures of relevance for particular regimes and the innovations under investigation. An example is the wave of liberalisation which has led to very different positions in terms of public and private responsibilities and rules, and induced the break up of monopolies in several systems, such as for electricity, leading to fundamental changes in actor strategies and patterns of competition. A second example is the entry into force of the Kyoto protocol and the diverse actions taken by public and private actors to reduce carbon emissions (Appendix 4).

Regime characteristics, problems, strategies and trends

The key here is to describe how actor positions and strategies are distributed along main issues/dimensions within the regime. Is there strong convergence and alignment along a dominant form of organisation and production and key technology, or is the regime characterised by more diversity? For the two major regimes being investigated here, differences can be observed. What are the major bottlenecks, critical problems for system growth (reverse salients) and to what extent are actors working to overcome them? To what extent are these critical problems shared within the regime and possibly among several regimes, and are multi-regime interactions facilitated by this? Which issues, rules (may) signify major controversies, along which dimensions is widespread divergence of actor strategies, what (multi-regime) coalitions can be pointed out, and to what extent and how are these internal (power) struggles related to outside factors and developments in other regimes?

Relevant niches: Opportunities and barriers for transition

Here the key is to describe the variety of emerging alternative technological and organisational forms, and analyse how their 'raison d'etre' is related to specific actor strategies, expectations, regime tensions and landscape factors. It is also key to examine the nature of the set of rules (and scripts) associated with the alternative and the way this relates to existing developments in regimes and the landscape, thus also presenting an overview of how the existing regime hampers niche development. Further, it is important to analyse the nature of learning processes that have taken place in the niche and still are necessary for the niche to develop in a significant way. Finally, it is needed to analyse the potential for niche cumulation patterns, the availability of protected spaces, the scope to connect to changing user patterns and growth markets, and the possibility of developing hybrid forms within the regime and/or with other niches.

We first give an indication for the type of factors relevant for the three innovation journeys that are under investigation:

5.1.1 Landscape factors and societal structures

One important landscape factor is the Kyoto protocol, the way it is implemented internationally and nationally and is affecting strategies and positions of actors. This factor is already impacting societal structures and institutional frameworks, and sociotechnical systems to a large extent, and plays a role in the emergence of all the innovations under investigation. A second factor is how extreme climate changes and events are going to affect the public, political opinions and decision-making in public and private sectors. A third factor is the role of the EU in establishing level playing fields, securing long term electricity supply, reducing dependence on fuels from outside the EU, increasing the share of renewables and biofuels. A fourth landscape factor with significant impact is the further development of the network and information society, where transactions and communication increasingly takes place through digital means, and changes in lifestyles occur. A fifth is the further economic expansion of China and Asia, and the way it impacts the economic and political global balance and markets and transactions across the globe. A sixth landscape factor is the way fossil fuel prices and markets will evolve. Will oil prices continue to skyrocket, and will this be followed by gas price hikes as scarcity of gas starts to increase? A seventh landscape factor is the extent and nature of security threats, such as the terrorist attacks witnessed over the past years. This triggers an increasing focus on the resilience of technological systems to such threats. Appendix 4 indicates the level of uncertainty of the different factors and the way they may impact broader societal structures.

5.1.2 Regime developments

The dynamic of the transport regime can be characterised by a number of major trends that have developed over the past decade and that are likely to continue into the near future. These include (some adapted from Elzen, Geels and Hofman 2004):

- A ban on HFC-134a is proposed by the EC directive for new cars by 2017, and a ban on new car models with HFC-134a by 2011, with a process of phasing out before that. This implies that the prospects for alternative concepts for mobile air conditioning are explored and developed, such as technologies based on CO_2 or HFC-152a.
- Automakers make growing investments in development and marketing of hybrid cars; some automakers already offer them and more are likely to follow in the coming years. These vehicles are more expensive than conventional vehicles but customers may be attracted by their fuel efficiency, lowering life-cycle costs. Public authorities may stimulate their sales by tax incentives and public procurement. Thus, R&D for redesigning cars is triggered, including R&D on alternative MAC in combination with the increasing stringency of MAC emission standards.
- All automakers make growing investments in the development of fuel cell vehicles; the main application domain in the near future is likely to be buses although some automakers are also working on fuel cell cars. Because of their high cost, market development for such vehicles may be largely dependent upon government support.
- There is an increasing attention for gaseous fuels (LPG, natural gas) among public authorities as well as in a variety of vehicle fleets with a certain inclination towards 'environmentally friendliness'; it is largely up to public authorities to stimulate their wider use.
- Local authorities increasingly attempt to create pedestrian zones, limited access zones, low-emissions zones, etc. Various forms of road-pricing will be implemented and become more common. These developments also lead to differentiated pricing and taxing of cars based on their emission profile, while zero-emission standards in specific areas for cars may be introduced.

Although it is uncertain how the design of electricity generation and use will develop and which energy technology will become dominant, it is possible to discern a number of regime trends that impact these developments. These trends are the following:

- There is increasing heterogeneity of actors involved in electricity supply and interactions of actors with different backgrounds. This is related to changes in market structures, e.g. new exchanges and the emergence of trading companies; in regulation due to the removal of entrance barriers; and to converging strategies of actors from different regimes, e.g. waste regime and its focus on closing material cycles and reduction of waste landfill and the use of the energy contents of (organic) waste for electricity generation.
- There is a trend towards more segmentation of electricity based on economic aspects, market aspects, and societal aspects, and this creates opportunities for niches. Economic aspects relate to price differentiation for electricity in periods of peak demand, and off-peak demand, and different contracts are being settled between producers and customers. Market aspects relate to specific requirements of electricity users, such as a level of reliability that is higher than average. Societal aspects relate to the differentiation of electricity to energy source or production location, such as the demand for green electricity, or domestic green electricity, or

electricity not produced by nuclear power.

