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Förord

Energi direkt från solen är en globalt sett underutnyttjad resurs med potential att täcka mänsklighetens energibehov många gånger om. De senaste åren har kostnaderna för solceller kraftigt sjunkit, och 2011 nyinstallerades dubbelt så stor effekt i solceller som vindkraft i Europa. Med denna utveckling kan el från solceller få en allt större roll också i det svenska energisystemet. Sverige har dessutom som mål att ha en fordonsflotta oberoende av fossila bränslen till 2030, vilket ökar pressen att ta fram alternativ och sätter ljuset på tekniker som direkt omvandlar solljus till bränslen – ”solbränslen”.

Mot denna bakgrund har Energimyndigheten beställt en rapport på områdena solceller, termisk solkraft och solbränslen. Rapporten ska ge en samlad bild av marknad och forskning, nationellt och internationellt, inom de berörda områdena. Rapporten sammanställer Energimyndighetens forskningssatsningar och ger rekommendationer för hur forskning, utveckling och innovation inom området kan stödjas framöver för att bäst bidra till omställningen av energisystemet.

Rapporten är författad under 2011 av Bengt Ridell, Ronny Nilsson och Björn Rehnlund från Grontmij, samt professor Bengt Kasemo från Chalmers. Synpunkter har under processens gång lämnats av en styrgrupp bestående av representanter från näringsliv och akademi, samt vid en workshop där ett 40-tal inbjudna intressenter kom med förslag och synpunkter.

Eskilstuna 2012

Birgitta Palmberger

Avdelningschef

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Executive Summary

Background and analysis

The current domination of fossil fuels for both total energy supply and electricity supply in the world is expected to remain for a long time. At the same time climate effects and decline of fossil resources put demands on development of sustainable energy sources. Two potential long-term sustainable solutions, which are the topics of this report, are solar electrical power and solar fuels.

Installed power for **solar electricity** from photovoltaic (PV) solar cells has shown a dramatic increase over the past few years, especially in Europe, with a tripling of installed solar cell capacity from 2009 to 2011[1]. Simultaneously the associated cost per kWh has decreased dramatically.

Globally solar electricity is dominated by crystalline silicon (c-Si) based solar cells. The price has decreased and some public sector support schemes have accordingly been reduced per energy unit, but are in absolute numbers still substantial. Thin film solar cells have also reached the market; they are cheaper to produce but have lower efficiency than c-Si cells. The same comment applies to polycrystalline and amorphous silicon films. New technologies such as dye sensitized solar cells (DSSC) and organic/polymer solar cells have not yet made any significant market impact, but R&D is intensive and niche applications exist. An interesting development for any type of solar cell is the area of concentrated PV (CPV), which reduces the required module area as well as land area required through concentration of the solar light by optical devices. Nanotechnology can improve both silicon and other types of solar cells, for example by employing nanostructuring of solar cells and plasmonics for enhanced light management and capture.

A complementary technology for utility scale electricity production is concentrated thermal solar power (CSP) based on optical concentration of solar radiation (similar to CPV), and heating of e.g. water to create steam that drives a turbine and an electricity generator. This technique is rapidly increasing in the sun-belt of USA and Southern Europe.

The global research about solar cells, as measured by publication frequency, is rapidly increasing. The dominating areas are silicon solar cells together with thin film solar cells, organic/polymer solar cells and dye sensitized (Grätzel) solar cells. Publications relating to using nanotechnology as a facilitator or creating "add-ons" for improvements of these solar cells are also rapidly increasing.

In Sweden the publication pattern differs from the global one. There is very little research on silicon cells, and most research concerns DSSC, thin films of non-

[1] EPIA 2011 Market Report

silicon materials and organic/polymer cells. The ongoing research is dominated by physics-chemistry disciplines, with much smaller activities at engineering departments. There is essentially not yet any fundamental research on CSP in Sweden, except for some recent single examples

Solar fuels is a much less mature area than solar cells or CSP. The area is dominated by fundamental research and some applied research. There is no significant commercial/market activity. Solar fuel production is the direct conversion of solar energy to useful fuel, either by using photoactive microorganisms, like algae or bacteria, or using photoactive synthetic devices, often referred to as artificial photosynthesis, photoelectrochemical, photocatalytic or photoelectrocatalytic devices. Historically solar fuels were almost totally focused on hydrogen production. More recently other fuels like alcohols and hydrocarbons have received increasing interest. One specific new interest is using CO_2 in solar fuel production, since it potentially may allow useful fuel production with solar energy, which is compatible with existing fuel distribution infrastructure and with sequestration of CO_2. In Sweden there is strong research on use of molecular complexes (artificial photosynthesis) and micro-organisms and some research on photocatalytic processes. However, the energy extracted per unit area by solar fuel production techniques is 10–100 times lower than energy extracted by PV on the same area.

The R&D arena in Sweden on solar energy is very much at the basic science level, with a structure that can be characterized as “bottom up”, i.e. with few ingredients that are initiated by demands (top down) from industry or the public sector. Academic activities at engineering departments are small.

Opportunities and needs for the future are based on the likely scenario that the ongoing rapid increase of installations of solar power in the world will continue to accelerate. This will create many opportunities for Swedish industry, not the least for export industry, at many different systems levels, from single components to full systems. A Swedish research program should not only serve the long-term research of the type that is already on-going, but should also support research at the engineering levels and top down initiated R&D, i.e., R&D initiated by needs in society and/or industry.

Proposal for a future Swedish research program

I. Continued support is recommended of ongoing or new internationally competitive research activities and environments, according to the bottom up principle. These activities should be based on, and evaluated with respect to, scientific excellence and their relevance to the solar power or solar fuel areas. Such support serves the long-term knowledge and competence needs in the solar electricity and solar fuels areas.

II. Complement the research activities described under I. with ”top down” based efforts in more specific areas. This will require a deeper analysis (inventory) of the needs and opportunities that can be identified for Swedish industry and society today and for a foreseeable future.

III. Take actions to achieve better coordination of the R&D efforts supported by public funding from various sources. The Swedish Energy Agency appears as the most suitable agency for such coordination.

The fast development of production technology, with corresponding decreasing costs for crystalline silicon may be a paradigm shift in the solar energy world. In this context the absence or weakness of special expertise in c-Si and Si thin film technology in Sweden could be seen as a decisive disadvantage, since the Si technology might be the leading technology for a foreseeable future. A strategic choice to be discussed is if Sweden should reconsider and find niche areas within the crystalline silicon technology where a leading knowledge may be gained and may be beneficial to Swedish industry, for instance enhancement of the c-Si technology by add-ons developed from existing competences in Sweden.

The solar hydrogen technologies have a long-term horizon and the development is to a great extent dependent on the introduction of hydrogen as a fuel for transport. The solar hydrogen technologies, including artificial photosynthesis and microbial hydrogen production, will most probably not reach commercialization in the coming decade. Market introduction, if and when, are unpredictable in this area. The different technologies should benchmark on other technologies that can be used for production of hydrogen from renewable sources, such as PV/wind together with electrolyser technologies. Switching to other solar fuels with essentially the same concepts as for hydrogen production, and/or involving CO_2 as raw material and alcohols/hydrocarbons as end products, are very interesting developments that should be regarded as parallel tracks and alternatives to hydrogen production.

Sammanfattning

Bakgrund och analys

Fossila bränslen dominerar världens energiförsörjning och tycks fortsätta göra det för en tid framöver, trots att de utgör en ändlig resurs. Samtidigt ställs allt högre krav att mildra klimateffekter på grund av ökade utsläpp av växthusgaser. Vi strävar därför efter att öka utvecklingen och användningen av hållbara energikällor. Två potentiellt långsiktiga hållbara lösningar, som beskrivs i denna rapport, är solkraft och solbränslen.

Installationer av solceller (PV) har visat en dramatisk ökning under de senaste åren, särskilt i Europa, med en tredubbling av den installerade effekten från 2009 till 2011[2]. Samtidigt har kostnaderna per producerad kWh också minskat dramatiskt. Den klart dominerande tekniken för solceller är baserad på kristallint kisel (c-Si). Priset för sådana celler har sjunkit väsentligt, och subventionerna har börjat minska, speciellt i Tyskland, men är i absoluta tal fortfarande betydande. Tunnfilmssolceller har också nått marknaden. De har lägre tillverkningskostnad men även lägre verkningsgrad än c-Si-celler. Nya tekniker såsom ”dye sensitized solar cells” (DSSC eller Grätzelceller) och organiska/polymera solceller har ännu inte nått en större marknad men intensiv forskning och utveckling pågår och speciella nischtillämpningar finns. En intressant utveckling är koncentrerad PV (CPV) då solljuset koncentreras med hjälp av optiska enheter vilket minskar den erforderliga modularean. Nanoteknik kan förbättra olika typer av solceller till exempel genom att använda nanostrukturering och ”plasmonics” för ökat upptag av solljuset.

En annan viktig teknik för elproduktion med hjälp av solenergi är koncentrerad termisk solenergi (CSP) baserad på optisk koncentration av solstrålning och uppvärmning av t.ex. vatten för att skapa ånga som driver en turbin med en elgenerator. Denna teknik ökar snabbt speciellt i solbältet i södra USA och även i Sydeuropa.

