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ScanWafer/REC:

– Mapping the Innovation Journey in Accordance with the Research Protocol of CondEcol

Audun Ruud and Olav Mosvold Larsen CondEcol

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Program for Research and Documentation
for a Sustainable Society (ProSus)
Centre for Development and the Environment
University of Oslo
P.O.Box 1116 Blindern
N-0317 Oslo, Norway
Tel: + 47 22 85 89 00
Fax: + 47 22 85 87 90
informasjon@prosus.uio.no
www.prosus.uio.no
Visiting address: Sognsveien 68, 4th floor

FOREWORD

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

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

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William M. Lafferty
Professor of political science
Director, ProSus

THE CONDECOL PROJECT

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

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

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

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

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

Oslo, December, 2005

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

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1 INTRODUCTION[1]

The term solar energy refers either to thermal[2] solar energy or solar cells. Solar cells utilise the photovoltaic effect (from which the term PV (photovoltaic) is derived); i.e. the direct conversion of sunlight into electricity. Jackson and Oliver (2000) emphasise that PV technology is not just a new type of energy technology, but actually constitutes a radical innovation that involves new technical, economic, financial, institutional and social features. In this study, therefore, PV technology constitutes Spoke 8 in the Eco-design Wheel, i.e. "New concept development" as described in the outline for the CondEcol project (Lafferty, Marstrander and Ruud 2003) of which this survey is a part.

The overriding goal of this report is to identify the barriers and driving forces associated with establishing and developing ScanWafer, an important actor in the international solar cell industry. This company is the world's largest manufacturer of the most important component in a solar cell panel; silicon wafers. The company utilises the most widespread approach to PV technology to date; multicrystalline wafers. ScanWafer has in addition made several technical innovations in the course of the production process and has therefore contributed to making PV technology more competitive compared with other forms of electricity generation.

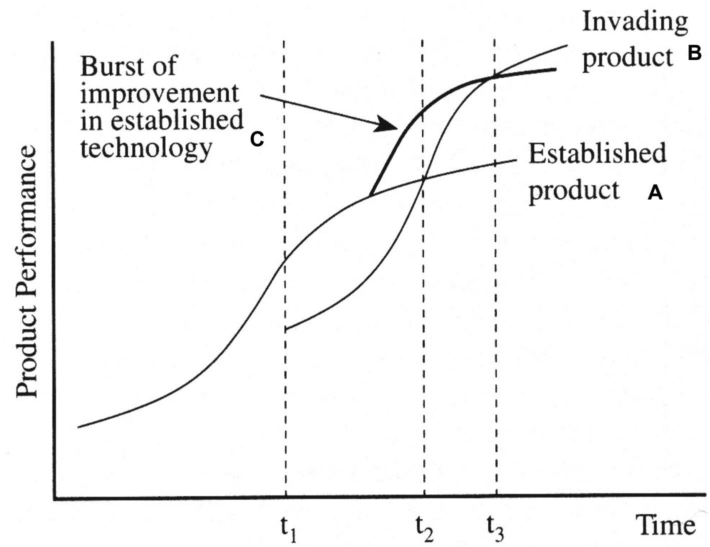
ScanWafer was established in 1994 and began production of wafers in Glomfjord, Norway in 1997. Production in Glomfjord was expanded in 2001, and in 2003 a new factory was opened in Herøya. The company is currently considering plans for further expansion, both in Norway and abroad.

Two important challenges, within the solar cell industry, are to reduce the energy demands of wafer production while at the same time increasing the efficiency of the solar cells, i.e. how the solar cells convert more electricity from the same amount of sunlight. These two factors can be illustrated with the help of the concept of "Energy Pay-back Time". Figure 1 in the appendix illustrates how much time it takes for a fully installed solar cell panel to generate (to pay back) the amount of electricity that was utilised to produce it. Radical changes have already taken place in this connection, and new ones are expected, for both the multicrystalline wafers manufactured by ScanWafer and the new PV technologies, thin film in particular. We envision three evolutionary features in the future expansion:

1. The dominant trend in PV technology today, multicrystalline wafers, will continue to consolidate its position in the market.
2. Alternative PV technologies that today hold a small share of the market will become increasingly competitive. This is linked to the alternative curve B in Figure 2 and may in this respect represent yet another radical innovation.
3. As a result of the "threat" posed by thin film, manufacturers such as ScanWafer can propose new but more incremental improvements in multicrystalline wafer technology, as represented by curve C in Figure 2 on the following page.

[1] This mapping was initiated in 2003 and finalized in spring 2005.

[2] Following subcategories: passive solar heat, active solar heat, solar cooling, solar boiling, electricity production from solar heat.



Source: Utterback (1996: 160).

1.1

This charting of ScanWafer's innovation journey has been compiled in accordance with the research protocol for the CondEcol project. Consequently Section 2 contains a general description of the technical features that make PV technology a more eco-efficient alternative compared with conventional electricity production. Also in this section references will be made to the new PV technology, thin film. In Section 3, and with Spokes 1-7 in the Eco-design Wheel as our points of reference, we will identify the eco-efficient advantages of ScanWafer in comparison with other manufacturers of multicrystalline wafers. Then we will move on to the non-technical aspects. In line with the research protocol, Section 4 contains a presentation of the key actors and specific events that have had an influence on ScanWafer. Conditions that have influenced the global development of PV technology are also important in this connection. Section 5 contains a short summary of the critical stages and decisions that have been important to ScanWafer's innovation journey. Finally, in Section 6, we will take a look at future challenges in the rapidly growing solar cell industry.

2 WHAT ARE THE MOST IMPORTANT FEATURES OF PV TECHNOLOGY AS A MORE ECO-EFFECTIVE ALTERNATIVE?

In this section we will present the eco-efficient potential of PV technology in comparison to conventional electricity production. We will illustrate this by beginning with the important stages in the life cycle of PV technology, from the use of raw material to the application of the solar cell panel, which is crucial to the eco-efficiency, and continued growth of PV technology. We will also place ScanWafer's entry into the solar cell industry on the global PV technology's S-curve and shed light on the company's contribution towards development along that curve. A more detailed account of ScanWafer's contribution is given in Section 3.

2.1 What is PV technology?

The photovoltaic effect was discovered by the French physicist Edmond Becquerel in 1839. Due to the special property of PV technology, namely the possibility of reliable access to electricity without connection to an electricity grid, PV technology can easily be adapted to meet different requirements. This was why solar cells were originally developed to secure access to electricity in the space programmes during the 1950's. The technology was further developed for other markets, such as telecommunications and building-integrated solar cell panels, for the same reason. Later on, another application for PV technology was found in installations connected to grids; so-called grid connections. During the past decade the global market for PV technology has been characterised by high growth rates; higher than in many other sectors of technology. In the period 1987-2000 the average annual growth rate was 18.9 per cent (EPIA 2001), but in the period 1998-2003 Alf Bjørseth estimates that the market had an annual growth rate of over 30 per cent.

2.1.1 Raw materials

Solar cells can be produced from different materials. However, the raw material silicon has been – and still is – the most important element in the solar cell industry. Silicon is one of the most common elements in the earth's crust (26 per cent) and is usually produced from quartz. Over 95 % of the solar cells produced in the world today use silicon in production.[3] In order to use silicon in the solar cell industry, it must be processed so that it attains a degree of purity of more than 99.9999 per cent. Melting silicon is an energy-demanding process and accounts for a substantial cost component for the PV industry. The higher the degree of purity, the more energy-demanding the process, but the higher the degree of purity, the greater the efficiency. This can be linked to Energy Pay-back Time as illustrated in Figure 1 in the appendix.

To begin with scrap material from the electronics industry was the only sufficiently pure source of silicon for the solar cell industry. This source was sufficient to meet the needs of the growing PV industry during the 1990's, but the demand increased rapidly. Today the solar cell industry uses a combination of several sources: electronic scrap, raw material scrap from the electronics industry and

[3] Source: www.solarserver.de

the industry's own recycled material, but the main source is specially made material, so-called solar grade silicon.