- A trend is seen where new services related to energy are emerging. Actors are mediating for collective purchase of electricity for a variety of consumers. The provision of electricity is increasingly promoted under one administrative umbrella together with water and telecommunications. Smart metering systems and software to reduce energy use and costs are also provided. The importance of marketing of electricity is becoming more and more important as electricity is changing from an invisible public good that is provided at the socket in your home to a visible marketable product.
- There is an increasing internationalisation of energy flows, networks and markets. In Europe the free electricity market induces international exchange of electricity, while adequate transborder transmission capacity is seen as one way to increase the security of electricity supply. Gas networks are expanding and LNG production and transport is a growth market.
- Increasingly gas is becoming a global source for electricity generation. The combined cycle gas turbine has become the most efficient means of electricity generation, while also being flexible in terms of scale. In Europe and the US major investments in new power plants were planned in the first decade of the century to satisfy demand and to replace obsolete power plants. The majority of these investments were expected to be in gas-fired power plants (combined cycles and gas turbines) because of their flexibility and relative low capital costs (to coal-fired and nuclear power plants). The integration of these power plants in a path towards a more sustainable electricity system is facilitated by the application of carbon capture and storage (CCS) and the production of hydrogen for a range of unfolding applications. Related to this, an emerging trend towards gasification of coal and biomass is becoming visible.

5.1.3 Niches and alternative constituencies

An increasing variety of technological and market niches for electricity and transport are based on several of the aforementioned trends. A patchwork of niches is in development in order to exploit the opportunities of the enlisted regime and landscape changes. Some niches are shared by both transport and electricity, such as fuel cell development for stationary and mobile power, and biomass for biofuels and power stations. Other technological niches in electricity generation involve micro turbines, hybrid micro turbines/fuel cells, tidal/wave technologies, biomass conversion technologies, PV technologies, wind turbine types, etc. Market niches involve the demand for higher quality electricity in the new economy, the ability to control power systems on-line and leads to local systems that combine a variety of emerging technologies. The pressure for carbon reduction enables further application of renewable energy technologies, with pro-active local communities and municipalities combining renewable energy and combating climate change in their sustainable development strategies. Various interactions between niches and between niches and regimes start to emerge, and are likely to become crucial for their survival. Biomass and biofuels develop a symbiotic relation with the regime. Biomass is initially co-combusted in coal-fired power stations, but a new generation of integrated gasification combined cycles opens up opportunities of combined gasification of coal and biomass. Carbon capture and storage enters the portfolio of options in the regime as carbon pressures and costs increase and open up an avenue for regime actors to position themselves as being part of a transition to a sustainable electricity system.

In the transport sector there is a lot of R&D in hybrid vehicles, with the first cars already running commercially (e.g. Toyota Prius). There is also extended use of biofuels. Niche-developments also involve the re-design of cars in order to facilitate the requirements of changing engines, fuel tanks, etc. Cars based on fuel cell drives demand fundamental new designs, and also open up opportunities for cars being mobile power stations. The development of new air conditioning systems is taken aboard in these processes of redesign and fundamental new designs. The broader cooling and heating field also feels the pressure of reducing the global warming potential (GWP) of the substances they use, triggering broader experiments with cooling and heating technologies with low GWP, among them CO_2 technologies.

5.2 Develop a basic scenario architecture by combining the different levels and making use of various patterns and mechanisms (Step 4)

Based on these dynamics and trends at different levels it is possible to sketch scenarios based on the interplay of these levels, and to indicate the position of the CondEcol innovations within these processes. This is subsequently done for the three innovations although the scope of the report only allows for sketching some initial linkages.

5.2.1 Solar energy and ScanWafer

If we look at the interaction of landscape developments and the regime (the incumbent electricity sector), PV has been able to develop into a niche within the electricity regime because it exploits environmental pressures and dependence on fossil fuels. Crucial for the steady expansion of PV have been processes of niche cumulation (the formation of successive market applications in which the technology further matures, from power source in satellites, to stand-alone applications, to the current application in rooftops) and a continuous path of improvement of the efficiency and reduction of costs as installed capacity increases, the so-called learning or experience curve. Based on this learning curve expectations are developing that take this learning curve more or less as given, and through extrapolation assume that an ongoing process of improvement will enable cost competition of PV with other energy technologies in two to three decades (see for example Sinke 2005 and EC 2005). However, realising this continuous improvement will depend on ongoing changes in concepts, production costs and balance of system costs. Thus both a technological cycle of efficiency increases and cost reduction takes place through ongoing R&D and this is fuelled by increasing demand and further market applications.

In this process the expectation is that multicrystalline technology will improve but will not be able to realise the levels of cost reduction that are envisioned for thin-film technology in the longer term. The cycle of expectations, requirements and results is important because it determines the direction of R&D and needs to be continuously maintained and reproduced. Indications for a change of the direction in the technological cycle towards thin-film technology is also provided by changing strategies of market actors, such as Shell that has recently divested its crystalline silicon solar business activities and reinforced its focus on thin-film technologies (Clean Edge News, 2006). A sustained technological cycle of improvement in combination with a sustained market cycle of increased demand can only emerge if these are firmly embedded in broader societal structures.