Den globala forskningen inom solcellsområdet ökar snabbt, vilket avspeglas i antalet publicerade vetenskapliga rapporter. Det dominerande området är kiselsolceller följt av tunnfilmssolceller, organiska/polymera solceller och DSSC-solceller. Publikationer som beskriver nanoteknik för att skapa ”add-ons” eller andra förbättringar för att effektivisera solcellstekniken ökar också snabbt.

I Sverige skiljer sig publikationsmönstret från den globala trenden. Det finns mycket lite forskning kring kiselsolceller. De flesta publikationerna avser DSSC, tunnfilm av andra material än kisel, och organiska/polymera celler. Den pågående

[2] EPIA 2011 Market Report

forskningen domineras av fysik-kemi- discipliner med liten verksamhet vid mera tekniska/tillämpade avdelningar. Det finns i huvudsak inte någon offentligt finansierad forskning inom CSP i Sverige, med undantag för några enstaka projekt.

Solbränslen är ett mycket mindre moget område än solceller och CSP. Området domineras av grundforskning. Det finns inga betydande kommersiella aktiviteter. Produktion av solbränsle är direkt omvandling av solljus till användbart bränsle, t.ex. genom användning av fotoaktiva mikroorganismer (alger, bakterier) eller m. h. a. fotoaktiva syntetiska enheter (ofta kallad artificiell fotosyntes). Historiskt sett har området varit fokuserat på produktion av vätgas. På senare tid har även andra bränslen som alkoholer och kolväten rönt ökat intresse. Möjligheterna att använda CO_2 i solbränsleproduktion har fått ökat fokus eftersom det potentiellt kan ge användbara bränslen producerade med solenergi t.ex. metan, som är kompatibelt med kommersiella bränslen och kan användas i befintlig infrastruktur. Emellertid är den energi som produceras per ytenhet genom solbränsleproduktion 10-100 gånger lägre än energiproduktion m. h. a. solceller. I Sverige finns en stark forskning kring användning av molekylära komplex (artificiell fotosyntes) och mikro-organismer samt viss forskning på oorganiska fotokatalytiska processer.

Forskningen i Sverige inom solenergiområdet har stort fokus på den grundläggande vetenskapliga nivån med en struktur som kan beskrivas som ”bottom-up”, dvs. med relativt få inslag av krav eller tillämpningsinsatser från industrin eller den offentliga sektorn.

Möjligheter och behov för framtiden baseras på det sannolika scenariot att den pågående snabba ökningen av installationer av solenergi, främst solel, i världen kommer att fortsätta att accelerera. Detta kommer att skapa många möjligheter för svenskt näringsliv, inte minst för exportindustrin med omfattning från enskilda komponenter till kompletta system. Ett svenskt forskningsprogram bör inte bara vara inriktat på långsiktig forskning av den typ som redan pågår, utan bör paras med forskning av mer teknisk/tillämpad natur och FoU initierat av behoven i samhället och industrin.

Förslag till ett framtida svenskt forskningsprogram

I. Fortsatt stöd rekommenderas till pågående och ny internationellt konkurrenskraftig forskning och miljöer, enligt “bottom up”-principen. Stödet bör grundas på och utvärderas med avseende på vetenskaplig kompetens och dess relevans för områdena solel eller solbränsle. Sådant stöd gynnar långsiktig kunskaps- och kompetensuppbyggnad inom hela solenergiområdet.

II. Komplettering av den forskningsverksamhet som beskrivs under I. med ”top down”-baserade insatser inom specifika områden. Detta kommer att kräva en djupare analys med inventering av de behov och möjligheter som kan identifieras för svenskt näringsliv och samhälle idag och för en överskådlig framtid. Efter denna typ av analys kan avancerad teknik- och innovationsupphandling vara ett effektivt redskap att utveckla svensk solenergiindustri.

III. Åtgärder för att uppnå bättre samordning av de offentliga FoU-insatserna. Energimyndigheten är sannolikt det lämpligaste organet för sådan samordning.

Den snabba utvecklingen av produktionsteknik med motsvarande minskade kostnader för kristallina kiselsolceller kan vara ett paradigmskifte inom solenergivärlden. Frånvaro av specialkompetens inom c-Si i Sverige kan bli en avgörande nackdel eftersom c-Si teknik kan vara den ledande tekniken för överskådlig framtid. Ett strategiskt val som bör diskuteras är om Sverige skall ompröva och hitta nischer inom c-Si tekniken där en ledande kunskap kan erhållas och bli till nytta för de svensk industri, till exempel förbättring av c-Si teknik genom ”add-ons”, som kan utvecklats med befintlig kompetens i Sverige.

Solväteteknikerna har en långsiktig utvecklingshorisont och är starkt beroende av införandet av vätgas som bränsle för transporter. Solväte, inklusive artificiell fotosyntes och mikrobiell produktion av vätgas, kommer troligen inte att nå kommersialisering under det kommande decenniet. Om och när marknadsintroduktion sker är oförutsägbart inom detta område. De olika teknikerna ska också jämföras med andra tekniker som kan användas för produktion av väte från förnybara källor såsom PV/vindkraft tillsammans med elektrolys. En intressant utveckling och parallellt spår är byte till andra solbränslen än vätgas, men med väsentligen samma koncept, där även CO_2 kan användas som råvara med alkoholer/kolväten som slutprodukter.

1 Introduction

On assignment of the Swedish Energy Agency a synthesis report has been elaborated with the objective to survey the current situation and trends regarding techniques, research and market for solar power and solar fuels from a Swedish perspective, based on international developments. The report also contains, in line with the assignment, proposals for actions by the Energy Agency in the actual area. The synthesis report has been elaborated during the autumn 2011 by Bengt Ridell, Ronny Nilsson and Björn Rehnlund at Grontmij AB together with Bengt Kasemo, professor in chemical physics at Chalmers. A steering group, with representation from Swedish Energy Agency[3] and Swedish research institutions and industry[4], has been functional during the assignment.

1.1 Background

Annual solar irradiation reaching the earth (approximately 800 million TWh) contains more than 10.000 times more energy than the annual consumption of fossil fuels in the world. The opportunity to efficiently convert the direct solar irradiation to useful energy carriers is of extensive significance for the development of a global sustainable energy system with minimal emissions of greenhouse gases.

Under the frame of several research programs, predominantly in USA, Japan and Germany but also in Sweden, different technical solutions for harvesting the energy content in solar irradiation has been developed since the 1970's. The Swedish Energy Agency has supported several solar energy research and development programs, and general public support for installation of photovoltaic applications has been in force since 2005 in Sweden.

The public support to research from the Swedish Energy Agency consists of support to technologies for direct energy conversion from solar irradiation to electricity (solar cells and thermal solar power) as well as technologies for production of hydrogen from solar energy (photochemical/photobiological splitting of water and artificial photosynthesis). The Energy Agency has identified a need for the establishment of an integrated structure for research, development and commercialisation in the area of solar energy.

[3] Linus Palmblad and Sara Bargi

[4] Andrew Machirant (Solar Energy Association Sweden), Lars Stolt (Solibro GmbH), Leif Hammarström (Uppsala University), Monika Adsten (Elforsk) and Christer Ovrén (ABB)

1.2 Objectives

The objectives of the synthesis is to survey the situation and give an accumulated and concentrated knowledge about status, needs and opportunities for Swedish research and Swedish industry within the area of solar power and solar fuels, to be used for prioritisation of further efforts. The synthesis shall identify strengths and weaknesses in areas fundamental for development of solar power and solar fuels, focused on the development in Sweden, but in an international context.

The synthesis shall also cover proposals for future Swedish research efforts and organisation of future Swedish research programs.

1.3 Methodology

The material for this report has been gathered from studies of scientific and technichal literature, reports from various agencies world-wide and in Sweden, and input from the steering group and individual researchers. Bibliometric studies have been done via Thomson Reuters' Web of Science.

1.4 Disposition of the report

The synthesis report opens with a general overview of the research areas, giving a general background to issues referred to in the report and a categorisation of the research areas.

In the subsequent chapters, chapter 3 and 4, firstly international research is described for the areas of solar photovoltaic cells (PV) and solar fuels respectively, after which the Swedish R&D efforts in both areas are described. Both chapters contain bibliometric analysis in order to quantify academic results for Swedish as well as international research. The chapters conclude with a summarising analysis of state of the art of each area of research. Strengths and weaknesses of Swedish research efforts are identified and analysed.

In chapter 5 the development of the market for photovoltaic cells is described and analysed together with a review of the opportunities for commercialisation of technologies for production of solar fuels in general and hydrogen more specifically.

The analysis of Swedish research efforts in relation to the expected market development is used as input to an analysis of challenges and opportunities for Swedish research as well as Swedish industrial activities in the area of photovoltaic cells and solar fuels (chapter 6). In the concluding chapter, chapter 7, a proposal for design and direction of a future Swedish research program is given.

