The Norwegian solar photovoltaic industry: a Triple Helix perspective

Antje Klitkou* and Helge Godø
NIFU STEP, Wergelandsveien 7, NO-0167 Oslo, Norway
* Contact E-mail: antje.klitkou@nifustep.no

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Introduction

During the last decade, a solar photovoltaic (PV) manufacturing industry centred in Norway has emerged and gained a share of 10 to 20 percent of various segments in the world market for solar PV feedstock, wafers and related components (Kirkegaard, Hanemann et al. 2010). According to experts, the future prospects for this new Norwegian industry is promising because of its focus on innovation and R&D (Bugge and Salvesen 2010). This development and its future prospects accord well with a Triple Helix perspective (Etzkowitz and Leydesdorff 2000). In contrast, more evolutionary innovation approaches did not anticipate this. An analysis by Narula (2002) suggests that inertia prevails in Norwegian large scale manufacturing industry, in particular its highly efficient and specialized metallurgic industry. Because of this, the analysis suggested that the industry was at risk because its specialization entailed structural lock-in, path-dependency and other factors that supposedly contribute to inertia, and, ultimately, to obsolescence. These evolutionary predictions have been contradicted in a number of ways: The metallurgic manufacturing industry has maintained its high profitability while simultaneously successfully expanded into manufacturing of PV. Although the success of this new Norwegian PV manufacturing industry may seem surprising, a Triple Helix perspective, with some adjustments, may provide a satisfactory explanation, in particular because this approach also accommodates the factor of human agency, development of knowledge and role of entrepreneurship, and related innovation dynamics (e.g. “niche creation”, “innovation regimes”), as will also be elaborated in the discussion of this paper.

The emergence and rapid growth of a Norwegian PV manufacturing industry may also seem surprising because the current domestic demand for PV-based energy production is negligible, i.e. microscopic for a number of reasons. Norway is not blessed with much sunshine (such as Spain, California or Arizona), but more fundamentally, Norway seems not to be dependent on PV because of its abundance of comparatively inexpensive hydroelectric power – a clean and renewable source of energy. Hence, policy measures and incentives, such as feed-in tariffs, tax credits, investment subsidies for solar PV deployment, which are used in countries such as Japan, Germany, Spain and USA, do not exist in Norway. The interest for PV technology development at Norwegian universities is less developed than in other countries. However, some research institutes have strong, albeit small, research groups doing PV R&D – and these collaborate closely with its counterparts in the PV manufacturing industry. As indicated, the emergence and rapid growth of a Norwegian PV manufacturing industry has its source in industry, in particular in energy intensive, large-scale metallurgic manufacturing industry – and was initially closely related to the activities of a few entrepreneurial industrial R&D scientists. Some of these describe themselves as “deviants” because of the initial resistance that they encountered in the industrial community in their early efforts to establish a PV manufacturing industry.

State of the art

Etzkowitz and Klofsten applied the triple helix model on the analysis of the innovative region around Linköping in Sweden (2005), highlighting the three main elements of the triple helix model: the role of the entrepreneurial university, collaborative relationships between universities, firms and government and that each institutional sphere also takes roles of the other two spheres.

The global shift in energy production from fossil fuels (in particular coal) and nuclear energy to more green energy production will require a massive transition to new energy production, i.e. establishment of a new energy production paradigm and associated radical technological innovation, such as solar PV. For today’s energy production system, this will imply what Schumpeter (1994) would term as “creative destruction” of our present, dominant modes of producing energy. In innovation research, explaining how and why radical innovations emerge and subsequently create new techno-economic paradigms has been an important research topic, as evident in theories on long waves (Freeman and Perez 1988; Perez 2002) and technological trajectories (Dosi 1988) and guideposts (Sahal 1985).

The *transition management approach* explains technological transitions by the interplay of processes at the macro, meso and micro levels. The macro level can also be defined as the *landscape* level which “refers to aspects of the wider exogenous environment". Landscapes cannot be changed by actors as they include factors such as "material environments, shared cultural beliefs, symbols and values" (Geels 2002). Landscapes that undergo change can exert pressure and destabilize *technological regimes* at the meso-level. Technological regimes are defined as "the rule-set embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures (Rip and Kemp 1998)". These features are embedded in institutions and infrastructures. Regime shifts involve changes in technologies and technical artefacts, as well as in user practices, policies, markets, industrial structures and supporting infrastructures (Geels 2002).