The case of Japan is illustrative. Here an alternative institutional logic is emerging that aligns activities of a range of actor groups. For political actors PV expansion is seen as a way to combine goals of climate policy with energy security and industrial policy. The reduction of carbon emissions is combined with the strategically crucial reduction of dependency on fossil fuels, but PV is also developed as a strategic growth market for companies rooted in the electronics sector. For business it is a way to capture a large share of an emerging global market, while utilising experience with electronics. Furthermore, the growth of the PV industry has created thousands of new jobs (Algoso et al 2005). The knowledge infrastructure has directed its R&D towards solving the problems faced to further improve PV and its integration, backed by focussed funding from government and industry. Residents from Japan have become increasingly engaged in rooftop programs and buy prefabricated houses with integrated PV systems as market incentives are given to reduce investment costs and through cheap loans, while regulations have been mended to allow for net metering, where home owners can sell excess electricity at the same price as the utility sells it (Algoso et al 2005). Pre-fabricated zero-electricity homes have emerged where owners have a zero electricity bill as they offer power to the grid at daytime, and buy back electricity at night for a third of the price (Algoso et al 2005: 18). Most importantly, the combination of these cycles and actor involvements have brought down the cost of PV and its integration significantly, also leading to a decrease in average government contribution from US $ 12 per watt in 1994 to 0.85 US $ per watt in 2003 (Algoso et al 2005: 19). A significant share of this cost reduction involves so-called balance-of-system costs, which are region-specific and thus not similarly applicable to other countries. The expectation is that further cost reduction will lead to a price of PV power equal to residential power prices in 2010, equal to business (office) power in 2020, and equal to industrial user prices in 2030. Here there are indications for pathways based on technological substitution and de-alignment and re-alignment. What is particularly relevant in terms of explanation and success factors seems to be the relative lack of power of the incumbent electricity industry versus that of the electronics conglomerates in Japan. This may be one aspect hampering the proliferation of this success story to other countries. Nevertheless, niche proliferation and imitation of this success story is very likely to follow, such as the report on the Californian solar strategy already suggests (Algoso et al 2005). Niche cumulation is also a process likely to continue, for example through the further development of prefabricated products with PV, such as in the case of Japanese homes.

Global demand for PV is dependent on more countries than Japan and Germany, but the two are the current dominating markets and serve as good illustrations for the purpose of this report. In both countries expectations regarding solar energy are high but based on rather different actor groups and underlying assumptions. In Japan there is a strong focus on reducing dependency on fossil fuel imports, and this runs parallel with a strong industrial policy for solar energy as it extends capabilities of already globally strong positioned electronics firms. In Germany, the discussion regarding renewable energy promotion is strongly politicised, implying that withdrawal of the Green party from government might reduce the basis for the high feed-in tariffs for solar energy. The stimulation of solar energy takes place mainly because of its lower carbon emissions. In other countries this discussion has led to much less emphasis on the solar route, as other options are considered to be more cost-effective. The Japanese success of integrating the solar route into an industrial (and employment) policy could be imitated by other countries and lead to increased backing of the solar route. Moreover, societal discussion regarding the most desired routes will broaden the discussion not only to cost-effectiveness – which would benefit carbon capture and storage and biomass as most promising options – but also on aspects of safety, health, land-use, aesthetics and pollution. In these discussions solar power is likely to emerge as one of the preferred routes as it scores relatively well on most of these aspects.

Next to the competition of PV with other niches, processes of niche-hybridisation are also likely to impact the further potential of solar power. Circumventing the problem of its intermittency will remain one of the core issues for solar power, and the development of energy systems based on various energy technologies and sources is one direction for reducing this problem. In the longer term, the linking of solar power to hydrogen may be a potential path. Competition of PV with other niches is one of three levels of competition that is occurring. The first one is competition with fossil-based electricity generation; the second one involves competition between different types of renewable energy, and the third one involves competition between different types of solar cells. How will this play out in the process of changes in politics (new agreements for carbon reduction, long-term strategies) and society (connecting PV to further digitalization, new gadgets etc.)? Increasing competition with fossil-based electricity may take place to further institutional adaptations that facilitate the integration of solar energy, ranging from fine-tuning its role in the power mix, to integration of panels in roof modules, to changing assessments of economic costs and benefits of solar energy. In terms of competition between different types of solar cells the general expectation is that the dominancy of multicrystalline cells will decrease in the medium to long term. It is likely that specific applications will emerge related to different types of solar cells, such as low cost production of thin-film based solar cells integrated in noise barriers that separate highways for neighbourhoods to give an example of a potential application. Another route for advancement is the integration of specific solar cells within other products such as textile fabrics, clothes, sun-glasses, etc. Some of these developments are also related to landscape trends involving changing lifestyles in interaction with further digitalization within society.

5.2.2 CO_2 as a medium for heating and cooling through Shecco technology

The emergence of the niche for the application of the Shecco technology is strongly related to landscape and political factors of international awareness and action regarding the ozone layer and climate change. The conclusion of the Montreal protocol led to the replacement of CFC-12 by HFC-134a as cooling medium in MACs and required significant changes and investments by existing regime actors, notable car and accessory producers. The prospect of even more radical change through the replacement of HFC-134a by CO_2 technology has been strongly opposed by car makers, especially in the US where improving the performance of HFC-134a MAC systems is seen as the most feasible route also in the light of the perceived uncertainties and higher costs for other options. Thus the US domestic economic structures with a powerful position of car makers and its interaction with political decision-making leads to a focus on optimising the existing system, whereas in the EU more distributed interests seem to play a role.

The experiences with CO_2 technology in other applications, which led to improvement of the technology and better understanding regarding some of the critical issues, have increased the legitimacy of the new technology. Especially the required higher pressures are considered an additional risk for which a build up of experiences with the new technology is necessary to gain credibility regarding its ability to reach safety standards. Also costs for the new system are higher, although the introduction and expansion of carbon emission trading will lower the cost gap with the existing technology. The development of other applications of the technology is one road towards further development based on niche accumulation. Already a pattern of niche cumulation is visible in the case of Shecco technology.

The technology was at the outset planned to be used in mobile air-conditioning systems for cars, but the first niches in the market involved the application of the technology for tap water heating through CO_2-based heat pumps in Japan as an alternative to electric hot water heaters. The further pressure to reduce carbon emissions through the Kyoto-protocol might become an additional factor supporting the process of niche cumulation. Potential niches are further applications in heating and cooling systems in households, and application in military vehicles. The broader cooling and heating field is also under pressure to reduce the global warming potential (GWP) of the substances they use, triggering broader experiments with cooling and heating technologies with low GWP, among them CO_2 technologies. Another road is the integration of the new technology in new car concepts (linkage of separate niches), such as hybrid or fuel cell cars, which holds promise because CO_2 technology enables both cooling and heating in cars, especially relevant for the new concepts where creating heating capacity is considered a bottleneck. Inclusion of CO_2 technology may strengthen the claim of the development of truly zero-emission cars based on hydrogen and fuel cells (initially not taking into account the entire hydrogen life cycle).