The amount of scrap material available is fairly constant but, because of changes in production volumes in the electronics industry, the demand is variable. This means that during certain periods pure silicon is available to the PV industry, while at other times it goes exclusively to the electronics industry. Both the solar cell and the electronics industries use more or less the same suppliers of pure silicon, the result being that there is currently direct competition between these two.

Because of the shortage of silicon available, the price of silicon for solar energy purposes has risen by 50 per cent just in the course of 2004[4]. At that time here was only one supplier of silicon who delivered exclusively to the solar cell industry. Increased availability of silicon with a sufficient degree of purity at lowest possible price is one of the main challenges facing the solar cell industry. Examples of alternative materials are indium and cadmium, but these have their disadvantages. Large-scale manufacture of solar cells based on indium is difficult because there is not enough of it, and cadmium is a toxic substance. To try and sell a "green" product based on these would consequently prove to be a challenge. So, despite this scarcity of silicon, it looks as though it will continue to be the preferred raw material for a long time to come.

2.1.2 Manufacture

Today PV technology is chiefly based on multicrystalline and moncrystalline wafers.[5] The difference between these two lies in the crystallisation process. Wafers of monocrystalline[6] silicon give solar cells with greater efficiency but they are more energy-demanding in terms of production.[7] Despite the fact that multicrystalline silicon provides solar cells with lower efficiency, they often compare favourably when compared in terms of watt per kroner – the so-called Energy Pay-back Time as illustrated in Figure 1. One main reason for this is the lower energy requirement for producing the wafer, but ScanWafer has also created advantages in the form of processing innovations. We will return to this point in Section 3.

An alternative to wafers does exist; so-called thin film. ScanWafer does not manufacture thin film. These solar cells are made of extremely thin films[8] of silicon or other materials such as cadmium and CIGS (Cupper, Indium, Gallium and Selenium). The thin film type today makes up 6 per cent of the market. The technological challenges are primarily linked to obtaining uniform layers of the active material. The motivation behind the development of thin film has been to reduce costs in the solar cell industry, particularly by overcoming the major challenge posed by the use of silicon as the raw material. When solar cells are produced from silicon wafers, more material is used than what is strictly necessary. This is because the wafers are sawn from silicon blocks and approximately 40-50 per cent of the silicon is lost as saw dust. The thinner a wafer is cut, the more wafers per kilo of silicon block are obtained, but it is difficult to avoid some breakage in the course of the production process. Thin film technology meets this challenge by requiring less material, be it amorphous silicon or another material.

Information provided by Alf Bjørseth, 10 December 2004.

[5] There is also a method that does not make silicon wafers based on ingots, but that instead casts silicon flakes. In 2003 this method accounted for 4.5 per cent of the market.

[6] Monocrystalline material is utilised in all microelectronics and it was in the electronics industry that competence in silicon was built up. Multicrystalline silicon was developed for the solar cell industry All the solar cells manufactured before 1990 were produced from monocrystalline silicon.

[7] Monocrystalline wafers have a longer crystallisation process and the crucible must therefore be kept hot for a longer period of time.

[8] The films are rarely thicker than a few micrometers (in comparison to wafers, which are approximately 200 micrometers), and are deposited on cheap substrates such as glass or metal.

Nevertheless, thin film has yet to show good efficiency. On the whole, therefore, it is not for the time being competitive enough compared with the wafers produced by ScanWafer.

Wafers and thin film have a theoretical maximum level of efficiency of about 30 per cent. This is because they are not capable of making optimal use of sunlight.[9] Erik Marstein stresses that the advantage with wafers is that they are the product of an established technology that manages to push technical boundaries and is therefore closer to the theoretical maximum level of efficiency than is the case with thin film. This could well prove to be the death blow for wafer technology if the Energy Pay-back Time for thin film is dramatically improved. The major advantage with thin film is also linked to reduced utilisation of materials. In response to this "threat" a drastic improvement of the currently dominant type of wafer may emerge; something that would further reduce the price per watt. Crucial in this respect is a reduction in energy consumption for wafer production, for example by way of new methods of silicon crystallisation and/or cutting of ingots. Other areas with potential for improvement are efficiency improvements in the whole of the solar cell production process. ScanWafer's improvement measures have contributed significantly to this innovation process.

In addition to research being done on thin film, research is also being carried out on a third generation of solar cells, in an effort to surpass the theoretical efficiency level of 30 per cent. The theoretical maximum level of efficiency is approximately 50-60 per cent. In order to achieve this, however, a new way of thinking is required. For example: more layers of material on top of each other or several solar cells on top of each other in a new structure. Erik Marstein's statement provides a good description: "In principle it's a case of making the same solar cell, but in a completely different way". So third generation solar cells can be based on both wafers and thin film, but from the way things look today thin film will eventually be the base. With the exception of some examples from space travel, where a so-called triple cell attained an efficiency of 32 per cent, no solar cells in this third generation have been commercialised and the direction is still very new. Those that have been developed, work at a high cost. The Energy Pay-back Time is therefore considerably lower for the wafers produced by ScanWafer.

2.1.3 Applications

There are at present four primary applications of PV technology: off-grid domestic, off-grid non-domestic, grid-connected distributed and grid-connected centralised.

Off-grid domestic and off-grid non-domestic serve the markets where there is little or no competition from other forms of electricity. This is due to lack of connection to an electricity grid. These are so-called stand-alone systems, as traditionally found in Norwegian mountain cabins. In such a market PV technology can survive at a price higher than that of conventional electricity.

In grid-connected distributed applications there is competition between electricity from PV technology and conventional forms of electricity generation, but this is restricted to the individual household. Any competition is therefore still limited.

The grid-connected centralised application is the most challenging market in which to get established due to the tough competition from, for example, coal power plants. At the same time this is the market with the greatest growth potential. Erik Marstein at IFE (Institute for Energy Technology) suggests that as long as the grid exists it is cheaper to build a power station based on coal, than to use solar energy for grids. Alf Bjørseth contests this and argues that, particularly in countries such as Japan

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[9] Calculations for theoretic maximum efficiency rates for solar cells are based on a number of assumptions. Among other things it is assumed, for the sake of simplicity, that all sunlight that strikes a solar cell is absorbed. In reality it would be difficult to attain total absorption; a normal solar cell reflects up to 10 per cent of the sunlight.

where energy consumption varies in step with the orbit of the sun, it is becoming increasingly possible for solar energy to compete with more conventional sources of power from electricity grids.

One problem with using solar cells is that the electric energy must be utilised immediately or stored for later use. Storing the energy can be done with the help of batteries. For storing larger amounts of electrical energy other methods must be used. One method is to produce hydrogen with the help of water electrolysis. Another method of storage is to sell electrical energy from one's own solar installation to the electricity grid. This method is becoming increasingly popular in Japan. Energy storage can also be achieved by regulating reservoirs.

Due to this need for storage, the system costs for off-grid applications are higher than for grid-connected ones. Up until 1999 grid-connected systems accounted for an average of only 20 per cent of the cumulated PV systems installed worldwide. Stand-alone systems made up the rest. This situation changed in 2000 and grid-connected systems accounted for as much as 50 per cent of the total number of PV systems installed. Successful incentive programmes for PV systems in Japan and Europe have been decisive for the growth in grid-connected installations. Due to poorly developed infrastructure, this is less feasible in many developing countries. There is however an enormous market potential in these countries for stand-alone systems (EPIA 2001).

2.2 Eco-efficient features of with reference to Spoke 8, PV technology.

Generating electricity from renewable energy sources often seems to be a solution to many of the environmental problems associated with using conventional technologies based on non-renewable sources. Electricity generation from PV technology is regarded as one of the most promising solutions in this respect. Tsoutsos et al (2005) stress that the greatest advantage with solar energy technology in this connection is that it contributes to reducing CO_2 emissions. The reason for this is that solar energy technology entails neither emissions into the air nor waste products through use.

Tsoutsos et al (2005) point out that all generation of electricity entails some kind of impact on the environment. The challenge with today's PV technology is that the production of solar cells is energy-intensive and, as Alsema and Nieuwlaar (2000) point out, emissions of CO_2 occur therefore almost exclusively during the production of solar cells and not during use. For carbon-based energy technologies the situation is reversed. Generally speaking more that 90 per cent of the greenhouse gasses that are released during the life cycle of the PV system will be linked to conventional energy consumption during production.