The notion of "niche creation" (Geels 2002) depicts how radical innovations are introduced and gradually evolve as they gain dominance and establish new technological regimes (Rip and Kemp 1998) and eventually create new techno-economic landscape (Cooke, 2008). In this, the conceptual framework of "innovation regimes" (Godoe 2000; Godoe and Nygaard 2006; Nerdrum and Godoe 2006) attempts to explain how such processes must be understood as outcomes of human agency (Godø 2008), i.e. that radical innovations are created on purpose – for a purpose. In this, as in the Triple Helix perspective, the notion of human agency, or more generally, the idea that innovation may be created because human beings, either individually, but usually collectively, define policy agendas and objectives or collaborate on solving these challenges, is fundamental. This provides a rationale for the current priority given to development of new renewable energy technologies. Although this perspective may become obscured by the complexity, size and volume of actions and processes that evolve over many years in efforts for creating innovative solutions (response to human agency), the quest for creating new renewable energy technologies for climate friendly, new energy systems has to be understood as a fundamental concern, hence, policy objective in most societies. This agenda emerged first after the oil crisis in 1973 and the break-through of environmental concern that came almost simultaneously, as evident in the "success" of the book *Limits to Growth* (Meadows, Meadows et al. 1989) that was first published in 1972.

Research focus

The paper addresses the development of interactions between key actors in the Norwegian solar photovoltaic industry and the Norwegian research system taking the Triple Helix perspective as a starting point. The paper analyses how different types of policy instruments strengthen the interaction of the solar photovoltaic industry in Norway and research organisations.

Methodology

The paper is based on a combination of qualitative (interviews and document analysis) and quantitative methods (project data and RD&D budget data).
Three different data sources have been used:

- Interviews with R&D programme managers of the Research Council of Norway (Brenna 2010; Moengen 2010), and researchers from NTNU, IFE and Sintef and industry experts from Elkem Solar, Metallkraft, REC Solar and REC involved in projects co-funded by industry and the Research Council of Norway (RCN); National and international collaborating patterns have been addressed in interviews with researchers and industry experts.
- Document analysis of R&D programmes, reports and policy documents;
- Project archive of the RCN (1996-2009)[1] and RD&D budget data (1975-2009) provided by the IEA.

This paper will present data on the interactions between existing companies, the emergence of a Norwegian PV manufacturing industry largely emerged from these companies, public R&D funding programmes and research organisations – and policy contexts that fostered the emergence of this new industry.

Findings

Global solar photovoltaic capacity has been increasing at an average growth rate of more than 40% since 2000 (IEA 2010). The European Photovoltaic Industry Association (EPIA 2010) estimates that there is a cumulative installed capacity of almost 23 GW in 2010, compared to 0.1 GW in 1992**Feil! Fant ikke**

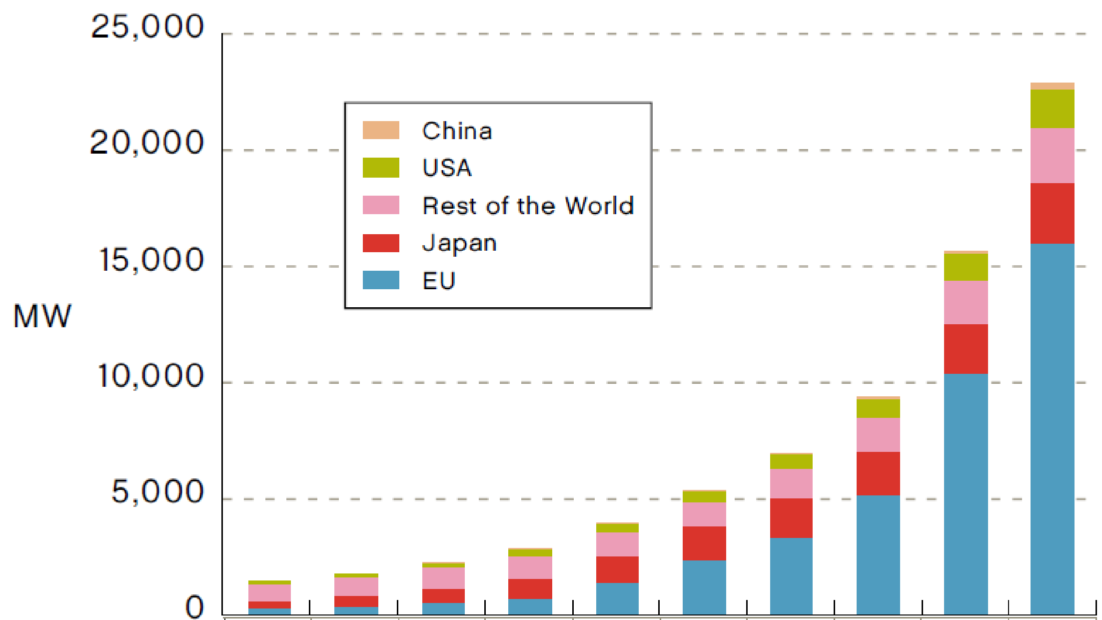
[1] One of the programme managers of the RCN pointed out that in the first years after 1996 not all project were registered there either. The project archive gives following information: the principle investigator (PI), the title of the project, the regional location and organisational and sectoral affiliation of the PI, start and end of the project, technological specialisation and in many cases also an abstract. The archive does not inform about collaboration partners in the project. Such information has to be gathered from the involved organisations, but this exceeds the scope of this paper.