2 Overview of solar energy conversion schemes

Solar energy consists of the radiation that is emitted from the sun and reaches the earth's surface. For solar energy harvesting the most interesting part of the solar spectrum is from the UV-visible to the near IR parts as this is the most energy intensive part of the spectrum. Devices to catch this energy can be roughly divided into three types:

- Solar energy converts to electricity
  - photovoltaic cells or what is usually referred to as "solar cells", which directly produce electricity
  - concentrated solar power (CSP), which produces intermediate hot steam that drives a steam turbine
  - thermoelectric devices that also use intermediate concentrated solar power, generating heat
- Solar energy converts to chemical energy i.e. chemical compounds that can be used as fuels,
- Solar energy converts to heat that is used without further refinement. This area will not be covered in this context.

2.1 Solar power

2.1.1 Photovoltaic (PV) solar cells

The most notable feature of solar PV systems is the conversion of the solar energy into useful electric energy. Photovoltaic (PV) is the collective name of the phenomenon, where a device, almost exclusively a solid material or molecules attached to a solid material, captures solar radiation (photons) and converts the solar energy into electrical current and voltage.

With this technique it is possible to convert solar energy directly into electric energy without converting it into intermediate forms of energy. Most importantly, there is the advantage of having very little carbon dioxide emission for each unit of electric power generated.

PV cells are often discussed in terms of generations of solar cells. The concept was introduced by Martin Green[5] as follows:

- First generation – (Mono)crystalline silicon (Si) solar cells
- Second generation – Low cost/modest efficiency thin-film materials such as CdS (cadmium selenide), CdTe (cadmium telluride), a-Si (amorphous silicon), CIGS (copper indium gallium selenide) and thin film poly(crystalline)-Si.
- Third generation – Low cost/high efficiency solar cells

The classification does not explicitly include (i) so called Dye Sensitized Solar Cells (DSSC) frequently referred to as just Dye Sensitized Cells (DSC) or Grätzel cells, or (ii) organic/polymer solar cells (OPV).

The first generation PV cells made from silicon (Si) constitute the dominant technology in the commercial production of solar cells. Crystalline Si (mono- and poly-) accounted in 2010 for 86.5 % of the total installed power and the accumulated installed fraction of crystalline Si is even higher.[6] The first and dominating technology of solar cells were made using a mono-crystalline silicon wafer. Continuous development efforts are being made towards silicon films of either polycrystalline or amorphous nature. The silicon cell has a broad absorption range but still requires relatively costly and energy-intensive manufacturing technologies. However, costs have been successively reduced and are projected to decrease further thanks to both technology development and considerably larger sales volumes. The theoretical limiting efficiency of crystalline silicon devices is approximately 29 % and there is still a long way to go to achieve this efficiency in commercial products.

Second generation PV cells are based on the use of thin-film materials such as CdS, CdTe, a-Si, CIGS and thin film poly-crystalline silicon. The use of thin-films reduces the mass of material required and the purity demand, which contributes greatly to reduced costs for thin film solar cells. Typically, the efficiencies of commercial thin-film solar cells are more modest (i.e. 10–15 %) compared with silicon wafer-based solar cells.

Third generation solar cells will, according to Green's definition, have considerably higher efficiency, 30–40 %, compared to today's solar cells on the market. Such cells may be developed along several different paths. They may be based on current leading types of cells (c-Si or thin film) by "add-ons" that increase their efficiency, like plasmonic or nano-wire enhanced solar cells (see chapter 3), or they may be found among emerging types of solar cells like the aforementioned DSSC or OPV cells, or they may be based on so called tandem cells, which utilize two types of solar cells stacked on top of each other, in order to collect a larger

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[5] Green (2001)

[6] Solarbuzz web site, http://www.solarbuzz.com/facts-and-figures/market-facts/global-pv-market (retrieved 10-11-2011)

spectrum of the solar light. In this context it is noteworthy that already today there are solar cells with 42 % efficiency produced industrially for space and so called concentrated photovoltaics (CPV)[7] applications.

Similar to the "third generation technologies" concentrating photovoltaic cells (CPV) are an emerging technology. There are two main tracks – either high concentration (> 300 suns similar 300 times concentration) or low or medium concentration with a concentration factor of 2 to approximately 300. In order to maximise the benefits of CPV, the technology requires high direct normal irradiation (DNI) and these areas have a restricted geographical range – the "Sun belt" of the earth.[8] Regarding total need of energy this belt is more than enough for global needs, but has other drawbacks related to their geographical locations, transmission issues etc.

Planned production capacity for crystalline silicon based solar modules and for thin-film modules for the period until 2015 is illustrated in figure 2.1.

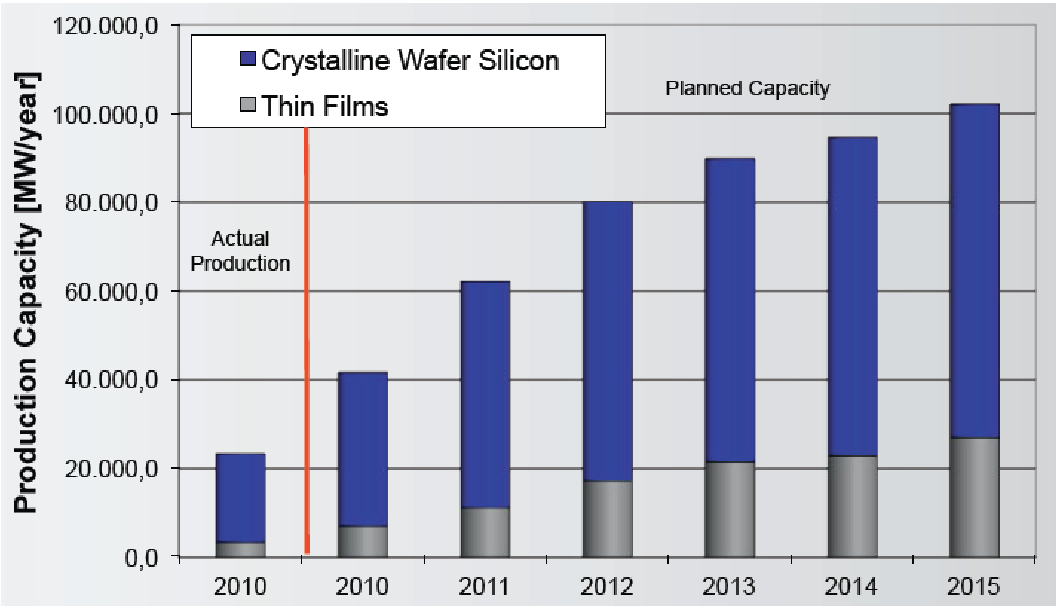

Figure 2.1: Annual PV production capacities of thin-film and crystalline silicon based solar modules Source: PV status report 2011 JRC, Ispra

The competitiveness and thus the sales of the leading Si based solar cells increase as the price level has decreased considerably the last few years and is still going down. Also the expected life time and the reliability have improved.

2.1.1 CSP Concentrated solar power

Thermal Solar Power or Concentrated Solar Power (CSP), in its most basic form, a CSP plant consists of a solar collector field with mirrors concentrating the solar

[7] See chapter 3.1.4

[8] JRC PV Status report (2011)

radiation to one or more receivers where radiation is converted to high temperature heat. The high temperature heat source can be used to drive conventional power generation equipment (such as steam cycles, Stirling engines, micro gas-turbines, etc.) to produce electricity. Significant amounts of waste heat are also available which are often wasted but could be used to drive other processes.

The dominating CSP technology today, which has been in use for about 30 years, makes use of linear parabolic trough mirrors with collectors producing steam for conventional steam turbine plants. The power range for these systems has been 30–80 MW_e with solar-electric efficiency around 15–20%. A high number of 50 MW_e plants of that type are presently being put into operation in Spain. Plants in the power range of 400 MW_e are built in the US and are planned for installation in North Africa.[9]

Other CSP technologies are so called Power towers where a tower with a receiver is surrounded by a large array of heliostat mirrors that track the sunlight and concentrate it to the receiver in the tower where steam is produced or the heat can be collected in molten salt that later produces steam. Solar parabolic dish systems are used in smaller plants where a parabolic-shaped concentrator reflects the sunlight to a receiver mounted in the focal point at the centre of the dish. The collected heat is used in a heat engine, typically a Stirling engine generating electricity.

2.2 Solar fuels

One of the factors limiting the widespread use of solar energy is its intermittent character. Geographic and seasonal variations typically do not match the consumption patterns, and ways of storing solar energy are therefore needed (unless a total global transmission net is anticipated, which, if at all practical, lies far in the future). One possibility is to store solar energy in chemical bonds, for instance in the form of hydrogen gas (H_2) or other fuels.