Consequently for each and every actor within the solar cell industry the choice of energy source and the energy demand are crucial factors in terms of the environmental impact that occurs in the course of the life cycle of the PV system. The ecological parameter of Energy Pay-back Time can be regarded as a simplified gauge of the life cycle. This parameter could be a good indicator of the possibilities for reducing CO_2 in PV technology. In this connection it is worth mentioning that during the 1970's PV technology was dismissed by many as a non-viable technology because the amount of energy that was used in the production of the cells was greater than the amount of energy which the technology could provide in the course of its life cycle. Technical improvements have however changed this situation radically, and PV technology has now evolved from being a "net energy drain" to being a viable energy technology which to an increasing degree can compete with more conventional technologies both in grid-connected and stand-alone solutions.

2.3 ScanWafer's role and innovations

Global PV technology has been characterised by a 30-40 per cent growth over the past 5-6 years. This means that, according to Figure 2, PV technology started out on the "steep part" of the S-curve around 1999. When ScanWafer was established in 1994 the annual growth was "only" 15-20 per cent. At that time the following actors were manufacturing monocrystalline and multicrystalline wafers: Solarex[10], BP and Crystalox. ScanWafer subsequently evolved into one of the leading manufacturers of wafers in the world.

Already in the 1980's the most important actor in terms of establishing ScanWafer, Alf Bjørseth, saw the possibilities that lay in solar energy. Former finance director for ScanWafer, Viktor Jakobsen, stresses that ScanWafer has become a successful enterprise, because it emphasized process innovations that made economies of scale possible.[11] The first production line, in Glomfjord 1, was based on "off-the-shelf" products, so-called open technology. In order to ensure continued growth cost-effectively, however, ScanWafer implemented various innovations to the production process. According to the management at ScanWafer the result of this has been that the company lies ahead of the competition when it comes to reducing the price per wafer and often has the lowest prices in the market. ScanWafer established itself in an already established industry, but has nonetheless contributed towards increased eco-efficiency by creating a more cost-effective production of multicrystalline wafers.

[10] Later bought out by BP.
[11] From conversation held at ProSus, 25 June 2004.

3 HOW CAN SCANWAFER'S PRODUCTION PROCESS BE CHARACTERISED IN TERMS OF THE FIRST SEVEN SPOKES IN THE ECO-DESIGN WHEEL?

With the help of the Eco-design Wheel we will chart out ScanWafer's contribution to the development of the dominant PV technology. By contribution we mean eco-efficient advantages in the production process compared with competing wafer manufacturers. In this connection ScanWafer's process innovations are central. To avoid too broad a comparison we will limit the comparison to *multicrystalline* wafer manufacturers.

3.1 Spoke 1: Selection of Low-Impact Materials

The raw material silicon is the second most accessible raw material on earth. Production of metallurgical silicon is energy-demanding and utilises carbon (C) as the reducing agent. This emits CO_2 as a by-product. Purifying the raw material entails no *direct* negative environmental impacts. Production of both pure silicon and wafers is energy-intensive and this can entail a considerable *indirect* negative environmental impact, depending on which energy source is used.

3.1.1 ScanWafer's competitive edge

Access to the electricity used in ScanWafer's production comes exclusively from hydroelectric power. Whether electricity from hydroelectric power actually constitutes a larger portion of the electricity consumption compared with the competitors, is however debatable. This is due to the fact that electricity from *different* sources is distributed through the same central grid and it is therefore not given that the percentage of renewable energy in the electricity distributed to ScanWafer is larger than that which is distributed to its competitors. Despite this, and given the sources of electricity production among competitors, it is highly probable that the electricity that ScanWafer utilises is relatively speaking considerably more environmentally friendly.

3.2 Spoke 2: Reduction of Material Usage

This spoke relates to the utilisation of input factors; raw material (silicon) and energy. Crystallisation is energy-demanding. In addition a lot of material is lost in the subsequent production process. The material loss is greatest when cutting the wafers, but breakage during the subsequent processes – washing, packing and inspecting etc – can also occur. Reducing material loss would therefore make large reductions in the total energy requirement per wafer.

3.2.1 ScanWafer's competitive edge

ScanWafer's competitive edge with respect to this spoke can be related to all the process innovations. The crystallisation furnace[12] requires lower energy consumption per wafer. According to

[12] ScanWafer's crystallisation furnace does not figure as a competitive advantage as far as ingot quality goes. Sauar refers here to efficiency.

Erik Sauar this innovation represents the company's greatest eco-efficient edge. By using a special saw ScanWafer can slice extra thin wafers and thereby utilise the raw material more effectively.[13] The washing of the wafers is done with a type of automated equipment that is less labour-demanding and takes up less space. This innovation reduces the possibility of breakage but, given the thinner layers, this is not easy to achieve in practice. Packing and inspecting the wafers is also carried out in such a way that the possibility of breakage is reduced.

3.3 Spoke 3: Optimisation of Production Techniques

ScanWafer has placed great emphasis on this spoke. In order to increase the cost efficiency of wafer production ScanWafer has made the following innovations[14] in the production process:

New melting furnace/crystallisation furnace
This innovation is related to the melting of silicon. The melting furnace is crucial to how much energy is used per wafer. ScanWafer has a melting furnace which is exceptional in comparison with those of its competitors. By using four crucibles in the furnace, ScanWafer's melting furnaces produce 1000 kg material per batch. By comparison competitors' furnaces can take only one crucible and can produce only 250 kg at a time.

New wire saw
Once the ingot is taken out of the melting furnace and cut up into smaller blocks (see illustration in the figure), these blocks must be cut into thin slices, or so-called wafers. The cutting is done with the help of a wire saw. ScanWafer has been involved in developing a wire saw that cuts wafers thinner than any of its competitors. This has made ScanWafer more cost-effective in that the company can produce more wafers for the same input factor.

Automation
Throughout the whole of the development work ScanWafer has gone in for increased automation.

Wafer washing
One example of automation is wafer washing. The new equipment is less labour-demanding and takes up less space.

Quality control and packing of wafers
One of ScanWafer's competitive advantages is that quality control and packing is fully automated and is done is such a way that the likelihood of breakage is reduced. ScanWafer therefore requires fewer employees than its competitors.

The production process from silicon to wafer is also illustrated at Appendix 2.

3.4 Spoke 4: Optimisation of the Distribution System

ScanWafer has no significant advantage in respect of this spoke.

[13] The material loss due to cutting alone will increase when the wafer becomes thinner (Alsema and Nieuwaar 2004)
[14] This selection of important innovations in ScanWafer's production process has been prepared by Erik Sauar.

3.5 Spoke 5: Reduction of Impact during Use

As mentioned in the introduction, the use of PV technology generates no emissions or waste products during use. In this respect ScanWafer does not have any eco-efficient advantage over other manufacturers of multicrystalline wafers.

3.6 Spoke 6: Optimisation of Initial Lifetime

This spoke does not appear to be relevant to wafer production.

3.7 Spoke 7: Optimisation of End-of-life System

There is great potential for increased recycling in wafer production.

3.7.1 ScanWafer's competitive edge

In 2002 ScanWafer signed an agreement with the German company SiC Processing GmbH for recycling silicon carbide.[15] With the help of a completely new recycling system which will serve ScanWafer *exclusively*, 80 per cent of the cutting fluid will be recovered. Roar Karlsen, Factory Manager in Herøya, emphasises that this system constitutes a significant environmental gain. The system also represents a significant reduction in costs.

3.8 Conclusion

The wafer is the most important component in a solar cell, and thus absolutely crucial to PV technology's eco-efficiency. The contribution that ScanWafer makes can be closely linked to two factors:

1. Reduced price per watt for electricity generated by PV technology. This has been achieved by means of improvements in the production process which can be linked to Spoke 3: "Optimisation of Production Techniques".
2. With a more energy-efficient production process the company has also reduced the indirect negative environmental impact.