referansekilden.). The highest growth rates achieve on-grid solutions, while off-grid solutions constitute less than 10% of the total PV market. The largest markets for solar photovoltaics are today in Germany, Italy, Spain, Japan and the United States. The global market of solar photovoltaics is still dominated by crystalline silicon; today 85-90% of the global sales are based on crystalline silicon.

The installed capacity in Norway was 8 MW_e in 2007 and is limited to off-grid installations, such as installations in cabins, leisure boats, light-houses along the cost (Moengen 2009). Since Norway has no incentive scheme for the installation of PV systems, the seasonal variation of solar radiation is large and the annual average irradiation just at about 1000-1200 kWh/m^2, the home market for a Norwegian solar cell industry is rather limited. Why could this industry cluster develop in Norway nevertheless?

There are special conditions which facilitated the development of the Norwegian solar photovoltaic industry cluster, such as industrial know-how about material processing in the light metal and ferroalloy industry, access to hydropower and private and public investors, availability of an educated work force, local government support, national and international R&D funding programmes, good connections to international technology suppliers and a strong international demand for silicon wafers. The configuration of these factors fit well into a Triple Helix perspective and will now be explained.

Figure 1: Historical development of World cumulative PV power installed in main geographies.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
China	19	30	45	55	64	68	80	100	145	305
USA	139	168	212	275	365	479	624	831	1,173	1,650
ROW	763	825	913	1,000	1,044	1,051	1,235	1,422	1,870	2,347
Japan	318	452	637	860	1,132	1,422	1,708	1,919	2,149	2,633
EU	189	286	422	633	1,319	2303	3,282	5,088	10,340	15,958

Source: EPIA (2010)

Although Norway lacks a public policy for promotion of a domestic market for PV energy production, there has been some public support for R&D related to PV, in particular funding of R&D collaboration between industry and research institutes. This funding, although modest, began subsequent to the oil crisis in 1973. In this period, a number of R&D programs on development of renewable energy sources were initiated, in particular ocean wave and wind energy technology development, but also bio-energy, solar and other “green” energy technologies were explored. During the 1980s and first half of 1990s, the level of public funding of renewable energy technological R&D gradually diminished, as in most other IEA/OECD member countries (Figure 2). Solar energy was addressed initially mainly by R&D programmes focussing on solar heating and cooling, but this domination was replaced by solar PV in 2000 (see Figure 3). As shown, from approximately 2003, the public funding of renewable energy R&D was increased dramatically; from 2006 this also happened to solar PV

R&D. However, as also shown in figure 3, the 2009 funding equivalent of 12 million Euros for PV R&D is not really impressive given Norway's vast fortune in terms of income deriving from energy production.

Figure 2: Norwegian public RD&D budgets for low-carbon energy technologies 1975-2009. In mill. Euro (2009 prices and exchange rates). Source: IEA.