Development of taxes, incentives, and standards within domestic institutional frameworks may provide impetus for the development and marketing of these types of cars. Specific niches may emerge in certain cities or neighbourhoods where only zero-emission cars are allowed. The further evolution of the EC directive and the response from various car makers is important. Also ongoing experiments play a role in establishing the potential of CO_2 technology. As new car models are likely to be prohibited to use HFC-134a by 2011, with a process of phase out before that, the development of cars already includes rethinking of the concept of mobile air conditioning. Several companies are promoting cooling (and heating) based on CO_2 and finished MAC products are already emerging. This indicates that CO_2-technology may witness increased attention in the short term. Furthermore, redesign and fundamental new design of cars as hybrid and fuel cell cars advance and open up opportunities to integrate new cooling and heating technologies within the new designs.

5.2.3 HydroKraft for hydrogen production and CO_2 removal from natural gas

Whereas the HydroKraft project was considered unfeasible in 1998, there are a number of developments that make the implementation of similar types of projects very likely in the near future. A strong influence takes place through the entry into force of the Kyoto protocol and its translation into domestic institutional frameworks. Increasing internalisation of carbon costs through for example emission trading schemes is visible. In many European countries the nearing of the 2008-2012 Kyoto targets in combination with the difficulty and costliness of realising reductions through improving energy efficiency and expanding renewable energy leads to an increased focus on carbon capture and storage (CCS) as an option for the short to medium term. This is evident also in the number of R&D and demonstration projects for CCS which are now significantly increasing. In Europe for example, EU funding for CCS has been significant in the sixth framework programme (around 70 million Euros in 2002-2006) and CCS is identified as an energy priority area in the seventh framework programme (2007-2013). Energy firms increasingly announce plans to (explore and) develop power stations based on coal or gas with CCS, also because increasingly existing power plants within the electricity regime near the end of their lifetime and need to be replaced in the coming decades. This also results in increasing discussion related to various aspects of the path, such as safety, risks, and relationship to other options. While the case suggests that the focus of Norsk Hydro has been foremost on technical and economic factors, long-term success of the innovation seems to depend significantly on political and societal processes. Some of the relevant aspects that need to be taken into account are:

- *The policy and regulatory framework for carbon emission reduction:*

  The economics of CCS are at the moment not yet favourable, application of CCS involves a reduction of the electric efficiency of thermal power plants of five to ten per cent to realise capture (IPCC 2005: 118) and involves costs of transport and storage. IPPC estimates costs per tonne avoided CO_2 in the range of 38 to 91 US$ for natural gas combined cycles, 30 to 71 US$ for pulverized coal power plants, and 14 to 53 US $ per tonne avoided CO_2 for integrated coal gasification combined cycle power plants. If storage also involved enhanced oil recovery costs drop with an estimated 20 US $ per tonne (IPPC 2005: 347). Especially the way in which avoided carbon emissions through CCS may become eligible under the carbon emission trading scheme and the way the price of avoided carbon emissions evolves under the scheme will have significant impacts on market actors' choices for CCS. The build up of such a regulatory scheme and the emergence of prices for avoided carbon emissions towards 50 Euro/ton can act as strong drivers for CCS deployment. However, in the coming five to ten years policy and R&D programmes and accompanying project subsidies are likely to remain the main incentives for CCS projects.

- *The legal framework for carbon storage:*

  Many legal implications of carbon storage are in many areas yet unresolved. This involves the status of carbon storage in international treaties such as the UN convention on the Law of the Sea, the London Convention and the 1996 Protocol regarding control of input of substances in the Sea and the OSPAR convention regarding the marine environment in the Northeast Atlantic (ECN 2006). Other issues involve the liability of leakage of CCS from reservoirs to neighbouring areas or the surface. Increasing clarity of the legal aspects of these issues is one of the processes that can contribute to the further deployment of CCS, but continued indefiniteness of some of these issues may hamper further deployment.

- *Public acceptance of CCS:*

  Whereas currently public awareness of CCS is rather low, and the public view seems to be relatively indifferent towards CCS, further deployment of CCS may however meet increasing opposition, especially if particular example projects are not well managed. Important stakeholders, such as environmental NGO's, are currently in the process of developing positions towards CCS. If CCS affects investments in renewable energy negatively and is developed by market actors as a long-term solution to the climate problem and not positioned as a bridging option towards a more sustainable energy system, they are likely to organise resistance against CCS. On the other hand, others take the view that CCS might be utilised if it prevents the return of nuclear energy to the political and market agendas. Of crucial importance therefore seems to be the way the story of CCS will unfold in long term visions for the energy system.

- *The role of CCS in fast-growing coal-dependent countries such as China:*

  The continuously high economic growth figures in China, involving higher industrial output and rising welfare levels trigger a need for new power plants as electricity demand soars. Much of this demand is likely to be met by coal-based power plants. Moreover, car use is also likely to rise steeply in the coming decades. If not accompanied by carbon reduction measures this would imply that China will overtake the USA rapidly as largest emitter of carbon emissions. In order to control carbon emission growth and to enable economic growth, CCS is likely to emerge as a significant option. The transfer of CCS technology to China, and funding of CCS in China through and outside Kyoto mechanisms are also important future issues for negotiation. China's position towards reducing carbon emissions under the Kyoto protocol is likely to be influenced by these issues. Collaboration between the EU and China on CCS has already been formalised, and further initiation of demonstration projects in China is likely. China has also entered the carbon sequestration leadership forum, where major countries seek ways to develop cost-effective CCS, and has initiated some projects on CCS through enhanced oil recovery.