The biggest challenge – and possible obstacle – that PV technology faces today is the lack of sufficient pure silicon at a cost-effective price. The acquisition of Solar Grade Silicon (which we describe in more detail in the next section) was a strategic decision that made ScanWafer stand out from the competition. Access to silicon is ensured and plans for further expansion can be advanced. In this way ScanWafer's efficiency measures pertaining to material and energy consumption create further eco-efficient benefits with respect to electricity production worldwide.

[15] A mixture of silicon carbide and polyethylene glycol comprises the cutting fluid that is used when the blocks are cut into wafers.

4 WHICH KEY ACTORS AND SPECIFIC CONDITIONS HAVE INFLUENCED THE PRODUCT DEVELOPMENT?

In this section we identify key actors and specific conditions that have directly or indirectly influenced the development of the company ScanWafer and its products. By *indirect influence* we here mean key actors or specific conditions that concern PV technology in general, and that have been of significant importance to ScanWafer in particular. By *direct influence* we here mean key actors or specific conditions that in the first instance have had significance for ScanWafer, though naturally their contact with ScanWafer in itself makes them important to the solar cell industry in general. In accordance with the research protocol we will categorise the relevant factors and actors by the degree to which they represent technological/productional, marketing, financial, regulatory or cultural and social motivators or obstacles.

4.1 Technology and manufacture

Only a few decades ago PV technology was regarded as a non-viable technology because the amount of energy that was used in the production of solar cells was greater than the amount of energy which the solar cells produced in the course of their life cycle. This situation has, however, changed radically. Technological changes that led to improvements in the Energy Pay-back Time (see Figure 1) have been a decisive factor in increasing profitability – and thereby competitiveness – in the solar cell industry.

Despite the facts that Norway is the world's largest manufacturer of metallurgic silicon and has cheap power and good access to cooling water, both of which are important elements in producing and processing silicon (Si), little interest in PV technology was expressed by the Norwegian industrial community (Christiansen and Buen 2002). One of the founders of ScanWafer, Alf Bjørseth, was formerly Senior Vice President of Technology at Elkem.[16] His main task there was to work on processes for cleaning silicon, but solar energy was also a point of reference.

In the beginning of the 1990's Elkem bought out the British company Crystalox, one of the best manufacturers of crystallisation furnaces for the production of silicon ingots. Alf Bjørseth was at one time chairman of the board at Crystallox, and developed detailed plans for wafer production. These plans were presented to Elkem's management in 1993. The company showed little interest, however, partly because of serious financial problems due to a fall in price for ferrosilicon products in the aftermath of the fall of the Berlin wall. At this time Bjørseth was approached by Reidar Langmo, leader of Meløy Næringsutvikling, about establishing a wafer production factory in Glomfjord. Inspired by an EC report on the considerable growth opportunities within solar energy,[17] Bjørseth decided to accept Langmo's invitation to realise plans for wafer production in Norway. He left his position at Elkem and, together with a group of consultants, designed a factory that made use of the best technology available.

Technical consultants Dr David Hukin and Dr Daniele Margadonna were key actors in the establishment of the factory in Glomfjord. David Hukin was founder of Crystalox but had subsequently left the company on health grounds. He was particularly interested in the crystallisation aspect of the production. Daniele Margadonna had been technical director for Eurosolare, a large Italian

[16] Incidentally, Alf Bjørseth has also previously led Hydro's research centre in Herøya.
[17] EC report: *Photovoltaics 2004*, published in 1994.

manufacturer of solar cell panels, later to be an important client of ScanWafer. His area of responsibility there had been the development of block sawing of ingots to wafers.

Norsk Hydro was a central actor in the start-up of ScanWafer. Through Meløy Næringsutvikling, which it owned together with Meløy Municipality, Norsk Hydro wanted to stimulate new business activities since it was at that time downscaling its own artificial fertiliser operation. Finn Nordmo, board chairman of Meløy Næringsutvikling, was factory manager at Norsk Hydro in Glomfjord and also contributed to making conditions favourable for ScanWafer's start-up.

The first of ScanWafer's factories in Glomfjord began production in June 1997. A team had worked on the design and construction of the factory, the selection of production equipment, product sales and financing. The collaboration between SND (Norwegian Industrial and Regional Development Fund) and DnB Bank in Mo was important during this phase. SND was willing to provide investment aid to ScanWafer on the condition that ScanWafer was granted a bank loan. In addition it required documentation on the existence of a market for the products. Langmo and Bjørseth therefore signed sales contracts with enough European clients to cover ScanWafer's production capacity for the first four years. Particularly important was the contract with Neste Advanced Power Systems (NAPS), a subsidiary company of the energy and chemical group Neste oy.[18] This secured support from SND, who then went in with 25% of the estimated total investment, estimated to be around NOK 70 million. With the sales contracts in place SND committed itself, which in turn made Nordlandsbank positive to financing. In addition, individual private investor communities were approached and also became involved.

Right from the start of ScanWafer the emphasis was placed on technology development. This was a natural consequence of the management having research and technology backgrounds. There are two innovations in particular that have been important for ScanWafer. In 1998 ScanWafer began collaborating with the German company ALD to develop a new and more efficient crystallisation furnace. Originally the furnace technology was offered to other wafer manufacturers such as the well-established Bayer Solar, but they declined for reasons that are not known. ScanWafer was therefore offered a part in a development project that would come to create significant competitive advantages. This is related to an agreement in which ScanWafer received ten years exclusive rights to the technology from 2000, in return for which they agreed to buy a certain number of furnaces from ALD. Another part of the agreement was that the German company would receive part of the settlement in shares. The crystallisation furnace was technically the biggest innovation for ScanWafer. It was finally installed in the second factory in Glomfjord, which began production in July 2001.

The other big innovation was a fully automated washing and quality control line that was developed by the technology team at ScanWafer. The introduction of this technology made the work-demanding operations of washing, quality controlling and packing the wafers much more automated. The number of employees in ScanWafer II was reduced in comparison with ScanWafer I. The number of employees actually doubled, but at the same time the new furnace technology made a fourfold increase in production capacity possible. A conventional furnace batch was approximately 275 kg. With ALD's new prototype production was increased to 1100 kg distributed among four crucibles. Although the price was double that of conventional technology, productivity was also doubled. As a result of the exclusivity agreement, ScanWafer continues to go it alone with this technology. The production line at ScanWafer's other factory in Glomfjord was built by the Norwegian company Tronrud Engineering AS. ScanWafer ensured that Tronrud could not deliver its engineering services to ScanWafer's competitors – even though some, according to Bjørseth, actually did approach Tronrud.

In addition to the production/technological conditions mentioned above, ScanWafer was already at this time concerned about accessibility to raw materials, and a number of development projects were

Neste is today integrated into the energy company Fortum.

put in motion. In this connection collaboration with Elkem was entered into, whereby the companies would put their projects into a jointly-owned company (Solar Silicon AS) which would in turn develop a new process. An important condition for the cooperation agreement was that both parties were to inform each other about rival projects. At this time Elkem had a secret collaboration with AstroPower (later to be taken over by GE Solar). This cooperation became public knowledge in 2001 and ScanWafer terminated its technical collaboration with Elkem.

By the summer of 2000 ScanWafer had reached full production at ScanWafer I. The product was well received by customers who, in addition to NAPS, also included Eurosolare and Photowatt. The demand considerably exceeded production capacity. In July 2000 two long-term sales contracts were signed with Mitsubishi Electric Corporation (Melco) in Japan and Shell Solar in the Netherlands. It was therefore decided to expand production by 40 MW (i.e. four times the production capacity of ScanWafer I). The increased production could only be realised by the technological improvements described above.

In July 2001 production began in Glomfjord II. This factory had a number of technological improvements compared to Glomfjord I, something that made its production potential extremely competitive. However, the start-up proved to be complicated. Not all the technological innovations or prototypes worked according to plan. The start-up was therefore more expensive than budgeted for and resulted in poor financial results in 2001.