Solar hydrogen is the generic name of a number of methods with the common goal to catch and convert the energy contained in solar radiation to hydrogen gas, H_2, via the splitting of water molecules, and where the thus formed chemical energy can later be used in different energy conversion systems such as fuel in fuel cells or even in combustion engines or as a raw material to produce other fuels such as hydrocarbons. Hydrogen is thus both an energy carrier and an energy storage compound. Hydrogen that is used today in industrial processes comes from a variety of feed-stocks. The most commonly used method is reforming of fossil fuels. On the long term, it would be much more attractive to produce hydrogen from a sustainable feedstock such as water and using a sustainable energy source such as the sun. Table 2.1 displays an overview of possible pathways for the conversion of solar energy and water to hydrogen. Three main routes may be distinguished, namely i. photobiological methods involving green plants or microorganisms, ii. electrolysis of water, where the required electricity may be

[9] Strand et al (2011)

generated in various sustainable ways, and iii. direct conversion schemes, either using solar light for driving thermochemical processes or for more direct conversion schemes using the energetic solar photons.

Table 2.1: Overview of conversion schemes for the production of hydrogen from water using solar energy.

<table>
<tr><td rowspan="7">Solar energy + water</td><td colspan="2">Biomass energy</td><td rowspan="7">H_2</td></tr>
<tr><td colspan="2">Photobiological (microorganisms)</td></tr>
<tr><td colspan="2">Solar thermal energy with thermochemical routes</td></tr>
<tr><td colspan="2">Solar photonic (photocatalytic and photoelectrochemical water splitting, artificial photosynthesis)</td></tr>
<tr><td>Solar PV / solar thermal electricity</td><td rowspan="3">Electrolysis</td></tr>
<tr><td>Hydroelectric energy</td></tr>
<tr><td>Wind energy</td></tr>
</table>

In photolytic (photocatalytic/photoelectrochemical) hydrogen production one and the same material, typically a semiconductor, harvests light and acts as electrode. The absorbed energy generates electron-hole pairs in the semiconductor, just as in the case of photovoltaic solar cells. The resulting charge carriers are used to drive water oxidation and proton reduction reactions, with the overall reaction summing up to the splitting of water into H_2 and O_2. This is in contrast to PV cells, where excited charge carriers are extracted in the form of an electric current. Photochemical approaches have potentially larger efficiency than hybrid schemes based on for instance PV in combination with electrolysis, but the latter path is still by far more effective. The fact that the same material is used as light harvester and electrode material is far from optimal and research efforts are made to develop layered materials or core-hole nanoparticles to optimize light collection and electrode functions independently.

Artificial photosynthesis strives to mimic photosynthesis in green plants or is at least inspired by this process. The border line between photocatalytic/photoelectrochemical and artificial photosynthesis approaches is a grey zone – the techniques have much in common but also significant differences. The term artificial photosynthesis is often used to describe water splitting systems where light harvesting occurs in macromolecular complexes, and donor and acceptor complexes are used to separate excited electrons and holes and to run reduction and oxidation reactions with these excited charge carriers, respectively. Note, however, that the term has recently also been used frequently in the context of CO_2 conversion using semiconductor materials. The solar conversion of carbon dioxide to hydrocarbon fuels has in fact emerged as an interesting alternative to hydrogen production via water splitting, due to the fact that the produced fuels (e.g. methane or methanol), in contrast to hydrogen, can be distributed with existing infrastructure. Given the rapidly increasing interest in solar-light driven carbon dioxide conversion, the topic will be covered in a separate section below.

3 Technology status and international research and development

3.1 Solar Power

3.1.1 Mono-crystalline and poly-crystalline silicon solar cells

More than 80 % of the current global production of solar cells uses wafer-based crystalline silicon technology. The technologies for production are well established, and are derived from the microelectronics industry production of Si wafers, and provide reliable products with acceptable efficiency and at least 25 years of lifetime.

The mono-crystalline silicon solar cell has the highest efficiency of siliconbased solar cells, up to about 24 % cell efficiency and 18 % module efficiency The mono-crystalline solar cells are sliced from large single crystals that have been grown under carefully controlled conditions. However, growing large crystals of pure silicon is a difficult and energy-intensive process, so the production costs for this type of modules have historically been the highest of all the solar module types. Production methods have improved significantly as well as the development of the technology using less materials etc., Prices for raw silicon as well as to build modules from mono-crystalline solar cells have fallen over the years, partly driven by competition among developers of different types of soalr cellsbut also by improved production for soalr grade silicon. Modules made from crystalline silicon cells gradually lose their efficiency as the temperature increases. IN hot areasthey need to be installed in such a way so that ambient air for cooling can circulate over and under the modules to improve their efficiency.[10]

It is cheaper to produce silicon wafers composed of multiple silicon crystallites rather than of a single crystal, as the conditions for growth do not need to be as tightly controlled in the former case and the crystals are made much bigger. In this form, a number of interlocking silicon crystals or rather crystallites grow together into a polycrystalline material. Modules based on these cells are cheaper per unit area than monocrystalline modules - but they are also slightly less efficient.

Yearly installation growth rates for silicon solar cells over the last decade were on average more than 40 % installed power, which makes solar photovoltaic power one of the fastest growing industries at present. A major advantage of mono-crystalline and poly-crystalline technologies is that complete production lines exist and can be bought, installed and be up and producing within a relatively short time-frame.

[10] Solar Facts and Advice web site, http://www.solar-facts-and-advice.com/solar-cells.html (retrieved 21-09-2011)

Research and development initiatives for mono-crystalline and poly-crystalline solar cells are mainly focused on continuation to expand solar grade silicon production capacities in line with solar cell manufacturing capacities and accelerated reduction of material consumption per silicon solar cell and W_p, e.g. higher efficiencies, thinner wafers, less wafering losses etc.The crystalline silicon solar modules are expected to continue to dominate in the residential and commercial roof-top markets due to higher efficiency and rapidly reducing costs. There has been a 40 % price reduction since the middle of 2009 until 2011, among others as a result of the improved supply of poly-crystalline silicon. When supply of solar grade silicon was constrained by limited production of poly-crystalline silicon, the price reached over 400 USD/kg. During 2011, the price has fallen to below 60 USD/kg[11] and supplies are readily available for mass production — driving a continuing decline in module prices.

Lower cost crystalline silicon modules support a key goal for solar known as grid parity, which describes a situation where the cost to generate solar power equals the cost of buying electricity from the grid. This has already been reached during the peak demand period in certain parts of the world. According to the European Photovoltaic Technology Platform group, solar PV is expected to reach grid parity in most of Europe over the next 10 years.[12]

3.1.2 Thin film solar cells

The term "thin film solar modules" refers to the fact that these types of solar modules use a much thinner layer of photovoltaic material than monocrystalline or polycrystalline silicon solar modules. Thin film solar cells consist of layers of active materials of a few micrometers (typically 1–5) thick compared with the thickness of crystalline-silicon cells at 100–200 micrometers. While these thin-film modules are expected to be much lower in price, they also have a lower module efficiency.

The previously experienced high cost of producing crystalline silicon wafers (which makes up 40–50 % of the cost of a finished module) has led many manufacturers to reduce the material cost by using thinner layers or less expensive materials, and more economical ways to produce solar cells. The three most common photovoltaic materials used in mass production of thin film modules at this time are:

- Amorphous Silicon (a-Si) PV modules were the first thin film PV modules to be commercially produced. Amorphous silicon is the non-crystalline form of silicon. An amorphous silicon solar cell contains only about 1/300 the amount of active material in a crystalline silicon cell. Amorphous silicon is the most well-developed thin film technology to-date and has an interesting avenue of further development through the use of hybrid

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[11] KPMG (2011)

[12] Solar Facts and Advice web site, http://www.solar-facts-and-advice.com/polycrystalline.html (retrieved 12-12-2011)

cells which incorporate some "microcrystalline" silicon (μc-Si) in order to combine the stable high efficiencies of crystalline Si technology with the simpler and cheaper large area deposition technology of amorphous silicon. Today the efficiency for commercial a-Si modules is 6 % and for μc-Si approximately 9 %.[13]

- Cadmium Telluride (CdTe) is the first and only thin film photovoltaic technology to surpass crystalline silicon PV in price per watt of peak power, but this price advantage seems to be eroding as the price of raw silicon has decreased and Chinese manufacturers increase their production of polycrystalline modules. There are some concerns about the future of Cadmium Telluride based modules, specifically the very limited availability of Telluride and increased concern about long-term toxic affects of Cadmium. The efficiency for commercial CdTe modules is today 10–12 %.[14]
- Copper Indium (Gallium) diSelenide (CIS or CIGS) technology has achieved cell efficiency levels of 20 % in laboratory, much higher than Cadmium Telluride. Unfortunately the material is more difficult to work with and many companies are struggling to bring a sufficiently efficient module to the market at an attractive price. Currently most manufacturers are producing relatively small amounts in the 1–30 megawatts per year range and CIGS technology remains a promising technology being able to reach efficiencies approaching 20 %.[15] Efficiencies of commercial CIGS modules are today 11–13 %.[16]

“Thin film” materials can be deposited on flexible substrate materials while crystalline silicon cells have yet to be placed on flat surface in general glass. However, while thin film solar cells are flexible, their flexibility is a feature of how they are constructed and how they can be installed, but not how they are going to end up being used. Like other solar modules, they typically still get installed flat and in a frame at an optimal angle facing the sun. Thin film solar cells have gained an important market share in Germany as they have relatively low investment costs and work well on roofs that face other directions instead of directly towards south. Thin films still have a relatively strong market position in the US with a substantial market share.