If we take a look at the different pathways for change (see table Appendix 3), the transformation and reconfiguration pathways seem to be the most illustrative for this route. In the transformation route regime actors adjust their actions due to landscape pressure without changing the fundamentals of the system. If one accepts that the pressure related to the climate change problem is currently still low, and will increase significantly in the coming decades, CCS can be expected as the technological option that is favoured by energy companies now involved in gas- and coal-based power generation. If governments maintain their focus on short-term cost-effective carbon reduction mainly through optimisation of existing systems, it is likely that CCS will be featured as the dominant route in order to reach the short term targets for the compliance with the Kyoto targets. Plans announced by a number of energy companies and governments seem already indicative for this (among them the Netherlands and Norway).

Resistance to full enveloping of this option may occur as the societal and political discussion regarding the various routes broadens to safety aspects, sustainability aspects, and the way short-term options may jostle longer term fundamental changes. Here, one might also discern a focus on reconfiguration, with CCS as a temporary option paving the way for hydrogen applications and long-term hydrogen production based on renewable sources. The level of dedication to and acceptance of CCS is therefore also interdependent with the evolution of a hydrogen economy. If CCS is successfully positioned as a bridging option in the development of the hydrogen economy, and if the vision of a hydrogen economy is able to fulfil its promise, CCS could be able to co-evolve with such a development to a hydrogen economy. Articulation of the promise of CCS as secure option to reduce carbon emissions in the short to medium term in combination with a hydrogen vision for the longer term can be seen as a short-term strategy and route to gain political and societal support for CCS and related projects such as HydroKraft.

6 CONCLUSION

This report has focused on three innovative energy technologies in development by Norwegian firms in relation to broader sociotechnical systems which they aim to penetrate. The current report is part of a larger project, the CondEcol Project, which explores the introduction of radical new energy technologies. Based on a specific mapping of innovation journeys as cases of innovation in specific firms, the goal of the project is to understand the factors and actors influencing the innovation process; as well as to develop management/governance tools for better long-term planning of the introduction and success of radical new energy technologies. The focus of the current report is to assess the three CondEcol innovations from a multi-level perspective, and to elaborate on the way these multi-level processes may interact with the innovations in the future. An assessment of existing scenario methods shows that most methods have either a macro or a micro bias. An alternative method is sketched that identifies typical patterns and mechanisms within processes of *breakthrough of innovations* and *transformation of sociotechnical systems*, based upon interactions between the macro-, meso-, and micro-levels. These are then used to outline and assess potential routes the specific innovations might take.

With regard to PV development it is expected that the cycle of technological improvement, expectations, and market expansion can be sustained through the further adoption and development of next-generation technologies such as “thin-film” techniques. In the short-term, multi-crystalline technology-based panels can ride the wave of market expansion. In the longer term, however, further market expansion will depend upon the elaboration of support schemes and continued learning with respect to ways to reduce the costs of the production and installation of PV technologies. If the promise of PV initially becoming competitive in the household market is realised, support schemes are likely to be expanded on the basis of further expectations of improvement.

The development of the Shecco technology has been characterised as a process of “niche cumulation”, where different market niches support the ongoing development of the technology. Dominant factors that influence the potential of the technology to penetrate the transport regime are, on the one hand, political, and involve the implementation of the EC directive. On the other hand, there are the crucial factors of market-resistance and technological change which depend upon the potential of the technology to develop in synergy with newly emerging car designs and engine technologies based on electric and fuel-cell propulsion.

The further development of HydroKraft is likely to be dependent upon the way political and societal opinions regarding carbon capture and storage develops. The development of incentives for carbon capture and storage (CCS) through a supportive policy and regulative framework is considered crucial. If CCS is furthermore successfully positioned as a possible “bridge” in the development of the hydrogen economy – and the vision of a hydrogen economy maintains a high degree of plausibility and support – CCS could be able to co-evolve as an integral part of the hydrogen economy. Articulation of the promise of CCS as a viable and secure option to reduce carbon emissions in the short-to-medium term in combination with a hydrogen vision for the longer term, can be seen as a possible initial strategy and path for the realization of political and societal support for CCS and related projects such as HydroKraft.

In an overall theoretical context, a principal conclusion can be drawn to the effect that it is the interaction of “landscape” developments and changes in societal structures that provide the basic gradients for change and integration of the specific innovations. Those actors and businesses able to identify the crucial variables of these external conditioning dimensions, and to align their strategies and products in positive synergy with these broader change processes, are more likely to succeed with market penetration in the long term. The sociotechnical scenario tool is specifically developed to provide more systematic guidance as to the directionality and potential of these alignments as a key ploy of the strategic management of innovative firms.

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8 APPENDICES

8.1 Appendix 1: Overview of selected scenario projects and methods

Scenario project and short description	Method	Scale and function
Forecasting		
1. IPPC (2001): Greenhouse gas emission scenarios up to 2100	Combination of four basic narratives ('storylines') and more detailed modelling and quantification (forecasting) where a wide range of scenarios are developed	Global scenarios to inform about potential emission paths, impacts, and mitigation potential
2. CPB (1997): Scenarios up to 2020 for economic aspects and sustainable development in the Netherlands	Forecasting mainly through modelling and trend extrapolation; regional economic development, energy and environment impact, spatial developments, and mobility patterns assessed based on three baseline scenarios	Dutch scenarios to inform about policy options to reduce the tension between growth of the economy, energy and mobility versus environment and space
3.RIVM (2000): Environmental Outlook 5 for the Netherlands, 2000-2030	Forecasting and modelling of the development of the quality of the Dutch environment in the coming 30 years	National scenarios to support Dutch environmental and energy policies
4. Visions (ICIS, 2001): Scenarios for the future of Europe, up to 2050, to raise awareness for sustainable development paths	Forecasting and descriptive approach with scenarios adressing multiple time and spatial scales. Storylines developed with qualitative information and underpinned with quantitative information at both regional and European scales.	Scenario development through stakeholder based workshops, integrated assessment through an inter-disciplinary and participatory process
5. IWG (2000): Scenarios for a clean energy future for the USA, outlook to 2020 and 2050	Through forecasting in combination with expert judgment three scenarios are developed based on different intensities of public policies. Quantitative focus for impacts until 2020, broader qualitative focus on technological breakthroughs to 2050.	Scenarios to inform policy makers about the potential effects of different policy approaches.
6. EC (2003) World Energy, Technology and Climate Policy Outlook to 2030 (WETO)	Combination of a model based business as usual description of the future world energy system, with scenarios where different clusters of technologies break through, and where carbon policies are implemented.	Global reference scenario serves as a benchmark for assessing alternative resources, technologies and policies.
Foresight		
7. Shell (2001): Scenarios of societal change and impact on business and energy development (2020 and 2050)	Descriptive scenarios complemented by quantification of some main factors (demographics, incomes, energy demand, fuel and technology mix)	Global scenarios with focus on energy development of an exploratory nature to support Shell's strategic decision making
8. EZ (2000): Energy and Dutch Society in 2050	Four future worlds are constructed based on two dimensions with two diverging outcomes: economic development (sustainable growth versus profits for now) and cooperation (open economy with global institutions vs protectionism) and matched with appropriate energy options	Scenarios to support a long-term energy policy strategy
9. FutMan (Geyer et al. 2003): The Future of Manufacturing in Europe, 2015-2020, The challenge for sustainability	Expert identification of key drivers for the future of manufacturing, expert assessment of key uncertainties, four framework scenarios developed, future technology needs and policy implications discussed	Interactive, expert based scenarios with a focus on policy implications
Scenario project and short description	**Method**	**Scale and function**