The collaboration with Norsk Hydro continued. When Norsk Hydro decided to close down its magnesium operation in Herøya in 2002, making 600 people redundant, the company reacted very positively to the possibility of wafer production in Herøya. ScanWafer III was already being planned and the plan was to establish production in southern Germany. However, after discussions with Norsk Hydro these plans were changed and it was decided to locate the factory in Norsk Hydro's industrial park in Herøya. ScanWafer III was completed in 2003 and had in principle the same technology and prototypes as ScanWafer II. The start-up proved to be expensive in this case, too, and the profits for ScanWafer in 2003 were poor. By 2004, however, all the factories were well underway and the profits were satisfactory.

Renewable Energy Corporation (REC) was established in Norway in 2000, but the origins of the company go back to the formation of the investment company Fornybar Energi AS in 1996. Fornybar Energi was an investment company that focused on investing in renewable energy in Norway and abroad. In 1998 two of the original investors in ScanWafer, Hafslund Venture and Lyse Energi, became shareholders in Fornybar Energi. In 1991 Scatec AS became the biggest shareholder in ScanWafer. Within a year this company invited the other shareholders in ScanWafer to establish a holding company, REC. The intention behind this was to pave the way for further development of ScanWafer, and also to invest in other parts of the solar energy value chain. In 2002 REC was the only solar energy company who had activities in all parts of the value chain, i.e. from production of silicon raw material to wafers, solar cells and solar cell panels, plus a small installations company. The most important event that occurred in 2002 from a strategic point of view was REC's investment in one of the factories owned by Advanced Silicon Material Inc (ASiMI), a company that produced high purity silicon for the electronics industry. This factory was situated in Moses Lake, Washington. A joint venture was formed with Komatsu, who at that time owned ASiMI 100 per cent, and REC took over the responsibility for production. The new company was organised to produce solar cell silicon and was given the name Solar Grade Silicon LLC (SGS).

Today SGS is the only company in the world dedicated to the exclusive production of high purity silicon for the solar cell industry. Solar Grade Silicon is today owned by REC (75 per cent) and ASiMI/Komatsu (25 per cent). Komatsu, who took over the factory from the crisis-struck Union Carbide, had previously invested large sums in improving the production process at the factory in Moses Lake. Part of this work involved a radical improvement of the technology for producing pure silicon; something that would result in a halving of the investment costs by building a new factory, and a halving of the operation costs. REC approved approximately NOK 60 million for completing the development. This is considered to be REC's biggest development project. Today REC is probably the company[19] that can both build new factories like SGS and produce high purity silicon for wafer production in the cheapest possible way.

Erik Sauar comments that reliable access to raw materials was a demand that ScanWafer's owners made on REC in order to ensure a 100 per cent merger[20] between ScanWafer and REC in 2000. The ability to see future limitations to accessing cheap materials was a pivotal element in ScanWafer's continued growth strategy. The innovations that REC has made in Solar Grade Silicon on the raw material side are therefore decisive factors for ScanWafer's continued growth.

As regards wafer cutting, the Swiss saw manufacturer HCT[21] is central. So far HCT has delivered all the wire saws to all of ScanWafer's factories. HCT is a recognised international supplier to both the electronics and PV industries. ScanWafer has made several suggestions for technological improvements to HCT which have resulted in a special type of saw to which ScanWafer has the exclusive rights.

4.2 The market

The most important motivation behind the development of modern PV technology has been the emergence of niche markets, where the price of silicon is of lesser importance to the users. The first commercial application of solar cells was on space ships in 1958, and in the 1960's space satellites represented an important market segment.

In the 1980's Norway, with its relatively high density of cabins, was one of the largest markets in the world for solar cells. Both the cabin market and telecommunications in Norway were important sources of motivation in the start-up phase of the Norwegian PV industry. But as a result of governmental backing, particularly in Germany and Japan, other markets have taken over, and REC/ScanWafer's activities are primarily export-oriented.

At the time when ScanWafer was established the barriers that did exist were primarily technical in nature, i.e. there were few who were capable of setting up such production due to lack of knowledge. The market was characterised as a seller's market in which Bayer Solar dominated the European sector. Many actors who bought wafers from Bayer Solar – for example Naps and Eurosolare – sought competition from other suppliers. This provided ScanWafer with the opportunity to enter the market for multicrystalline wafers.

ScanWafer's first important customer was Naps[22], at that time the solar energy division of the Finnish company Neste oy, Finland's largest industrial concern. This convinced SND that the market was interested and it provided project funding for 25 per cent of the investment costs for Glomfjord I. Later on, in July 2002, ScanWafer/REC signed large and long-term contracts with Mitsubishi and Shell. These secured the financing for the building of Glomfjord II and were also important for getting established in Herøya.

Erik Sauar comments that barriers to estblishment are emerging in the industry. The reason for this is that purchasing off-the-shelf products is too expensive; production can never be sufficiently cost-effective. This is why exclusivity agreements, such as the one ScanWafer made with ALD, are

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19 According to Bjørseth rival companies, i.e. manufacturers who are trying to attain similar results, are: Wacker (Germany), Tokoyama (Japan) and Elkem. Elkem is also beginning to achieve promising results and is considering a pilot project.

20 At this point in time REC owned 50 per cent of ScanWafer.

21 www.hct.ch

22 www.napssystems.com

increasingly being worked out. Innovations related to cutting are also developed in collaboration with the supplier.[23]

4.3 Financing

The economic crisis at the beginning of the 90's was a decisive factor for Elkem's decision not to pursue Alf Bjørseth's plans for wafer production. The difficult financial situation and strategic plans to consolidate the company's core activities were the reasons why Elkem sold its ownerships interests in Crystalox in 1995 to the Crystalox management. Interestingly enough, Elkem became a part-owner of REC in 2004.

Bank loans from Nordlandsbanken enabled ScanWafer to purchase the first raw materials, so-called offcuts[24], from the crystallisation process in the Japanese electronics industry. This raw material was an important factor in manifesting and legitimising ScanWafer's plans vis à vis potential customers. The financial support from SND and Meløy Næringsutvikling was also decisive for establishing ScanWafer. Such support contributed to raising credibility with respect to other financial actors. Most important of all, however, was the signing of sales contracts so that SND, banks and investors could be assured that there was a market. The first financial investors were NSV Invest, Fornybar Energi AS, Furuholmeninvest, and Beam Holding.

Together with Norsk Hydro, Meløy Næringsutvikling[25] attempted to generate activity in Glomfjord in connection with the redundancies made at Hydro's fertiliser plant. Reidar Langmo was Managing Director of Meløy Næringsutvikling at that time. Langmo saw the potential that lay in Bjørseth's plans for wafer production and, together with Bjørseth, became an important founder by virtue of his central organisational and financial position. Due to its relationship with Hydro Energi, Meløy Næringsutvikling was also a central actor when it came to securing cheap electricity for ScanWafer. Erik Sauar emphasises that entrepreneurs who have good ideas but who lack capital will to a large degree be dependent on investment aid in order to realise their ideas. This characterised the situation during the start-up phase in Glomfjord.

Mitsubishi Electric (Melco) played a crucial role in establishing ScanWafer's second factory in Glomfjord in 2001. This contact was a result of Bjørseth's extensive sales efforts in Japan at the end of the 90's. Melco needed wider access to wafers and signed a long-term contract with ScanWafer in July 2000, with delivery to start one year later in July 2001. The conditions of the contract included full access by Technology Director Mr. Namba, whereby he could personally inspect cost and processing documentation. The agreed price was cost price plus 20 per cent profit. This was also a way to build confidence. This agreement was supplemented by sales to Shell, who had also taken over Siemen's solar cell activities.

In connection with the signing of the contract with Melco, Bjørseth again refers to SND and DnB, who had taken over Nordlandsbanken. The sale resulted in the loan and the subsidy being granted. Einar Seljås at DNB-Mo has been a central financial figure in connection with ScanWafer's production development. Melco is today a major player in the solar cell industry, and Viktor Jakobsen believes that the company's growth was largely due to the supply of wafers from ScanWafer.

As mentioned earlier, ScanWafer's original plan was to establish its third factory in southern Germany, and already in 2002 it had secured financial aid for this from the local authorities in Bayern.

[23] Whether new technology should be developed only in cooperation with suppliers or in cooperation with both suppliers and competitors is an important decision. The advantage with open technology is that the costs are shared and there is the opportunity to share experiences and get feedback from others. At the same time such cooperation can deprive an innovator of important ownership advantages.