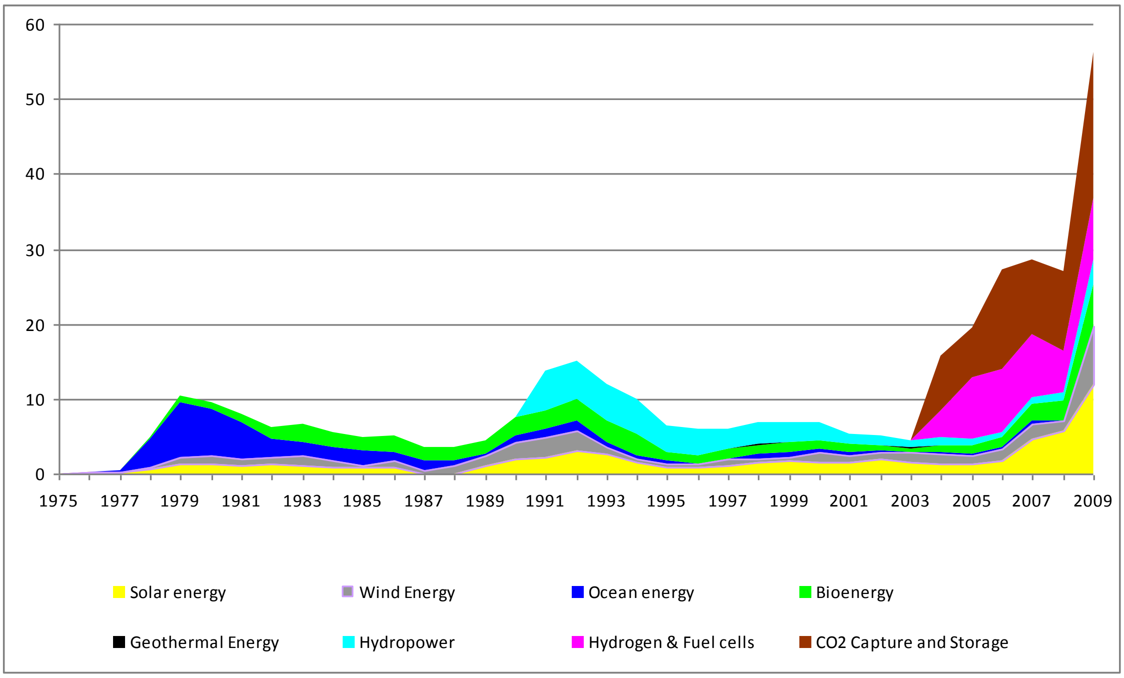
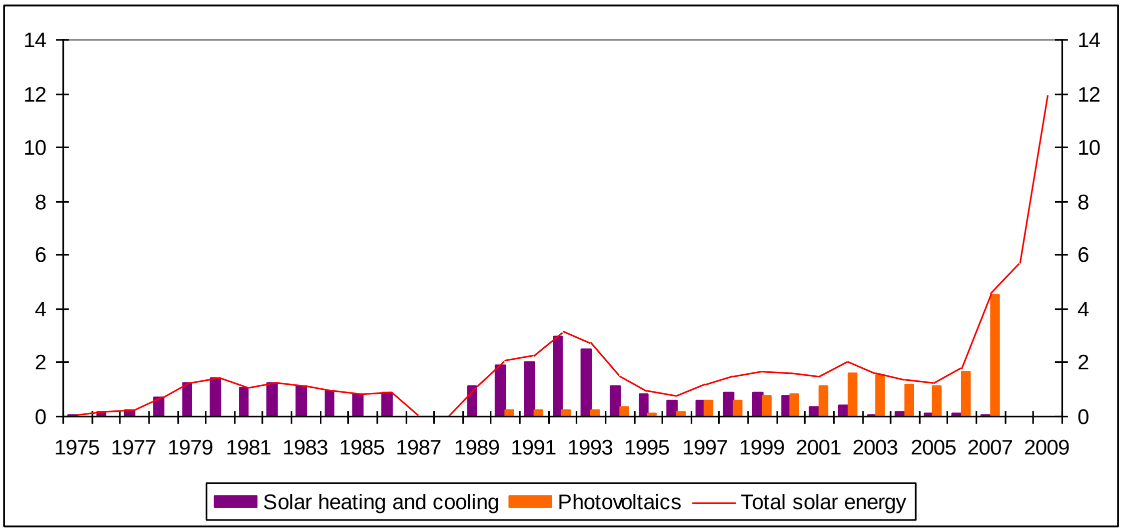


Figure 3: Norwegian public RD&D budgets for solar energy 1975-2009. In mill. Euro (2009 prices and exchange rates). Source: IEA.