10. ECN (2000): Potential futures for 2050 and assessment of the role of actor strategies and expectations in realising them	Three carbon lean future states (blueprints) of the electricity system are assessed on technological options, economic expectations and societial acceptance	Expert based construction of three blueprints based on available technological options and interaction with stakeholders in assessing their legitimacy
11. STT (1999): Development of visions regarding a new electricity system in 2020	Expert-based description of potential developments in the electricity system with a strong focus on the technical potential of new energy and transmission technologies.	Scenario for the development of the Dutch electricity system and its connection to a European and global grid
Backcasting		
12. Dutch Sustainable Technology Development (STD) program (Weaver et al, 2000): illustration of the potential of sustainable technologies in the long-term (30 to 50 years)	Future visions are developed based on the need to achieve a factor 10 to 50 reduction in the claim on eco-capacity. After a future vision is developed, backcasting is used to describe a pathway linking this vision back to the present day, thus aiming to define actions in the near term to realize this vision.	Public support for long-term innovation by development of sustainable visions for specific needs and by case studies and illustrations
13. COOL: Future state of energy system, 2050 (Faaij et al, 1999; Hisschemoller and Mol 2001; Tuinstra et.al. 2002)	Participatory integrated assessment through interactive backcasting based on national 'normative' future state with 80% reduction of CO_2 in 2050, dialogue with stakeholders at national, European and global level.	Exploration of potential paths to future state and main barriers through stakeholder sessions.
14. SusHouse (Vergragt, 2000): Scenarios for sustainable household functions (food, shelter, clothing) by 2050	Creativity workshop with stakeholders to produce ideas on how to bring about factor 20 sustainability improvement followed by construction of design oriented sociotechnical scenarios; and by an environmental, economic and consumer acceptability assessment	National scenarios for specific functions
Technological roadmapping		
15. EPRI (1999): Electricity technology roadmap to 2025-2050	The development of a vision for opportunities for electricity related innovation in the US to benefit society and business with participation of over 150 electricity stakeholder organsiations	Develops a vision for electricity as a clean, flexible and potentially growth enabling technology and develops a R&D agenda to realise this
16. Kema (2002): Electricity technology roadmap for the Netherlands to 2050	In a process with 100 representatives from different organisations (mainly technically oriented) a vision is developed regarding the long term technical change patterns in the electricity system	Focus on different technological options, the role of infrastructure, and various barriers for a cleaner electricity system, articulation of R&D agenda
Breakthrough methods		
17. Noori et al (1999): Method for assessing breakthrough potential of new product or service, application for electric vehicle	An umbrella approach that assesses future goals, needs, desires, and product development direction, and works backward to the present to determine what steps must be completed to reach that state	Combination of forecast of quantifiable variables with qualitative analysis of uncertainties through scenario creation and investigation.
18. Socrobust (Jolivet et al, 2002): Management of breakthrough innovations to become embedded in society	Develops a methodology for bringing breakthrough innovations to the market based on scripts of the future inherent in envisaged products or technologies and the assessment of their societal robustness	The methodology is developed as a project management tool for either business, government or other organisations; i.e. decision supportive

8.2 Appendix 2: Scenario methods to inform business strategy

8.2.1 Shell: Energy Needs, Choices and Possibilities, Scenarios to 2050 (Shell, 2001); People and Connection, Scenarios to 2020 (Shell, 2002); Scenario's: An Explorer's Guide (Shell, 2003).

Shell has a long tradition in the construction of global scenarios to be better prepared for the future, starting from its pioneering efforts in the 1970s (Van der Heyden, 1996). While these scenarios were previously concentrated on issues such as oil price, the environment, and political and financial trends, the more recent scenarios have a stronger focus on external developments that have a direct bearing on strategic questions facing multinational corporations, such as issues regarding the function of corporations, the nature of reputation, organizational learning, leadership and core purpose (Shell 1998). Therefore recent scenario exercises look at main forces of societal change, and interpret how these may affect business strategy and future energy needs. Shell's approach is to develop scenarios that are plausible and challenging stories, not forecasts. For Shell, the major functions of scenarios are (1) to help the company prepare for discontinuities and sudden change; (2) to help create a common culture, or language, through which the future can be imagined; and (3) to challenge the mental maps which are held, in order to help envision and create new possibilities (Shell, 1995). More recently Shell (2003) stated that the main functions is; the confrontation of assumptions by making mental maps more explicit, recognising degrees of uncertainty and mapping these uncertainties, widening perspectives through collaboration and conversation, knowledge diversity, and reframing questions, and addressing dilemmas and conflicts.