[24] Parts of the ingots that were of no further use value to the electronics industry.

[25] www.meloynett.com/mnu.htp

However, Norsk Hydro had resolved to close down its magnesium factory in Herøya and, as in Glomfjord, needed to stimulate alternative employment opportunities for those who were made redundant. Hydro's offer of financial aid for the start-up led to ScanWafer changing its plans. Hydro could in addition offer wage support for manpower during the planned training period, and was therefore a decisive financial actor in the establishment of the factory in Herøya.

Viktor Jakobsen also singles out DnB as a decisive actor in this connection because the bank was the biggest lender. Sauar stresses that the competence that existed in Herøya and the investment subsidies (which were roughly the same size as those being offered in Germany) were decisive. In addition to the two most important financial actors, DnB and Norsk Hydro, the Dutch company Good Energies also contributed financially to the establishment in Herøya. This company acquired ownership interests in REC when the original owners pulled out. REC provided the additional financing in order to realise ScanWafer III in Herøya, which by that time had become a wholly-owned subsidiary.

4.4 Regulatory bodies

The governments of most countries have objectives to introduce large-scale renewable energy production. The EU has resolved that 22 per cent of electricity consumption should by 2010 be generated from renewable energy sources; the so-called RES-E Directive. The market conditions for PV technology differ from country to country, including those within the EU. The reason for this could be that the subsidy programmes are different; something which the example of Japan clearly illustrates.

4.4.1 Japan

Japan is the leading PV nation in the world today, both in terms of production and consumption. The main objectives for the Japanese introduction of New Energy[26] as a national energy policy were formulated in the New Sunshine Project in 1993.[27] This was a follow-up to the Sunshine Project started in 1974 during the first oil crisis. This successful programme underwent a reorganisation in 2000 which, among other things, led to the establishment of the New PV Technology Programme. This programme was called Advanced PV Generation (APVG). Due to an administrative reorganisation of the Japanese government structure, the New Energy Development Organisation (NEDO) has also been restructured (independent of the government), and has acquired a new role in the implementation of the APVG programme. The chief priorities for this programme were linked to reducing the country's import dependency[28] on petroleum. 53 per cent of Japanese energy consumption is based on petroleum. At the same time there was a wish to find new measures to meet Japan's obligations under the Kyoto Protocol.

In 2002 Japan introduced new guidelines for mitigation work on GHG emissions. The new approach was a "policy mix" that combined voluntary measures on the part of industry with restrictions and market-based instruments. In 2003 the Renewable Power Portfolio Standard (RPS) was introduced. This required that New Energy should account for a fixed percentage of the electricity

[26] In addition to biomass, thermal solar energy, PV technology and wind energy, this concept in Japan includes innovative utilisation of fossil fuels (co-generation), fuel cells, etc, and recycled fuel energy such as waste power generation.

[27] The Monitoring Programme for Residential PV Systems, administrated by the New Energy Foundation (NEF), was the first implementation programme for PV technology in Japan. The programme lasted from 1994-1996. The authorities subsidised 50 per cent of the installation costs and also subsidised local authorities with 40 per cent of the total installation costs.

[28] As of 2003, Japan is practically 100 per cent dependent on imports for access to petroleum.

supply and that this requirement could be met by buying and selling obligations from/to producers of renewable electricity.[29]

An important political ambition behind the Japanese introduction of New Energy is "the establishment of a prospering market". Through the formulation of long-term goals[30] industry will receive incentives for planning activities based on the expectation of establishing a market for New Energy. Industry can relate to such a long-term policy and the results, in the form of a growing market for "new energy", are very positive. The Japanese long-term goals were criticised for being unrealistic but this criticism has since proven groundless.

Integration of PV systems in new housing has been a decisive factor in promoting the use of PV technology in Japan. Japanese PV production has grown rapidly as a result of the development of "roof type" technologies and the Programme for Development of Infrastructure for the Introduction of Residential PV Systems subsidy programme in 1997. For Japanese housing companies the introduction of PV technology has been successful for the following reasons: access to PV modules (proximity to producers); limited land area; and high prices for land (PV panels on the roof or building-integrated PV systems are therefore advantageous). The increased environmental awareness among the Japanese population combined with high electricity prices has increased understanding of the concept of the Life Cycle Cost (LCC) for a whole building.[31] Roughly 50 per cent of the PV systems sold in Japan every year are sold in connection with the sale of new houses. It should be emphasised here – as underlined by Bjørseth - that the education and training of architects, designers and electricians installing PV systems are crucial to establishing and maintaining a market and its infrastructure.

Low interest rates and high prices for grid electricity are two important factors that have contributed to solar cells becoming lucrative in Japan. In Japan net metering[32] and grid connection of PV systems are routine. The price is higher during the daytime peak load, and that is a time of day when one does not consume the electricity oneself. In practice this means that PV system owners are able to pay off their investment because sales during peak load generate greater revenues than does their own electricity consumption during the evening and early morning.

4.4.2 Germany

The first subsidy programme for installing building-integrated PV systems in grid-connected applications was the German 1000 Roof Programme. In 1995 this programme reached its goal of installing one thousand small PV systems in households and small enterprises (Jackson and Oliver 2000). The subsequent introduction of the Renewable Energy Sources Act (EEG)[33] has also been important here. This administrative arrangement entails a twenty-year contract between German authorities and producers, specifying guaranteed prices for the duration of the contract period. This reduces the risk taken by the investors.[34] In addition the state bank Der Kreditanstalt für Wiederaufbau (KfW) granted loans at low interest rates to those who bought new PV systems under the 100,000 Roof Programme which was terminated on 30 June 2003. The German market accounted for approximately 20 per cent of the world market in 2000, but during this period Germany had a limited production[35] of

[29] The Ministry of Economy, Trade and Industry (METI) sets the aggregated goals (special treatment concerning PV) for the different forms of energy for a period of eight years ahead.
[30] Already in 1994 goals were formulated that entailed obligations up to 2010.
[31] LLC includes the house's total CO_2 emissions and compares this figure with corresponding overviews for conventional houses.
[32] Net metering: the consumer pays only the difference between the electricity generated from his own PV system and the electricity he buys from the net.
[33] Erneuerbare Energien Gesetzes
[34] Source: *Økonomisk forum*. 6:2004
[35] Germany has today expanded its wafer production through Bayer Solar, among others.

wafers. This made Germany the largest importer. In September 2003 EEG underwent revision. It was proposed that the 100,000 Roof Programme be phased out, but installed PV systems on buildings (roofs and facades) would still qualify for extra financing to compensate for the phasing out of other subsidy measures. This could further stimulate the demand for PV technology.

4.4.3 Norway

Of all the different political subsidy measures that exist, Erik Sauar believes, that instruments that stimulate a demand for the end product in a value chain, are the most successful. The situation in Germany in which the owner of the solar cell panel gets a price guarantee for the electricity sold to the grid is mentioned as one such example. Such subsidy arrangements stimulate competition among the actors when it comes to supplying the products to the end users at the cheapest possible price. There are at present relatively few building-integrated PV systems in northern Europe[36], but this market will grow in time.

Norway, however, has never had a subsidy programme for the use of solar cells as in Germany. Subsidy programmes for renewable energy are an item on the national budget and such subsidising can therefore vary considerably. The establishment of ENOVA (a public enterprise owned by the Royal Norwegian Ministry of Petroleum and Energy) has contributed to subsidy schemes becoming more stable. ENOVA provides investment aid for new systems and receives its financing through a fixed share of the revenues from the country's electricity bills. Sauar stated last year that ScanWafer had not had much contact with ENOVA. One reason for this is that ScanWafer has a large market that is outside Norway. Sauar further emphasises that the mandate which ENOVA has from the Storting (the Norwegian Parliament) is such that it would not be feasible for ENOVA to focus on anything other than the cheapest form of renewable energy.