However, during 2010–2011 in fact the main reason for slower adoption of thin-film modules is the rapidly declining cost of c-Si wafer based cells and modules, mainly driven by large new manufatcuring facilities (particularly in China). Thin-film technology is not being pushed as much commercially as they are still under basic development. The rapid cost reduction of c-Si – the business case for Thin Film has worsened considerably and does not look likely to recover in the short to mid-term.[17]

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[13] Mehta (2011)

[14] Mehta (2011)

[15] Green et al (2011)

[16] Metha (2011)

[17] Solar Energy Association Sweden, Andrew Machirant

Although module costs for thin-film modules (which account for around 50 % of the total installation cost) have been declining as a result of more efficient manufacturing and economy of scale – installation costs have remained about the same. Consequently if twice as many modules are required to get the same results – the overall cost advantages of lower module prices disappear quickly. It is therefore essential that the R%D of thin films focus on reduction of material costs, less substrates etc.

The three most viable thin-film photovoltaic technologies - cadmium telluride (CdTe), copper-indium gallium (di)selenide (CIGS), and amorphous silicon (a-Si) - continue to mature and develop. Except for the market leader on CdTe modules, First Solar, many manufacturers have had a hard time making significant commercial inroads as the price of crystalline-silicon modules decreased over the past couple of years. In the long term there is an advantage for Si based solar cells with regard to material abundance and availability of established extraction/refining processes. The former is much larger for Si as a raw material, compared to several elements used in other thin film solar cells.

3.1.3 Organic solar cells

Several new solar cell (photovoltaic) technologies have been researched in the last years, with respect to finding an effective alternative to silicon-based solar cells. Research and development in this area generally aims to provide higher efficiency and lower costs per watt of electricity generated. The term "third generation solar cells" is somewhat ambiguous in the technologies that it encompasses, though generally it tends to include, among others, non-semiconductor technologies (including polymer-based cells and biomimetics), quantum dot technologies, hot-carrier cells, dye-sensitized solar cells and upconversion technologies.

The reasons for introduction of materials other than silicon-based materials are to use the full spectrum of the sun-light. Conventional solar cells are made from one material and utilize one electronic band gap. The band gap puts an upper limit to the extractable voltage. The so called Shockley-Queisser limit is a measure of the upper obtainable efficiency of a perfect solar cell based on only one solar cell material with only one electronic band gap. The efficiency limit of a perfect silicon solar cell is about 30 %. Organic and hybrid cells utilise materials or cell structures incorporating several band gaps to enable improved efficiency.

Conjugated polymers combine the electronic properties known from the traditional semiconductors and conductors with the ease of processing and mechanical flexibility of plastics. Polymer solar cells have attracted considerable attention in the past few years owing to their potential of providing environmentally safe, flexible, lightweight, inexpensive, efficient solar cells.

The prospect that lightweight and flexible polymer solar cells can be produced by roll-to-roll production, in combination with prospective high efficiency, has spurred interests from research institutes and companies. In the last five years there has been a great increase in the understanding and performance of polymer solar cells. Comprehensive insights have been obtained in crucial materials parameters in terms of morphology, energy levels, charge transport, and electrode materials. Efficiencies of 5 % are routinely obtained and recent record efficiencies reported by some (mainly industrial) labs are 7–8 %.[18] [19]

One important feature of solar cells in general is the service life, which for large and medium scale installations should be at least 20 years or more. Service life for organic solar cells is still a critical factor, though, because the cells are susceptible to oxidation and can be damaged by humidity. There is still a lack of long-term experience from product life of flexible cells. However, the life time is continuously being improved and in addition there are niche applications where service life much shorter than 20 years can be accepted.

The current focus is predominantly on improving the efficiency of organic solar cells. The emerging technologies of Grätzel photovoltaics, generally referred to as Grätzel cells or as dye-sensitized (solar) cells (DS(S)Cs), have attracted significant interest. They are considered to hold the potential for considerable reductions in costs per unit area as well as improvements in weight, transparency and physical variables compared to inorganic thin film and silicon based solar cell varieties.

The Grätzel cell is a form of solar cell where nanotechnology is applied. Titanium oxide particles in a porous, multilayer arrangement are coated with photo-sensitive dye molecules surrounded by an electrolyte. Thus there are two interpenetrating phases, the porous TiO_2 particles connected together, and the liquid phase. Incoming sunlight hits the photosensitive dye molecules and excites the electrons in the dye molecules and the electrons are then rapidly transferred to the adjacent TiO_2 particle and conducted through the titanium oxide particles to the anode. The dye molecules take up an electron from electron carriers in the electrolyte. The electron carrier in the electrolyte picks up a new electron at the cathode. The circuit is then closed. Since manufacturing technology is not so advanced and the material used is cheap the manufacturing costs are low. Efficiency is about 11 % as best research cell efficiency.[20]

3.1.4 Concentrating photovoltaic cells

Concentrated photovoltaic (CPV) technology uses optics such as lenses or mirrors to concentrate a large amount of sunlight onto a small area of solar photovoltaic materials to generate electricity. Unlike traditional, more conventional flat module systems, CPV systems are often less expensive to install in suitable areas even though concentrating devices are needed, because the concentration allows for the production of a much smaller area of solar cells for the same power as for non-CPV.

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[18] R. Service (2011)

[19] Dennler et al (2009)

[20] NREL (2010a)

Photovoltaic solar cells produce electrical energy that in practice is essentially proportional to the amount of light energy that falls on them. In principle, by putting ten times the amount of light on a solar module it is possible to make ten times the amount of electricity. One major problem is that the cell efficiency typically goes down as the temperature goes up. This means that to keep the increase in output, the temperatures have to be kept down. The second problem is that the cost of concentrator and tracking system can defeat the cost saving from having fewer solar modules.

CPV systems operate only in direct sunlight.. Diffuse light, which occurs in cloudy and overcast conditions, cannot be effectively concentrated. To reach their maximum efficiency, CPV systems must be located in areas that receive plentiful direct sunlight and solar tracking devices are often attached to the system. Expected future efficiencies of CPV multijunction photovoltaic cells are nearly 50 %.[21]

CPV systems are categorized according to the amount of their solar concentration, measured in "Suns"[22]. CPV is typical categorized in three different levels; low (2–100 Suns), medium (100–300 Suns) and high (300 Suns–) concentration. For the low level, for economic reasons, conventional or modified silicon solar cells are typically used. At these concentrations, the heat flux is low enough that the cells do not need to be actively cooled. A solar collector with a low concentration ratio can have a high acceptance angle and thus not require active solar tracking in all instances. [23] The medium level CPV systems require two-axes solar tracking and cooling which makes them more complex. High concentration (HCPV) systems employ concentrating optics consisting of dish reflectors or Fresnel lenses that concentrate sunlight. The solar cells require high-capacity cooling to prevent thermal destruction and to manage temperature related performance losses. Multi-junction solar cells are currently favored over single-junction silicon cells as they are more efficient and have a lower temperature coefficient, less loss in efficiency with an increase in temperature. Even if the cost of multi-junction solar cells is roughly 100 times that of silicon cells of the same area, the small cell area employed makes the relative costs of cells in each system comparable and the system economics favour the multi-junction cells. Multi-junction cell efficiency has now reached 40.8 % for a three-junction cell[24].

The optics needed to concentrate the light has limited efficiency themselves, in the range of 75–90 %. Taking these factors into account, a solar module incorporating a 40 % multijunction cell might deliver DC efficiencies around 30–36 %.[25]

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[21] Kurz (2011)

[22] One Sun equals 1,000 W/m2 at the point of arrival

[23] The European Photovoltaic Technology Platform (2011)

[24] GaInP/GaInAs (1.3 eV)/GaInAs(0.9 eV)

[25] Kurz (2011)

Luminescent solar concentrators

A type of concentrators which are still at the research stage are luminescent solar concentrators. They are composed of luminescent plates either totally impregnated by luminescent species or fluorescent thin films on transparent plates. The luminescent collectors absorb the solar light, which is converted to fluorescence light guided to the plate edges where it emerges in a concentrated form. The concentration factor is directly proportional to the plate surface and inversely proportional to the plate edges. The fluorescent concentrator is able to concentrate both direct and diffuse light, which is especially important on cloudy days and in areas where bright solar light is not so common.

3.1.5 Thermal solar plants

In Solar thermal plants (CSP = concentrated solar power) the sunlight is concentrated and converted to heat that produces electricity in a thermal process. These plants use direct sunlight, which makes it difficult for CSP to compete in countries in Northern Europe including Sweden where direct sunlight is not as common as in countries in the sunbelt.