Nature of the method

In 2001 and 2002 Shell presented its latest version of scenarios, with two global scenarios (to 2020) that focus on societal changes that change the business context (Shell, 2002) and two energy scenarios (to 2050) that focus on the way the energy system may develop (Shell, 2001). The projects combine driving forces shaping the socio-economic context with central forces that shape the evolution of the energy system. These central forces are based on expert opinions, the scenarios focus on a global scale and involve qualitative stories complemented by quantified elements (eg population growth, economic/income growth, energy demand, fuel mix development etc.), with a strong focus on landscape factors (cultural, institutional) and driving forces. For example, the global scenarios focus on the way globalization is shaped by people with diverse motivations, power, and cultural values. They especially explore "the interplay of the different and developing ways people connect with each other – in 'geographies of connection" (Shell, 2002: foreword).

Some elements of co-evolution of technology and society are integrated into the scenarios. Shell scenarios for example take into account two clear trends in consumer preferences: "an increasing stress on cleanliness, for environmental and health reasons, and the growing value placed on flexibility, saving time and avoiding disruptions" (Shell, 2001: 16). This gives rise to an increasing interest in different types of energy technologies, not only based on their cost-performance characteristics, but also because of some other qualities these technologies possess. Another interesting feature of the Shell scenarios is the focus on fundamental drivers for discontinuity in energy patterns, such as energy resource scarcity, new technology (with solar photovoltaics and hydrogen fuel cells seen as two potentially disruptive technologies), and social and personal priorities. The Shell scenarios thus

acknowledge the importance of fundamental changes that may come about, which is different from scenarios that extend existing trends.
The Shell scenarios also take into account radical technologies such as fuel cells and photovoltaics. In the scenario 'Spirit of the coming age' Shell describes how the fuel cell breaks through as it first is used in some small scale applications 'at the fringes', such as for fuel cell powered bicycles, computers and cell phones (Watch the fringes is therefore one of the notions Shell introduces in its scenario work) (Shell 2001: 46-48). Moreover it describes the emergence of a new way of distribution for the fuel, through fuel boxes that can be distributed like soft drinks and can be bought by consumers anywhere and at anytime. It is less clear how this process unfolds through sequences of changes in society, businesses and technology.

8.2.2 Developing the right breakthrough product/service: an umbrella methodology (Noori et al. 1999)

This project focuses on finding out what kind of breakthrough products or services are likely to survive in the market place. The project develops a methodology to assess the way the market may unfold in the future, and what potential products or services that are radically different from the existing range of products and services have to serve the needs of future customers. Its main rational is that existing marketing techniques focus on the existing market and do not take into account possible changes that may occur in user preferences, either due to changing trends within society, or due to a process of learning as early customers gain experience with the product. The project uses the case of the electric vehicle as an example of a breakthrough product.

8.2.3 Technology roadmapping (based on Phaal et al. 2004; Strauss and Radnor 2004)

Technology roadmapping is a flexible technique that is widely used within industry to support strategic and long-range planning. The approach provides a method for exploring and communicating the relationships between evolving and developing markets, products and technologies over time. It is proposed that the roadmapping technique can help companies survive by providing a focus for scanning changes external to the company and a means of tracking the performance of individual, including potentially disruptive, technologies. "Typically based on strategic plan requirements, roadmaps incorporate product attributes and lay out steps over time to achieve defined goals, related development requirements, allocation priorities, and defined evolution plans for flagship or core products and platforms. The roadmap is a visual tool that identifies and describes specific customer requirement-driven technology clusters and specifies potential discontinuities and critical requirements related to technology decisions. The process of developing the roadmaps itself encourages thinking and cross-organizational communication" (Strauss and Radnor 2004: 52).

8.2.4 Societal robustness of breakthrough innovations: the Socrobust Project (Laredo et al. 2002; Jolivet et al. 2002)

Socrobust is an acronym for societal robustness and this project focuses on management of breakthrough innovations to become embedded in society. In this project the theoretical considerations of sociotechnical change scholars are a departure point to understand the embedding of technology in society. "Some analysts go so far as to say that "*sound management practices for the development of incremental improvements may well be detrimental to the development of discontinuous, breakthrough innovation*" (Socrobust 2002: 7). The main objective of the project is to develop a methodology that helps managers to assess the capacity of a project (focused on breakthrough, radical or architectural innovation) to find its way in society. This tool can then be applied to evaluate projects that concern breakthrough technology until the project has generated enough learning and the technology has matured enough to become part of the conventional evaluating procedures (e.g. return on investment calculations and cost-benefit analysis). One fundamental insight this project departs from, based on actor network theory developed by Callon (1987) and Latour (1992; 2005), is that a new technology has inscribed in it already a vision of the world in which it would work (a so-called 'script of the future', see also de Laat 1996). Thus a fundamental part of the project is not only focused on whether the technology functions, but whether the sociotechnical configuration in which the technology would work is likely to unfold, or whether in the process of shaping the innovation it is also possible to shape the social configuration in which it can function. Thus progress of a project is not merely evaluated in technical and economic terms but also in social terms, such as the way certain controversies are solved, acceptance is gained, actors gain belief in its promise, and as expectations become more specified and articulated. This is where the term societal robustness comes from and it refers to the question of whether the technology is societal robust enough to become embedded within society.

Nature of the method

The Socrobust methodology consists of four steps and ten tools, with the basic sequence as follows (Socrobust 2002: i):

- *"The initial step is to describe the project from different angles: first a narrative of events to date; second a mapping of the cast of actors currently implicated in the project; and third a detailing of key events or turning points along the way. Having established a picture of the past, the next challenge is to image and describe a future world in which the project has succeeded and its goals have been achieved. This future working world is represented in different ways: via a revised mapping of the actors who will be involved and a more precise specification of anticipated relations between them.*

- *The second step is to look back over this descriptive material and identify the key changes which will have to take place if the gap between the present and future working world is to be closed.*

- *The third step homes in on these key changes but from a new perspective. The purpose here is to put the key changes in context, to check on their viability given events in the world beyond the project, and to thereby assess and evaluate the project's present positioning and the key assumptions on which it depends.*

- *Having made this assessment, the final step is one of identifying plausible and relevant next steps and of identifying those on which the project manager can act".*

Table 3 presents a description of the main tools developed in the Socrobust project for the management of breakthrough innovations.