ENOVA does not have the mandate to take into account the fact that solar energy has greater potential and causes less environmental damage compared to other forms of renewable energy technology. Such a mandate is irreconcilable with running introductory programmes for solar energy and therefore there is no point in discussing such matters with ENOVA. Instead it is necessary to approach the Storting. Sauar refers to the submission of a so-called Document 8 proposal from SV (Socialist Left Party) in which the government is asked to form a strategy for the commercialisation of solar energy.[37]

What then about SND? The total financial support received by ScanWafer to date for Glomfjord and Herøya adds up to NOK 20 million in subsidies and NOK 15 million in loans. According to Steinar Fredheim, consultant in Innovation Norway, such support was justified from the point of view that it was a corporate economic and socio-economic project which would otherwise have been established abroad. In addition, ScanWafer met the following concrete priority factors on which SND (Innovation Norway) based its assessments: new business, innovation, environment, international potential and area of restructuring.

ScanWafer's contact with SIVA (The Industrial Development Corporation of Norway) during the planning of the establishment phase in Herøya illustrates the limited contact with the regulatory authorities. ScanWafer was at the same time in the process of creating a project package for DnB in connection with possible financing from them. Collaboration with SIVA turned out to be complicated and time-consuming. Since DnB was already an important financial supporter and had to have the project package as quickly as possible, cooperation with SIVA was terminated and ScanWafer chose instead to pursue larger loans from DnB, something which DnB accepted.

[36] Source: www.pvnord.org
[37] Document no. 8:93 (2002-2003).

In the light of our conversations with central figures in ScanWafer and despite the financial support from SND, our impression is that the regulatory bodies have been of little significance for establishing the factories in Glomfjord and the factory in Herøya. Alf Bjørseth points out that it was rather the markets created by the authorities in Japan and Germany that have made ScanWafer's sales possible.

4.5 Cultural and social organisation

4.5.1 Research, education and legitimacy

ScanWafer is involved in EU projects under the 5th and 6th Framework Programmes. None of these projects has proven to have any great direct value in the form of commercially viable research results. The projects have however been successful in terms of creating networks, among both technology suppliers, cooperation partners and potential customers.

As regards relevant research funds **in Norway**, a previous criterion was that the new technology should better the Norwegian energy balance. In Norway the most electricity is consumed when the solar energy inflow is the lowest, and vice versa; solar energy does not score well in terms of the energy balance requirement. This is in stark contrast to the net metering system in Japan. Electricity from PV technology is far from being able to compete with conventional electricity in Norway. By comparison, wind energy is closer to becoming a competitive alternative in Norway, though the costs associated with grid connection may prove to be an obstacle there.

The discussion about supplying electricity to developing countries has not been a central issue in respect of requests for research funds.

4.5.2 Prevailing competence

It was important to ScanWafer's establishment in both Glomfjord and Herøya that industrial parks were already established there. This is because ScanWafer could thereby benefit from the competence of established and competent colleagues with experience from industrial activity and shift work.

4.6 Summary

Public subsidy programmes for solar energy abroad – particularly in Japan – and suitable conditions in Norway for wafer production lay the foundations for ScanWafer's success. Public bodies in Norway do not seem to have been decisive influences, but SND provided significant financial aid to the establishment in Glomfjord once sales contracts were signed.

The closure of industries in established industrial communities in Norway has been decisive for ScanWafer's establishment and growth. It also appears as if key industrial and financial actors, and relationships between these two, have been decisive for the establishment itself.

Alf Bjørseth is the most important actor behind the establishing of ScanWafer. His contribution in terms of knowledge, vitality and credibility with various technical, financial and commercial parties appears to have been absolutely crucial.

ScanWafer was started up at a time when the dominant PV technology was already established. Despite this, the company managed to get access to technological prototypes which have made radical improvements in productivity possible. The company initially utilised existing technology, but already when setting up Glomfjord it sought new solutions that involved considerable risks. Whether or not this represented radical or incremental changes is somewhat unclear, but ScanWafer undeniably realised an innovation that provides significant eco-efficient gains.

5 WHAT HAVE BEEN THE IMPORTANT DECISIONS AND CRITICAL STAGES IN THE DEVELOPMENT OF SCANWAFER SO FAR?

1. 1993: As a result of the fall of the Berlin Wall the supply of cheap metallurgic silicon from Eastern Europe became great, prices fell and Elkem experienced financial problems due to a decline in the market. All new investments were stopped and Bjørseth's proposal for wafer production was turned down. Bjørseth left Elkem.

2. 1994: Norsk Hydro phased out production of artificial fertiliser in Glomfjord. Meløy Næringsutvikling and Norsk Hydro tried to stimulate new industrial activity. ScanWafer was founded by Alf Bjørseth and Reidar Langmo (10.10.94), inspired by optimistic market evaluations made for the period up to 2010.

3. 1995: ScanWafer signed a sales contract with Naps (24.11.95), which in turn secured financing from SND for setting up Glomfjord I. Nordlandsbanken provided funds, enabling raw materials to be financed and production to be started.

4. 1997: Glomfjord I began production with 25 per cent capacity utilisation, equivalent to 2.5 MW solar efficiency of a total capacity of 10 MW. There were major technical challenges.

5. 1999: Bjørseth established good contacts in Japan. Melco's need for wafers was decisive for the establishment of ScanWafer's second factory in Glomfjord in 2001.

6. 2000: Sales contracts with Melco and Shell were signed, thereby securing sales of production from Glomfjord II despite a fivefold increase in production capacity.

7. 2001: Production started up at Glomfjord II. There were considerably fewer problems than with Glomfjord I.

8. 2002: REC's acquisition of SGS in USA for the production of silicon made the expansion of ScanWafer's production capacity in Herøya possible, as well as creating possibilities for expansion in Norway and/or abroad.

9. 2003: Hydro's strong desire to create new jobs in Herøya was decisive for setting up ScanWafer's factory in Herøya instead of in Germany.

6 FUTURE PROSPECTS

Today's solar cell industry is primarily based on crystalline silicon wafers. This industry is growing by over 30 per cent each year and future opportunities are enormous. Major changes in the energy system take a long time to materialise, and even if conventional energy carriers continued to prevail over the next 30 years there would be significant opportunities for an enterprise like REC and products from ScanWafer. The following example illustrates this point.

According to Bjørseth's estimations, today's global electricity production is 16,300 TWh. Today's solar energy accounts for approximately 4 TWh. The IEA (International Energy Agency) estimates the future growth rate for electricity generation to be 2.8 per cent, which means that the world's total demand for electricity in 2020 will be 26,000 TWh. If we assume a 25 per cent growth in production of solar energy, electricity generated from solar cells in 2020 could account for 186 TWh, or 0.7 per cent. Despite enormous annual growth rates it is obvious that there would still be room for the growth that ScanWafer is seeking.

6.1 ScanWafer: What are the current plans for future production and marketing?

ScanWafer is preparing to expand existing production both in Glomfjord and Herøya. Also, a new factory is to be built in Herøya. This factory will not involve any major technical modifications. In addition a new factory in a new location is planned. Potential locations are Årdal or Høyanger, or one of the German states with good financial aid schemes for companies establishing new industrial production.

If the new operation were to be established in Norway, investment aid would be crucial. Any such aid would probably have to be compared with potential investment aid offered in Germany. According to Erik Sauar the advantage of locating in Germany would be proximity to customers. Sauar stresses that the interest and commitment shown by the local authorities in Årdal is considerable. The potential loss of 800 jobs due to the gradual reduction of Hydro's aluminium operation is a major political issue. The fact that Årdal also has a significant metallurgic research community adds to the seriousness of this situation.

As is the case in Glomfjord, Årdal is an industrial community with long traditions, a fact that makes ScanWafer's potential establishment there a politically important issue. SIVA is considering building/renting the actual production building, so ScanWafer would not need to invest in the building itself. Innovation Norway is actively taking part in the discussions and the authorities are now expressing greater interest than was the case when Glomfjord I was presented to SND. Steinar Fredheim at Innovation Norway says that financial aid from Innovation Norway to Årdal in connection with the transition would amount to NOK 105 million.