The sun's heat can be collected in different ways[26]:

- **Solar Parabolic Troughs** that consist of curved mirrors which form troughs that focus the sun's energy on tubes. These tubes contain synthetic oil that flows to a heat exchanger to heat water and produce high-pressure steam. The steam then powers a turbine, which runs a generator to produce electricity.
- **Solar Parabolic Dish** systems consist of a parabolic-shaped concentrator that reflects solar radiation onto a receiver mounted at the focal point. The collected heat is utilized directly by a heat engine, typical a Stirling engine, mounted on the receiver which generates electricity. This technology is especially useful for smaller plants but as they are modular the can be combined to larger plants.
- **Solar Central Receivers or "Power Towers"** consist of a tower surrounded by a large array of heliostats. Heliostats are mirrors that track the sun and reflect its rays onto the receiver, which absorbs the heat energy that is then utilized in driving a turbine and an electric generator. A field of reflectors beams the light to the top of the tower, where a tank of water or molten salt sits. The heated fluid then goes through the similar steps for steam generation and electricity production.

[26] Wang (2011)

Table 3.1: Comparison of Major Solar Thermal Technologies

	Power Tower	Parabolic Dish	Parabolic Trough
Applications	Grid-connected electric plants; process heat for industrial use.	Stand-alone small power systems; grid support	Grid-connected electric plants; process heat for industrial use.
Advantages	Dispatchable base load electricity; high conversion efficiencies; energy storage; hybrid (solar/fossil) operation.	Dispatchable electricity, high conversion efficiencies; modularity; hybrid (solar/fossil) operation.	Dispatchable peaking electricity; commercially available. The most common technology in large multi-MW plants

Source: Status Report on Solar Thermal Power Plants. Pilkington Solar International GmbH: Cologne, Germany,1996.

Research areas

The CSP Parabolic through technology is well proven and the present development trends are[27]:

- Higher turbine inlet temperatures by developing heat transfer media with the ability to withstand higher temperatures.
- Efficiency improvements on mirrors and receiver pipes by optimised glass qualities and surface coatings

The cost break down of a parbolic trough plant today shows that the solar collectors is the most costly part, around 50 % of the investment while the thermal conversion unit represents only around 24 %. Any reduction in the LCOE[28] will increase the economic competitiveness of the technology.

- The first focus can be placed on reducing the cost of the power plant components as well as the costs for operation and maintenance.
- A second focus can be placed on increasing the net electrical output for a given power plant by optimizing plant design, reducing parasitic consumption as well as improving operational strategy.

Parabolic trough plants generally heat the heat transfer fluid to about 390 ^{o}C, which is lower than the temperatures from power tower plants and Stirling engines.

For the Power Tower technology researchers are working on boosting the temperatures of the molten salt so that a smaller amount of it is necessary to produce the same amount of electricity. Finding materials that will keep molten salt stable at high temperatures is another goal as molten salt can start to decompose and cause plugged pipes and valves when it reaches 600-650 ºC. Power Tower designs can achieve around 550 ^{o}C and higher.

[27] Strand et al (2011)

[28] LCOE; Levelized cost of energy. LCOE analysis considers costs distributed over the project lifetime, expressed as cost per kWh

Another research area for improving the efficiency of CSP technologies is the use of gas turbines in the process for instance in Air-bottoming cycles.

The use of water can be an issue for these technologies as they often operate in a desert like environment. Stirling engines use less water than the other two technologies; here the water is mainly used for washing the dishes. Parabolic trough and power tower designs, on the other hand, need far more water to condense the steam for re-use after it has gone through the generator. The latter two can use dry cooling by running fans, but that adds costs and lowers the plant's efficiency.

Market issues

As mentioned the CSP plants require direct sunlight which limits the physical market to areas with a large amount of direct sunlight for instance in sunbelt of the USA, Mediterranean countries or desert like areas. As the technology also is dependant of access to water this may represent a limitation for application in these areas.

The CSP market is expected to meet a growing future, especially in the USA and Spain and during later years also China and Iran. About 17.5 GW of power projects are under development worldwide, and the United States leads with about 8.67 GW, according to GTM Research. The California Energy Commission alone approved nine CSP projects totalling more than 4.1 GW within a four-month period 2010. Spain ranks second with 4.46 GW, followed by China with 2.5 GW. About 1.17 GW of CSP power plants are already online. Spain is home to 582 megawatts of them, followed by the United States with 507 megawatts. Iran, interestingly, takes the third place with 62 megawatts[29].

3.1.6 Efficiency and electricity production cost for different PV technologies

Table 3.2 summarises the current efficiencies of commercial, best prototype and laboratory modules for each specific type of PV technology together with the production cost for each type of technology.

Table 3.2: Achieved efficiency and production cost for commercialized solar cell technologies as of 2011. Please note that these numbers change fast.

	Wafer based		Thin film		
	c-Si	multi c-Si	a-Si or a-Si/μc-Si	CdTe	CIS or CIGS
Maximum lab efficiency (%)[1]	25.0	20.4	12.4	16.7	19.6
Maximum module efficiency (%)[1]	22.9	17.8	10.4	12.8	15.7
Commercial Module Efficiency (%)[2]	14-20	14-15	6-9	10-12	11-13
Commercial module production cost (USD/Wp)[2]	1.4-1.7	1.1-1.4	0.9-1.3	0.7-0.9	1.0-1.3

[1] Green M.A., Emery K., Hishikawa Y., Warta W., and Dunlop E.D. Solar cell efficiency tables (Version 38); Prog. Photovolt: Res. Appl. 2011; 19:565–572.
[2] Mehta, S. Pv Technology, Production and Cost Outlook: 2010-2015; GreenTechMedia Research 2011.

[29] Wang U, Renewable Energy Research June 2011

The presentation in table 3.2 covers a majority of commercial PV technologies. Dye sensitized cells (DSC) and polymer solar cells are in a state which is approaching commercialisation. Lab efficiencies of 11 % have been obtained for DSC and for polymer cells a certified record efficiency of 8.3 % has been reported by Konarka. The state of commercialization is illustrated by the fact that the production of a DSSC module on stainless steel recently has been announced by DyeSol and Tata Steel.[30]

Values based on field installations of CSP and thermal solar plants are presented in table 3.3.

Table 3.3: Achieved efficiency and production cost for CSP and thermal solar plants

	Concentrating PV cells	Thermal solar plants
Module efficiency (%)	27	7
Production cost (USD/Wp)	1.5–8.0	2.5–6.0

3.1.7 International bibliometric analysis of PV solar cells for electricity production

Bibliometrics (or bibliometry) can be defined as the statistical exploitation of scientific publications in order to measure specific values or parameters or trends. This analysis makes it possible to assess the activity of the producers (researcher, laboratory, institute, faculty, etc.) or distributors (periodical, publisher, etc.) of scientific information, both in quantitative and in qualitative terms. A bibliometrics analysis focused on the search word “solar cell” gives around 16 000 hits. “Photovoltaic” alone gives ca. 27 000 hits (of which 21 000 from year 2000 –Nov. 2011). “Photovoltaic” and “solar cell” together give 39 000 hits.

By bibliometry it is also possible to identify leading research groups or individuals, regional differences and trends (e.g. comparing different countries), identifying main funding agencies etc. Errors and uncertainties can be introduced by “false hits” e.g. when a particular acronym or search word mean entirely different things, or one can miss desired hits when authors do not use common search words in their title or abstract of an article. In the search below the interest is in trends, and to avoid “false hits” only “photovoltaic” is used as search word for the global search. This means that the numbers are in an absolute sense lower than if all PV articles were searched for, however, trends are likely to be the same. There are however some significant differences; “photovoltaic” seems to give more weight to emerging technologies, while “solar cell” seems to give more weight to established (silicon) technologies. Furthermore, since the more recent developments are of main interest, the searches were, if nothing else is said, restricted to the time 2000–November 2011.

The countries giving the largest contributions to the number of “Photovoltaic” publications are shown in table 3.4.

[30] Stanford University, Carl Hägglund November 2011

Table 3.4: Bibliometry results for the 12 countries giving the largest contributions jn "photovoltaic" since year 2000

Country	Number of hits	Country	Number of hits
1. USA	4 700	7. France	900
2. China	3 100	8. Spain	900
3. Japan	2 000	9. Italy	900
4. Germany	1 400	10. Taiwan	800
5. South Korea	1 100	11. India	800
6. England	1 000	12. Australia	500

If all countries in Europe are summed together the number of publications are over 8 000 in total. Among the Nordic countries Sweden has a number of publications that is almost as many as for the other Nordic countries together.

Table 3.5: Bibliometry results for the Nordic countries

Country	Number of hits
Sweden	260
Denmark	160
Finland	90
Norway	40

On a per capita basis Sweden has a high number, almost 30 publications per one million head (pmh) versus around 15 for USA and Japan and 2.3 for China.

The six leading countries – USA, China Japan, Germany, South Korea and England – are producing around 50 % of all publications. However, if Europe is counted as a whole it has the largest number with over 8 000 publications. Sweden is number eleven in Europe but has among the highest per capita publication number worldwide. Ongoing research and bibliometry for Sweden is further commented on in chapter 4.

Considering the publication (and citation) trends for the top three countries above, which have produced around one third of all publications, the picture is as described in figure 3.1.