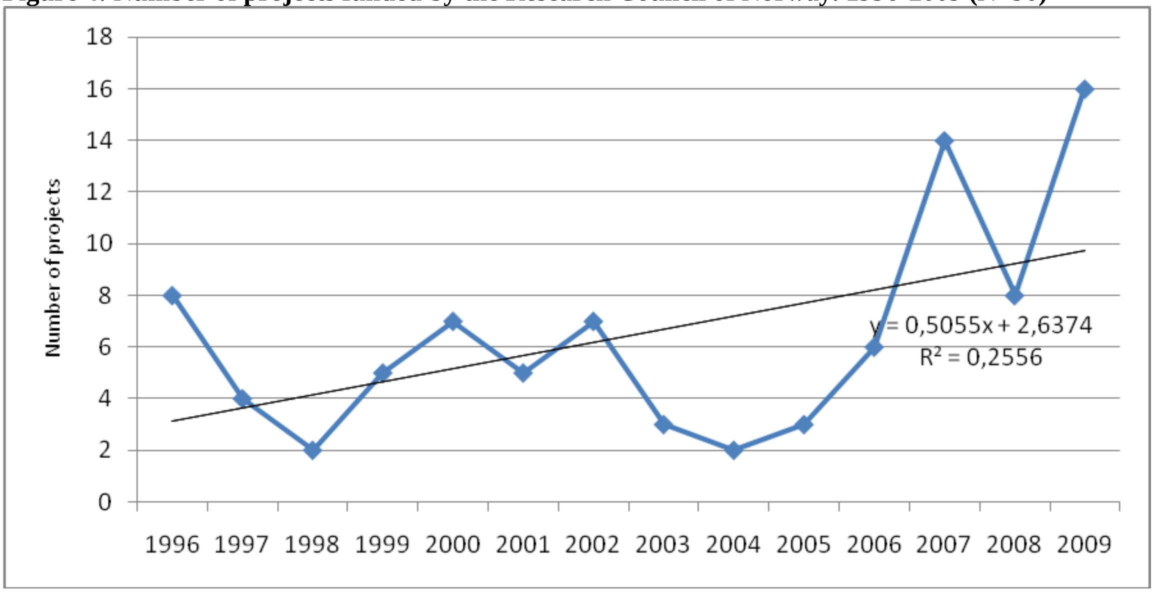
In the latter part of the 1990s, a number of R&D programs were initiated, in which industrial R&D entities and research institutes collaborated on solar PV. At this point, an embryonic PV manufacturing industry was established in Norway – and the subsequent rapid growth began. This establishment and growth point to the importance of developing a knowledge base and technological competence and R&D capability – and its strategic role for promoting innovation in industrial firms. In this, the Triple Helix perspective, with its institutional emphasis on a close relationship between academia, industry and government, may be fertile for explaining the emergence of the Norwegian PV manufacturing industry. In order to understand this, we need to look more closely to the strategic role of knowledge development and associated competence building related to the R&D activities that supported the emergence of a Norwegian PV manufacturing industry.

In the 1980s the Norwegian Parliament had prioritised funding of R&D on material technology in general (Brenna 2010). Public support of research on photovoltaic energy came on the agenda at the end of the 1980s in

Norway. A SINTEF-report from 1988 for the public research funding organisation NTNF[2] states that although Norway is (in 1988) a large producer of silicon, it lacks competence for developing solar cells - and that the prospects were not quite visible at that point (Hagen 1988; p. 13). However, in 1989, a ”Solar energy programme” (1989-1994) was initiated and later, the Norwegian research councils started several research programmes where industry and R&D organisations collaborated. The Solar energy programme was funded by the NTNF and the Ministry of Petroleum and Energy (OED), but it had more focus on solar thermal energy while funding of solar PV was only marginal (Moengen 2010). The metallurgic manufacturing company Elkem had received some funding from the solar energy programme for the development of a new production process of metallic silicon as an alternative to the dominating Siemens process (Henriksen 2010). This was followed up also by the next R&D programmes of the RCN.

According to informants, other policy instruments in addition to the programmes funded by the RCN played an important role in promoting the initial and later development of a Norwegian PV manufacturing industry. (Brenna 2010; Henriksen 2010; Moengen 2010). Such policy instruments are the Norwegian tax credit scheme SkatteFUNN (started in 2002), Public and Industrial Research and Development Contracts administered by Innovation Norway (founded in 2004) and its predecessors since 1996, co-funding provided by the Norwegian Industrial and Regional Development Fund (SND) and the Government Consultative Office for Inventors (SVO). Several regional policy instruments, such as county based investment funds and business development incubators, and industrial funds from larger industrial players, such as Norsk Hydro have also helped promote the development of this new manufacturing industry.

Figure 4: Number of projects funded by the Research Council of Norway. 1996-2009 (N=90)



Data Source: Research Council of Norway Project Archive.
Based on the starting year of each project

The public funding of PV R&D is seen in the project database of the Research Council of Norway. In the period from 1996 to 2009, this agency funded 90 projects with relevance for solar photovoltaics (Figure 4).

The projects were funded in different types of instruments under the Research Council of Norway. Funding for solar photovoltaic energy R&D has been given in two different types of funding streams from the RCN: Innovation oriented funding for the development of industrial activities in the silicon processing industry mainly by the Ministry of Trade and Industry (NHD) and R&D funding for the development of the Norwegian energy system by the Ministry of Petroleum and Energy (OED).

The *innovation oriented* projects have the firms’ own strategies in focus, such as capacity building and potentials for increased value added. The main funding source is the Ministry of Trade and Industry and R&D. They are co-financed by the industry and the main feature of such projects is that the project owner collaborates with

[2] NTNF is an acronym for Norges Teknisk-Naturvitenskapelige Forskningsråd (“The Norwegian Research Council for Technological and Natural Science Research”). In 1993, NTNF was incorporated in the new Research Council of Norway.

R&D organisations. Such collaboration involves funding of R&D at these R&D organisations, capacity building at these organisations, but also collaborative R&D processes where also the industry contributes with R&D capacity.