Sauar comments as follows: "The conditions for newly-established enterprises in countries such as Germany are far better than in Norway. ScanWafer's competitors in Germany and Japan have wider access to investment aid and research funds".[38] To illustrate this point Sauar gives the example of the selection of a location for Crystal Silicon on Glass (CSG), of which REC is part-owner and Sauar is a board member, where Germany was chosen because the company would almost automatically receive

[38] Sauar does not believe that the extent to which new enterprises in these countries are "green" or not has any importance for these conditions.

40 per cent in establishment aid. In particular Sauar seeks more available research funds in Norway. The total available research funds for which ScanWafer can apply this year amount to NOK 6-7 million. By comparison the total available sum of research funds for CO_2-free gas power plants is much bigger, despite such projects perhaps being inferior in terms of eco-efficiency. ScanWafer's annual production in 2005 will be almost equivalent to the amount of energy produced from one of the planned gas power plants operated by Naturkraft – but without the CO_2 emissions!

The biggest bottleneck in continued growth is access to pure silicon. REC is in a strategically favourable position here, in that the company owns SGS, the only producer dedicated to solar cell silicon in the world. The ideal situation for ScanWafer would be that Solar Grade Silicon LLC also supplied other solar cell producers so that ScanWafer did not have just the one supplier and SGS just the one customer.

An agreement on this was signed in 2002, but happened to late to ensure good supplies for 2003. In 2004, however, SGS sold out of stocks, and now sells to four wafer manufacturers, i.e. approximately half of the large wafer manufacturers in the world. As SGS is the only solar cell manufacturer who actually produces silicon, the recent price increase for silicon is not especially worrying.

When it comes to improving wafer technology there is still much to be done. ScanWafer is not just working continuously on marginal modifications, but on radical ones. Sauar singles out the following areas within the manufacturing process which have a lot of potential: the raw materials (for example purification of silicon in gas form); the crucible (reusable crucible[39]), the crystallisation process, and cutting of ingots and wafers (including reducing breakage). In addition to this REC, and Bjørseth in particular, are looking at second generation solar cell technology – thin film – as well as utilising solar cells in hydrogen production.

6.2 Future prospects for the global PV industry

A large number of studies indicate that solar energy could become an important source of electricity in the future. Yet the example given at beginning of this section indicates that, even with a 25 per cent annual growth, the percentage of solar energy for the world's total electricity production will be negligible. Nevertheless Shell and others carried out a study which indicates that, by the middle of this century, the PV industry will come to be as big as the oil and gas industries. Road maps that show how such goals can be reached have been prepared by various organisations.

Increased use of PV technology for electricity generation is dependent on a steadily expanding access to silicon and wafers. But the development of technology within the global PV industry will naturally also influence ScanWafer's development potential.

In the first generation of solar cells there is today a competitive situation between monocrystalline and multicrystalline wafer manufacturers. It is quite possible that the differences in the efficiency of the cells from these two technologies will become bigger, but at present the cost of electricity supplied by monocrystalline and multicrystalline cells is fairly similar. There exists a theoretical possibility that monocrystalline solar cells will attain a greater efficiency around the year 2009 and this will increase the value of monocrystalline wafers compared to multicrystalline wafers. There is also a possibility that multicrystalline solar cells will attain improved efficiency. Thanks to access to information on monocrystalline processes received from Sitech[40], a new monocrystalline silicon wafer manufacturer established next to ScanWafer's two factories in Glomfjord, ScanWafer manages to stay up-to-date with developments made on the rival monocrystalline wafer. In *Photon International* (2004) it was

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[39] Currently ScanWafer must use a new crucible every time.

[40] The company was established around the same time as ScanWafer's first factory in Glomfjord was built. Sitech has the same owners as REC, but REC has no ownership interests in Sitech.

emphasised that interest in monocrystalline solar cell processes has grown considerably during the course of the last year.

The reason for this is the subject of some disagreement. AstroPower's bankruptcy in 2003 could be a contributing factor, but Bjørseth finds this difficult to understand because AstroPower was aquired by GE Solar, who maintains a strong orientation towards multicrystalline wafers. Greater efficiency has also been suggested as a possible explanation, but this difference has always existed and therefore does not appear to be a triggering factor. A more likely explanation could be that the supply of multicrystalline material has not been big enough to meet the demand. The interest in monocrystalline solar cells could also be explained simply by the reduction in price resulting from cost reductions through scale economies. Furthermore, technology development within the electronics industry is tending towards constantly larger ingots. This is why a number of crystal extractors for monocrystalline silicon are now being adapted for solar energy purposes. Whether monocrystalline solar cells will become market leaders of first generation solar cells will also depend greatly on price and access to raw materials because the crystallisation process for monocrystalline ingots requires a feedstock of a superior quality.

This could in turn stimulate the development of thin film as a more cost-effective alternative. In parallel with this it is also apparent that solar energy is moving directly towards visions of the hydrogen society. There are today electrolysers that split water into hydrogen, but this requires access to considerable supplies of conventional electricity. Prototypes that split water, and are based on solar energy, have already been developed, and this splitting can also be attained by using the wafers produced by ScanWafer.

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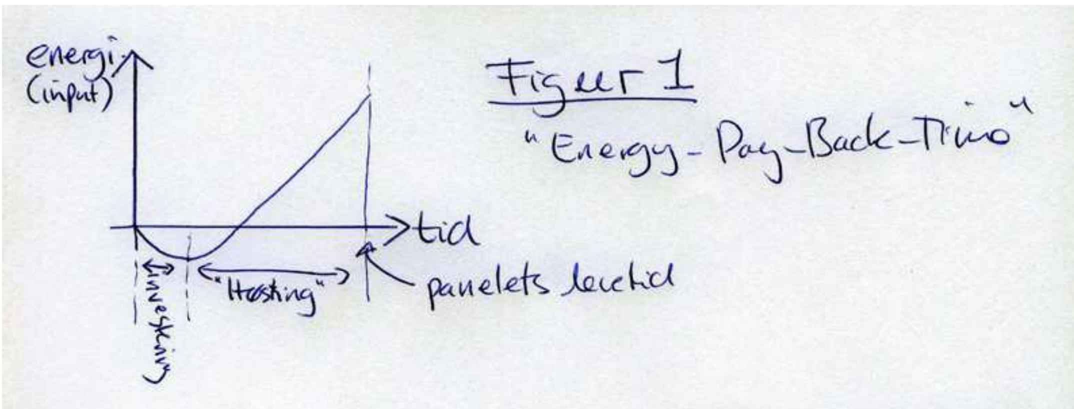
7.2 Oral sources

Alf Bjørseth and Erik Sauar, Renewable Energy Corporation A/S
Erik Marstein, Institute for Energy Technology
Viktor Jakobsen, former employee of Scanwafer, now associated with the Environmental Foundation Bellona
Fridjof Salvesen, KanEnergi and the Research Council of Norway
Other informants are mentioned in the footnotes.

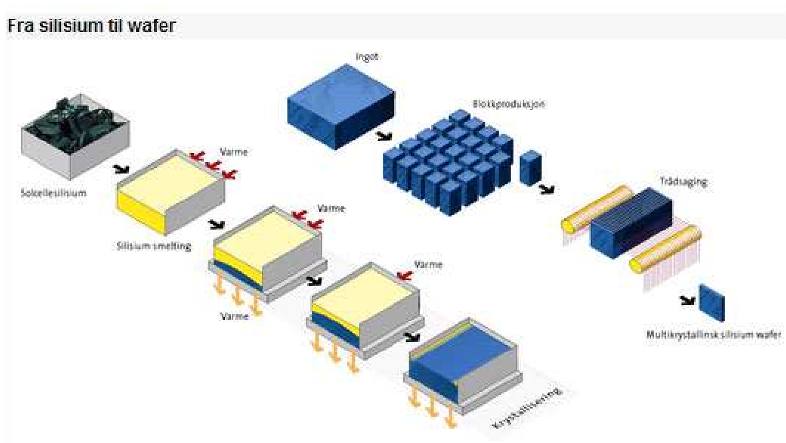
This memorandum/report is concluded in collaboration with Alf Bjørseth, REC.

The following figures are referred to in the text:

8.1 Figure 1: Energy Pay-back Time



8.2 Figure 2: From silicon to wafers.



Source REC's web site: http://www.rec-pv.com/text/view/3524.html