The publication rate per year is increasing very rapidly – 2010 has more than twice as many publications as 2007, and the trend seems to continue for 2011. Note that the bars for 2011 is only for the period January - November and will most likely rise above the 2010 bar.

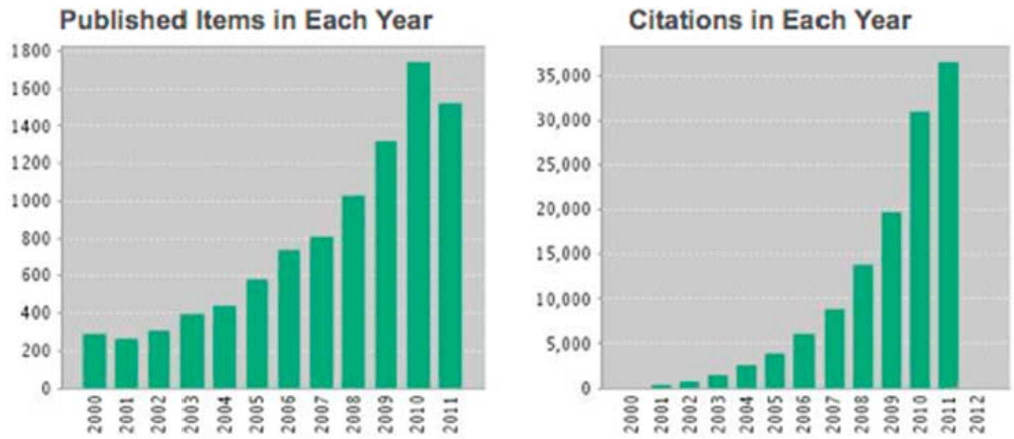

Figure 3.1: Publications and citations for the search word "photovoltaic" 2000–Nov 2011 for the three top countries USA, China and Japan

The analysis can be more detailed by adding related key words as additional search words, in order to identify which materials and types of solar cells that are most researched, for example "silicon", "thin film" or "organic". A search with additional key words in the five most frequently publishing countries give the results as described in table 3.6.

Table 3.6: Bibliometry search with "photovoltaic" together with the quoted additional key words. Numbers in paranthesis refer to the same search but where "photovoltaic" was replaced by "solar cell"

Additional key word	Number of hits
Silicon	2 700[1] (5 100)[5]
Thin films (all kinds including Si, CIGS, and organic)	2 300[2, 3] (2 900)[5]
Grätzel/DSSC/DSC	1 500 (2 500)[5]
Organic	4 600[4] (2 000)[5]

[1] Almost 600 of this number are Si thin films.
[2] 1 300 is the number obtained if Si and organic films are excluded.
[3] 172 of this number represent organic thin films.
[4] This number may be too high, since the words "organic" or "polymer" may be used in several other contexts, both together with the other types of solar cells, e.g in connection with "dye" or coatings and in connection with opto-electronic devices.
[5] Number in paranthesis are obtained if "photovoltaic" is replaced by "solar cell".

The change of "photovoltaic" to "solar cell" has a quite large effect on the numbers for Silicon and Organic – most likely because Silicon is much more frequently referring to real, ready solar cells while Organic more often is referring to more basic research.

The bibliometry analysis was also extended with two other search words, for less mature but promising directions in solar cell research, namely the word "nano" and the word "plasmon" or "plasmonics" (note that "photovoltaic" still was kept as a search word when "nano" or "plasmonic" were added). The number of hits for "nano" was 440 and for "plasmon/plasmonics" it was 160. These are small fractions of the total number, but are among the most rapidly growing ones. Note that these technologies to considerable extent represent "add-ons" and methodological approaches to enhance efficiency of any types of solar cells.

To sum up there is no doubt that the research is rapidly growing with a doubling rate in publications over less than three years. Silicon is still large as a research field, but not by far as dominating as it is on the market. Organic PV (OPV) is actually very large, larger than Si, and thin films (excluding silicon and organic films) come close to Si. Also dye-sensitized cells get a quite high number.

Concentrated solar power

With the search words "concentrated solar power" or "thermal solar electricity" 83 articles are found, that is a very modest number. Figure 3.2 also shows that concentrated solar power is a late-comer on the stage. No hits are found for Sweden.

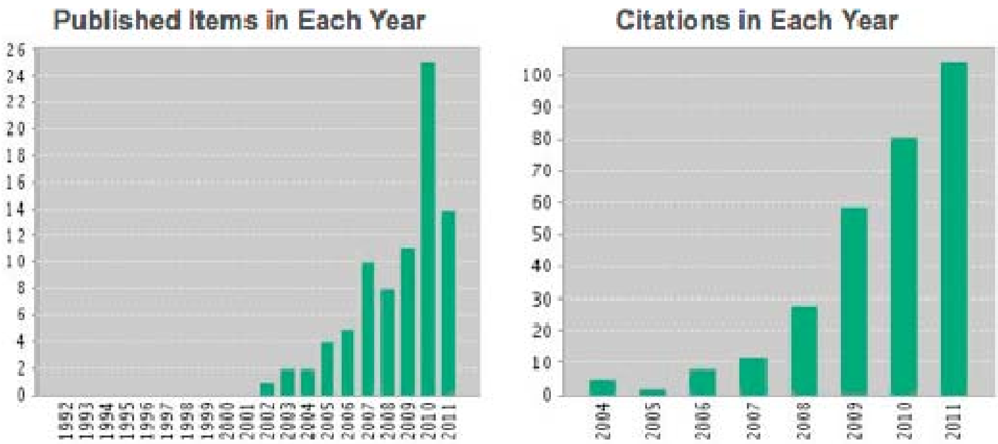

Figure 3.2: Publications and citations for the search word "concentrated solar power" or "thermal solar electricity" 1992– Nov 2011

3.1.8 Leading funding agencies and international research initiatives

The European Union has co-financed solar energy research projects through grants from the framework programmes, today the FP7. The volume for 2012 is 15,6 million EUR and for coordination of ERANET calls for solar electricity another 2 million EUR. ERANET is a support for joint calls between member states. The plans are to increase the budget substantially in the new FP8 or Horizon 2020 intended for 2014–2020.

The Photovoltaic Technology Platform is a European initiative which aims at mobilising all the actors sharing a long-term European vision for PV technology. The Platform has developed a Strategic Research Agenda and a corresponding implementation plan for education, research and technology development, innovation and market deployment of PV solar energy in Europe. These documents are intended to form the basis for new research programmes in Europe.

An edition 2 of the Strategic Research Agenda was launched at the conference *26th European Photovoltaic Solar Energy Conference (EU PVSEC)*, held in Hamburg, 5–9 September 2011. The update of the agenda was prompted by, in particular, the strong market growth and the increased ambitions for renewable energy (EU targets by 2020). In the update of the agenda two major new goals for CPV (the old ones have already been reached) have been introduces together with a greater focus on systemic issues in general (e.g. grid integration, handling variability in production and smart grids).[31]

The Solar Europe Industry initiative, SEII, was launched in June 2010. It is an industry-led initiative which has developed a ten years research, development and demonstration roadmap for PV in Europe. The SEII is a joint initiative between the European Photovoltaic Industry Association (EPIA) and the European Photovoltaic Technology Platform (EU PVTP), in collaboration with the EC and the Member States.

In Germany the largest funders are Deutsche Forschungsgemeinschaft , European Commission, German Federal Ministry of Education and Research, German Federal Ministry of Environment and Nuclear Safety, Alexander von Humboldt Foundation, Frauenhofer Institute, Max Planck Society and Helmholtz Association.

In England the most significant funders for solar research are Engineering and Physical Sciences Research Council (EPSRC), Royal Society, European Commission and BP Solar and in France they are Centre National de la Recherche Scientifique (CNRS), European Commission and Agence National de la Recherche (ANR).

In USA the Department of Energy (DOE) and US National Science Foundation (NSF) are by far the largest funding agencies as judged form the number of publications they are quoted as supporters in. However, there is a very large spread showing that many sources are in action; universities own funds, private foundations, other governmental offices than DOE (e.g. Department of Defense).

In Japan the main funders are Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan Society for the Promotion of Science (JSPS) and New Energy and Industrial Technology Development Organization.

For other leading countries within solar energy research the funding situation is more diffuse.

Research efforts that are specifically highlighted at the conference *26th European Photovoltaic Solar Energy Conference (EU PVSEC)*, held in Hamburg, 5–9 September 2011 are:

[31] The European Photovoltaic Technology Platform (2011)

- US SunShot initiative is a national co-operation between businesses, universities and national laboratories, to make solar energy cost-effective applications in 2020. Costs of installed systems will be reduced by 75% in order to "restore US leadership in the global Clean Energy Race".[32]
- The update of the Photovoltaic Technology Platform Strategic Research Agenda described above.
- Sophia European Research Infrastructure, which is a project targeted on coordination of solar cell research to avoid unnecessary duplication of results and to give researchers access to different laboratories across Europe.[33]

3.1.9 The international research front for solar cells

A summary of the international research on solar cells is based, in addition to general studies of literature, on conference coverage of the KVA[34] solar conference held in Stockholm on 30 to 31 May 2011 and the conference *26th European Photovoltaic Solar Energy Conference (EU PVSEC)*, held in Hamburg, 5–9 September 2011.[35] In the following focus is on assessment of technical potential for solar cells and prognosis on research in solar cell technology.