- Funding of industrial activities in the Norwegian processing industry targeted at the improvement of *silicon processing*: this was mainly provided by the innovation oriented programmes under the RCN specialised in material technology, which started with the programme EXPOMAT (Innovation programme for export oriented material production and processing, 1991-1995, not covered by the database). The programme decided to give funding to user-driven R&D projects instead of basic funding of the public research organisations. This approach supported an alignment of public R&D and industrial needs (Brenna 2010). Still more relevant became a new generation of programmes after the Research Council of Norway was established, including PROSMAT (Innovation programme for processing and material technology, 1996-2001), PROSBIO (Innovation programme for process- and biomedical industry, 2002-2005), and since 2006 the more general User-driven research based innovation programme (BIA). Recently, the Norwegian Ministry of Trade and Industry has given targeted basic funding to a strategic institute programme (SIP-NHD) for supporting R&D on silicon processing.
- Funding of industrial activities for the *production of solar cells* – mainly provided by the innovation oriented programmes introduced by the Research Council of Norway, such as NYTEK (Innovation programme for effective and renewable energy technologies, 1995-2000, co-financed by OED and NHD), VAREMAT (Innovation programme for industrial manufacturing and materials conversion, 2002-2005) and since 2006 BIA was very important for the development of the knowledge base at the public research organisations and the solar PV industry in Norway (Skaret 2001).

R&D Funding from the OED for the development of environmental friendly energy has to serve different technologies, such as offshore wind, bio-energy, geothermal and ocean energy, hydrogen and carbon capturing and storage. Photovoltaic solar energy is not prioritised in the Norwegian energy system because of the rather low annual average solar radiation at about 1000-1200 kWh/m^2 compared with Southern Europe with up to more than 2200 kWh/m^2 (Šúri, Huld et al. 2007). Therefore *research funding* of solar energy was just one among other possibilities.

However, over the last years this has been adjusted somehow.

- Recently, especially the strategic research programme Clean energy for the future (Renergi, 2004-) including the Centres for Environment-friendly Energy Research (FME) should be highlighted (compare Moengen 2009; Moengen 2010). The FMEs have a long-term perspective giving funding up to 8 years. The FME scheme was introduced in 2009, and one of the FME centres is promoting Solar photovoltaics (Marstein 2010). It has the goal to give the Norwegian photovoltaic industry access to world leading technology and scientific expertise. It is concentrating the most important firms and research groups from research institutes and universities specialised in solar photovoltaics.
- The strategic research programme Nanotechnology and new materials (NANOMAT, 2004–) gives funding to the development of new generations of solar cells based on nanotechnology.
- The OED has also given targeted basic allowances by strategic institute programmes (SIP-OED) for supporting R&D on highly efficient solar cells.

In addition there was a strategic university programme financed by the Ministry of Research and Education.

The following figure summarises the development of the funding schemes, while Table 1 shows the information in more detail.

Figure 5: Main Norwegian innovation and R&D funding schemes for solar photovoltaics 1990-2009

1990-1994	1995-1999	2000-2004	2005-2009
EXPOMAT			
	NYTEK	NYTEK	
	PROSMAT		
		PROSBIO	
		VAREMAT	
			BIA
			SIP-NHD
SOL-EN			
		EMBA	
		RENERGI	RENERGI
			NANOMAT
		SIP-OED	SIP-OED
		SUP-KUF	

Note: The colours indicate different funding sources: blue for NHD, green for OED, violet for a mixture of NHD and OED, and yellow for KUF. The saturation of the colours indicates the importance of the scheme.

The involved actors can be grouped in mainly two groups: industry and public research organisations.

Over the years, the diversity of industry actors in the PV business doing R&D has increased: In the start of the period was only one firm active in the field – Elkem AS (Sogner 2003; Henriksen 2010). Afterwards REC Scanwafer AS was established and started doing R&D, while now about 20 firms receive funding from the RCN as project leaders (see Table 2). Companies participate also in several of the projects lead by public research organisations. At present, the Norwegian photovoltaic industry consist of about 50 enterprises (Moengen 2010).