Table 3: Tools for the management of breakthrough innovations (based on Jolivet et al, 2002)

Tool	Description of tool
Composition of the future network	Description of the future network expected to emerge if the project has become successful. This helps to identify new critical actors who should be enrolled and aligned, and it provides a point of reference for further discussion about relevant spokes persons to involve and/or relevant actions to undertake in order to better identify competing views and approaches
Future working world	The future working world reveals the infrastructure/institutions necessary for the emergence of a market for the new product (regulations, standards, labels, physical infrastructure) and articulates the context in which the necessary transactions (between users, producers, and prescribers) become possible. This implies assessing users' needs, preferences and their related competences, considering changes in the market infrastructure, and describing the triangular relationships between users, producers and prescribers (intermediaries, experts, consultants, and advertisers playing a role in shaping users).
Key changes table	It is now possible to compare the present state of the network and the hoped-for future working world. Key changes have to be characterised through specifying new practices that will have to become taken for granted and present practices that will have to be discarded (with implications for actors likely to represent a source of opposition /compromise), in terms of envisioned material infrastructure, and rules of the game necessary to make the anticipated future world a reality.
Project positioning table	This provides an overall assessment of the project positioning vis à vis the related key changes for dimensions such as: - the development of new shared knowledge about what the technology can do and how to do it (new paradigms and designs) - changes in the legal, administrative and regulatory environment, including issues about norms and standards, but also ethical issues, issues about the environment, and about quality and consumer safety - changes in user-producer relationships, such as aspects of customer preferences, and new knowledge required for customers to value and use the qualities of the new products.
Capacity for action table	The final step of the methodology tries to assess the project's margins for maneuver. The likelihood of a key change to occur is related to the nature and scope of collective agreement. This depends upon the existence of a space for debate, a forum, where the required reshaping is discussed. The actors that make up the forum, the arguments exchanged, the solutions sketched and the actions / directions defined, are all ingredients of the potential robustness of the outcome arrived at. A further element concerns the centrality of the project within the forum, that is its capacity to enlist key actors in the forum, to ensure that the project's position is not marginalised and that its goals are internalised by relevant groups in the forum.

8.3 Appendix 3: Taxonomy of transition pathways based on multi-level processes

Table 4 : Taxonomy of transition pathways based on multi-level processes (Source: Geels and Schot 2005)

Transition pathways	Main MLP-dynamics	Role of actors	Key-words	Empirical examples
1. Transformation	Landscape changes exert pressure, and the regime adjusts. Development trajectories are reoriented and change direction. Niche-innovations may play a role, but not prominently.	Criticism from regime outsiders. Incumbent regime actors adjust goals, guiding principles, search heuristics.	Adjustment	Hygienic reform of waste disposal (from cesspools to sewer systems)
2. Opening a new domain	Niche-innovation with new functionalities opens up new domain. Regime absent. Landscape developments create positive context.	Pioneers, enthusiasts, spin-off firms explore niche-innovation. Much uncertainty.	Explore and build	Birth of aviation
3. Technological substitution	Competitive niche-innovation threatens regime. If technology has a steep learning curve, a rapid breakthrough may occur. Otherwise, niche-innovation may remain stuck in niches, until landscape changes create favourable environment.	Incumbent firms and regime actors against outsiders and newcomers.	Competitive struggle	From sailing ships to steamships
4. De-alignment and re-alignment	Early landscape changes create much pressure on regime. Regime de-aligns, creating space for multiple niche-innovations. Co-existence creates uncertainty. Eventually re-alignment around one option	Incumbents lose faith and legitimacy. Space for many new actors. Prolonged search and contestation.	Fall apart, search and rebuild	From horse-drawn carriages to automobiles, via bicycles and electric trams
5. Reconfiguration	Distributed regime changes through sequence component change. Some are adoptions of positive niche-innovations. Some are negative component replacements.	New actors develop component-innovations. Regime actors adopt these innovations.	Cumulative component changes	From traditional factories to mass production

8.4 Appendix 4: Level of uncertainty and impact on societal structures

Landscape factor	**Level of uncertainty**	**Impact on societal structures (P: Politics; K: Knowledge; E: Economy; S: Society)**
Governance of the climate problem	High	P: The Kyoto Protocol entering into force leads to increasing efforts in combating the problem towards 2012, European emission trading with decreasing absolute ceilings after 2012; E: Carbon costs become an increasingly relevant consideration in decision making S: Organisation of some users, NGO's, around carbon-free lifestyles
Climate events	High	P: Extreme developments can trigger further intensification of carbon reduction policies E: Insurance sector strongly affected, large emitters start paying higher prices
EU integration	Medium	P: Further EU integration may enable a stronger position on a global scale and stronger decision-making with regards to shared problems such as energy security and climate change.
Digitalisation/ values	Low	E: The new economy leads to changing interactions between companies, much more network-based; Also demand for high quality electricity leads to expanding market niche S: New interaction patterns opened up by internet, fast formation of networks enabled, digital boycotts as means of pressure, lifestyles influenced by digitalization
Asian expansion	Low	P: Increasing focus on decoupling economic growth and environmental impact as pollution becomes major hampering factor for growth E: New economy and high growth and scarcity of fuels, materials induces demand (breeding ground) for alternative concepts and technologies S: Emerging middle-class increasingly organises for, and demand, clean and healthy environment
Fuel prices, markets	Medium	K: Direction of R&D influenced by fuel prices E: Volatile and higher fuel prices trigger market applications, new firms, venture capital for alternatives (biofuels, biomass, wind, solar)
Security threats	High	P: Focus on increasing resilience of systems to threats K: Increasing direction of R&D towards diverse systems with higher resilience