Table 1: Funding instruments under the Research Council of Norway supporting solar photovoltaic technology development. 1996-2009 (N=90)

Type of project	Name of the programme	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	*Total*
Innovation	Effective and renewable energy technologies (NYTEK)	4	4	2	1	3	2									*16*
Innovation	Process- and biomedical industry (PROSBIO)	1						1								*2*
Innovation	Process- and material technology (PROSMAT)	2			1											*3*
Innovation	Industrial manufacturing and materials conversion (VAREMAT)									1						*1*
Innovation	User-driven research based innovation (BIA)											1	4	5	8	*18*
Basic allowance	Strategic Institute Programme NHD													1		*1*
Strategic priorities	Centres for environment-friendly energy research (FME)														1	*1*
Strategic priorities	Clean energy for the future (RENERGI)							2	2	1	2	4	1	2	3	*17*
Strategic priorities	Energy, environment, construction (EMBA)	1			3	4	2	2								*12*
Strategic priorities	Nanotechnology and new materials (NANOMAT)										1		8		3	*12*
Basic allowance	Strategic Institute Programme OED: Energy sector							1				1				*2*
Science	Physical sciences and technology								1						1	*2*
Science	Heavy equipment												1			*1*
Science	PhD stipend							1								*1*
Basic allowance	Strategic University Programme - KUF						1									*1*
	Total	*8*	*4*	*2*	*5*	*7*	*5*	*7*	*3*	*2*	*3*	*6*	*14*	*8*	*16*	*90*

In 1989, the Norwegian ferroalloy producers established a research association, the Norwegian Ferroalloy Producers Research Association, FFF (Brenna 2010). The FFF was founded by representatives from the companies Elkem, Tinfos Jernverk and Fesil as a non-profit organisation, and FFF obtained about half of the initial annual budgets from the RCN (FFF 1994). The RCN was present at the board meetings of the FFF as an observer. The FFF had the objective to carry out joint research on ferroalloy processes and products and to contribute to capacity building. Research on silicon as a raw material for the chemical industry was one of the priorities co-funded by EXPOMAT. This priority was strengthened later with support from PROSMAT. In 1993, on request of the RCN, FFF carried out a foresight study on future R&D perspectives for the Norwegian ferroalloy industry (Nygaard 1993). The report from this study recommended FFF to continue giving priority to R&D on silicon for solar cells. The study also predicted a strong increase in demand for such silicon especially on the U.S. market, but observed that Norwegian industry at that time was not able to produce silicon with the requested degree of purity. The report also highlighted the positive results from the national co-operation which was funded under EXPOMAT: In addition to the collaboration organised by the FFF, the report identified the collaboration between Elkem and Sintef as a competitive advantage. A stronger integration between Elkem and universities was pointed out as a need for further development. Two of the most important R&D projects were the projects ‘From sand to solar cells’, I and II (Brenna 2010; Moengen 2010). The purpose of the project was to develop the knowledge base on silicon materials for solar cells at the NTNU and Sintef. The project was initiated with funding from the NTNU’s Industry idea fund and later co-funded by the RCN, Elkem and Scanwafer.

Norwegian public research organisations, i.e. both universities and independent research institutes, are also involved in doing solar photovoltaic R&D, often in close collaboration with industrial companies. Research organizations doing PV R&D are the Institute for energy technology (IFE, 10 projects) and Sintef Materials and Chemistry (3 projects). A newcomer is NORUT in Northern Norway. Sintef is very close to the NTNU (university in Trondheim - 3 projects), one of the most active universities in addition to the University of Oslo (4 projects), but the universities have different specialisation profiles in terms of research topics. The largest companies co-finance master education and PhD students at the Institute for energy technology and the NTNU as their main contribution to these projects. A large number of so-called knowledge-building projects with user involvement contribute to capacity building and are aiming at improved recruitment conditions for Norwegian companies.

Table 2: Norwegian companies leading R&D projects co-funded by the RCN (N=62)

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Total
3G SOLAR AS													1		1
ABALONYX AS														1	1
Elkem AS Carbon	1														1
Elkem ASA	2	1	1	2	1	2	2							1	12
Elkem Solar AS - Kristiansand										1	1	2	1	1	6
Fesil Sunergy AS											1			1	2
FFF	2			1			1			1					5
HyCore ANS												1			1
Hydro Aluminium Vekst AS					1										1
INNOTECH SOLAR AS														2	2
Isosilicon AS														1	1
KanEnergi AS								1			1				2
Metallkraft AS														2	2
Norsk Solkraft AS												2			2
NorSun AS													1		1
Norwegian Silicon Refinery AS		1													1
REC ASA											1				1
REC ScanCell AS													1		1
REC Scanwafer AS		2			4		1		1			1			9
REC Solar AS												1			1
REC Wafer Norway AS														1	1
Scatec AS														1	1
Solar Silicon AS			1	1	1	1									4
Sweco Norge AS											1				1
Umoe Solar AS													1	1	2

Source: Project archive of the Research Council of Norway

According to one analysis, the companies apply different technology approaches for improved silicon based wafers (Ruud and Larsen Mosvold 2005). Hence, they have developed horizontal diversity, but less a vertical integration in the value chain. Norwegian firms function as suppliers of wafers for international photovoltaic module producers, but there are also new segments in the industry specialised in – repowering and upgrading of degraded solar cells. The most important firms have also international networks where they are active in different parts of the value chain, such as the REC Group. The REC Group manufactures solar cell modules in Sweden. The most central industry players with more than 10 projects each are REC and Elkem. They are engaged in a large variety of projects aiming at new technology development and capacity building in Norwegian universities and research institutes.

Norwegian processing industry specialised in silicon has over many years developed its expertise and we argue that it is by no means dominated or even locked-in by its technological specialisation. In order to be competitive, the industry has strong incentives to increase profitability by decreasing energy costs related to manufacturing of PV, which explains why they have developed high quality, efficient process technologies. The high diversity of advanced technology approaches funded by the industry indicates this industry is advanced also in a global comparison. The research institute sector and especially IFE and Sintef are eager to serve this industry and have invested in infrastructure and people to enable this task. The only bottleneck highlighted by the industry is a lack of human capital from national universities. Research collaboration is addressing these shortcomings. Research institutes host PhD candidates from the universities in industry co-funded RD&D projects, and infrastructure relevant for further RD&D on solar PV has been built up by Sintef and NTNU, Sintef and University of Oslo and the Institute of energy technology.

Contributions

As seen in the material presented in this paper, the establishment and subsequent growth of a Norwegian PV manufacturing industry is closely related to the prolonged R&D efforts that were initiated many decades ago. Early in this period, the idea that Norwegian metallurgic industry could expand into PV manufacturing was not an explicit objective. Based on an evolutionary innovation approach, one analyst (Narula 2002) even predicted that this industry was at risk because of what was interpreted as "inertia" due to its high efficiency and specialization. By funding public R&D in collaboration with industry for a long time (decades), and by this fostering a community for development of renewable energy technology (innovation regime), the Norwegian R&D system has been able to leverage the embedded knowledge and know-how in the traditional (but highly sophisticated and advanced) metallurgic industry. This constituted the foundation of a new solar PV manufacturing industry in Norway.

Looking back, this development fits into the notion of co-evolutionary process (Carlsson and Stankiewicz 1991) with a global reach: The new Norwegian PV manufacturing industry emerged "just in time" to meet a surge in demand caused by initiation of new energy policy measures in countries such as Germany, Spain and USA, thereby giving this fledgling industry what some would call a "flying start", i.e. a strong demand for PV products in international markets. In this development, a few Norwegian industrial scientists qua entrepreneurs were able to anticipate this and seized the opportunities that emerged by building up the new PV manufacturing industry. However, without the industrial, technological and scientific knowledge base and the R&D activities that had been undertaken earlier, it seems difficult to imagine how this could have been achieved otherwise. Furthermore, once PV manufacturing began, firms were also given framework conditions by government (financial support, credits, manufacturing infrastructure, etc.) that were benign – and that the entrepreneurs were able to utilize in order to expand their industry. Hence, explaining how and why this new Norwegian PV manufacturing industry emerged, the Triple Helix perspective provides a fertile framework. The new Norwegian PV manufacturing industry emerged as the result of a prolonged, albeit loose interaction between:

- *Industry*, specifically the "traditional", highly efficient, specialized and technologically sophisticated metallurgic manufacturing industry of Norway,
- *Government*, reflecting policy goals and public concerns advocating the need for changing traditional energy production systems, and for providing funding and framework conditions for R&D, technology development and industrial infrastructure,
- *Academia*, specifically technologically specialized research institutes for undertaking and pursuing R&D relevant for development of new energy technology, of which contribution to development of solar PV manufacturing has been one of its priorities. This R&D community is also working with other energy technologies, such as fuel cells, wind and ocean energy, bio-fuels, etc., i.e. development of the knowledge base, which in the future may experience the type of success as seen in solar PV.

Implications

Gradually, during the last decade, the topic of climate change and the need for societies to shift their energy consumption to renewable energy sources has gained increasingly high priority on policy agendas in most OECD member countries. During the regime of the US president Bush jr., much attention was given to hydrogen and fuel cells, but afterwards, other types of renewable energy technology, such as wind power and solar PV have become more in focus. According to the International Energy Agency's predictions (IEA 2010), solar PV has now almost obtained "grid parity" in terms of costs. IEA expects that by 2050, the cost of solar PV will be approximately 1/3 of today's, i.e. solar PV will become very competitive in the future, more so than fossil fuel power generation and other types of renewable energy sources. However, this will require substantial R&D and technology development – and economic incentives in order to promote the diffusion of solar PV in societies. At present, the share of energy production from solar PV is miniscule. In a Triple Helix perspective, the implication of this is that a close relationship and coordination between industry, government and academia (including research institutes) will be required.

The presented results will have implications for future analysis of the national and regional interaction between industry, universities, research institutes and government.

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