The future for silicon-based solar cells seems in principle to be dependent on the conditions to obtain silicon and the price of silicon. The price for silicon solar cells has decreased rapidly during the last years, but further price cuts seem possible. As the cost for silicon is a substantial part of the total cost for solar cells, a reduction in the price for silicon results in decreasing production costs for solar cells but also in that the significance of other production cost components are augmented. The availability of silicon and the price of silicon also affect the direction of research activities. The general trend in photovoltaic research and development is towards higher efficiency. At the current cost level – which will be further reduced – the materials cost becomes dominating. These costs are predominantly not driven by the semiconductors themselves but other components such as substrate, encapsulation, electric connectors, junction bix etc. For example the dependence on silver in manufacturing of solar cells has to be addressed more strongly, since it represents an increasing share of the price.[36] Further cost reduction will more and more depend on enhancement of efficiency.

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32 SunShot Initiative web site, http://www1.eere.energy.gov/solar/sunshot/ (retrieved 2011-10-05)

33 SoPHia European Research Infrastructure web site, http://www.sophia-ri.eu/ (retrieved 2011-10-05).

34 Royal Swedish Academy on Science (Kungliga Vetenskapsakademien)

35 Widén (2011)

36 Widén (2011)

Access to raw materials for the manufacture of thin film solar cells is also alerted. Limited availability of indium (In) and tellurium (Te) is frequently addressed as barriers for CdTe and CIGS solar cells to be produced on a large scale and significant cost reductions may not occur. Information on resource availability for In and Te varies widely, but there is no clear evidence that access is severely restricted. Although it is acknowledged that the scarcity of In might be an issue, some data argues that the current known economic indium reserves would allow the installation of more than 10 TW of CIGS-based PV systems.[37] Methods for efficient use of materials as well as recycling are in any case important research fields in thin film solar cells development.

Research on organic solar cells seems to be focused on achieving efficiencies over 10 % and production costs below one USD per W_p. To reach mass production the production costs probably have to be further lowered, to a level of 0.25 USD/W_p. The notion conceived at the conferences is that organic solar cells probably have the potential of being the cheapest technology since their production is based on printing technology.[38] On the other hand the relative cost for proper encapsulation becomes successively higher the lower the efficiency is.

Several conference participants judged that there is a very high potential for development of concentrated photovoltaics (CPV) over the next ten years and that the CPV are likely to be the most competitive solution for large-scale ("utility-scale") solar electricity installations. According to a prognosis made by GreenTech Media (GTM) CPV-installations can be expected to increase from 5 MW in 2010 to more than 1000 MW in 2015.[39]

The prospective success of CPV is highly dependent on the development of multi junction solar cells. With increasing efficiency for multi junction solar cells it is possible to further improve cost-effectiveness of CPV systems. Thereby areas with lower annual direct irradiation levels will be more cost effective to be utilised for expansion of CPV. Within the next few decades, large parts of southern and central Europe and the USA can be included in these areas. It is important to reach efficiencies in the range of 50 %. At this level CPV will seriously be competitive compared to conventional power plants based on for example coal or natural gas.

In addition to research and development of efficiencies and production costs for existing and new solar cell technologies the report from the conference in Hamburg[40] reports an increasing focus on the impact on the electricity grid and the operation and balance of the power system when the shares of solar energy in the system increase. The effects of higher shares of solar energy contribute for example to increased load flow in parts of the grid, involving higher or different

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37 IPCC, Special report on renewable energy sources and climate change mitigation (SRREN), 2011

38 Widén (2011)

39 GreenTech Media (2011)

40 Widén (2011)

loads on components, and reverse power flow with risk for voltage increase affecting the stability of the grid. The impact on the electricity grid is particularly evident in Germany. The international co-operation in IEA-PVPS Task 14 involves studies on physical grids with a high share of solar power. The work is targeted on recommendations for integration of solar photovoltaic in the grid.[41]

3.2 Solar Fuels

One major weakness of direct electricity production with solar light is the intermittency problem (the sun does not shine all the time at a given geographic location), which must be remedied by either storage, normally from day to night, or by establishing back up power generation from other sources or (far in the future if ever) connection between time zones on the globe.

For this and several other reasons it is of interest to explore direct generation of solar light to fuels – here called *solar fuels*, which can be stored and used at a later occasion e.g. for electricity production, or in combustion engines in the transportations systems. Originally this idea was focused on hydrogen production, *solar hydrogen*, but more recently the concept has been broadened to potential production of other fuels like alcohols, using direct solar light.

It should be said already here that the "solar fuels" area is much less mature than the solar electricity area; the latter is already installed at rather large scale, a cost and price structure has been established as well as considerable industrial activities worldwide. This is not at all the case with solar fuels, which is an area in early R&D development, where it is still not clear if and in that case when it will generate industrial/commercial activities.

As a natural consequence of the relative immaturity of the solar fuel area, compared to solar electricity, the description below will be quite different and much more research oriented than the previous chapters on PV and CSP.

There are several techniques explored to generate storable solar fuels. Solar fuels that can in principle be produced include synthesis gas (syngas, i.e. a mixture of carbon monoxide and hydrogen), pure hydrogen (H_2) gas, dimethyl ether (DME) and liquids such as methanol and synthetic diesel. Hydrogen has a very high energy density on a per mass basis and its use is clean, thus making it an attractive option for a future fuel. There are, however, also serious challenges associated with hydrogen, including difficulties to store and transport it efficiently as a consequence of its low energy content on a per volume basis, and the need for a new, dedicated distribution infrastructure. It is therefore interesting to convert hydrogen further into (liquid) hydrocarbon fuels, which are easy to store and compatible with existing distribution infrastructure. Direct conversion schemes, which allow the production of hydrocarbon fuels from CO_2, are also interesting and are currently explored at the research level.

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[41] IEA-PVPS Task 14 web site, http://www.iea-pvps.org/index.php?id=58 (retrieved 2011-10-05).

3.2.1 Research and development

Three main routes for the de-carbonized production of hydrogen from water are available, namely

i. electrolysis of water, where the required electricity may be generated in various (sustainable) ways including solar PV and CSP systems,

ii. photobiological methods involving green plants or microorganisms, and

iii. direct conversion schemes, either using solar heat (thermochemical methods) or solar photons (photochemical methods).

Electrolysis is a proven technology and is today applied on a reasonably large scale - about four percent of hydrogen gas produced worldwide today is produced by electrolysis. The path of using PV or CSP electricity is therefore often considered a benchmark for emerging solar fuel technologies such as ii and iii. The conversion efficiency of a state-of-the-art alkaline electrolyzer to produce H_2 from H_2O is around 70%, resulting in solar-to-hydrogen conversion efficiencies of 11-14% if the electricity is generated in a solar PV cell (at 15% efficiency) or using CSP technology (at 20% efficiency). Direct solar H_2 production via (ii) or (iii) is yet much less efficient.

Photobiological hydrogen production

Certain photosynthetic microbes as well as cyanobacteria produce hydrogen directly from water in their metabolic activities using light/solar energy. Selected groups of unicellular green micro algae have evolved the ability to capture solar energy and to use it to split water to produce molecular oxygen as well as protons (H^+) and electrons (e^-).

Green algae for photobiological H_2 production

Green algae are the only known eukaryotes capable of oxygenic photosynthesis that are equipped with a hydrogen metabolism. In green algae, H2 production is a fully light-dependent process since the [FeFe]-hydrogenases are coupled to the photosynthetic electron transport chain via a specific ferredoxin. In 2000 a 2-stage system was developed by NREL/DOE in which the green algae (Chlamydomonas) in stage 1 carry out complete photosynthesis (open system) and in stage 2, in a completely anaerobic process, develop and evolve hydrogen.

One problem with the system is that both stages are light-dependent. Furthermore because oxygen is produced along with the hydrogen, the technology must overcome the limitation of oxygen sensitivity of the hydrogen-evolving enzyme systems. Researchers are addressing this issue by screening for naturally occurring organisms that are more tolerant of oxygen, and by creating new genetic forms of the organisms that can sustain hydrogen production in the presence of oxygen.

Recent studies on the feasibility of algal biofuel production, performed by the Solar Biofuels Consortium[42], a collaborative effort between universities of Queensland, Australia and Bielefeld and Karlsruhe in Germany, concluded that a diversification into various co-products is an important part for the development of a standalone microalgal biofuels industry, independent of the fuel being produced. Consequently, photobiological production of hydrogen may have to be combined with the production of other bio-fuels such as biogas (bio-methane), oils for biodiesel, and the separation of valuable co-products and recycled nutrients and CO_2.

Cyanobacteria for photobiological H2 production

Since modelling and engineering is much easier in prokaryotic organisms cyanobacteria (blue-green algae) are often chosen as the microorganism for development of H_2 production. Cyanobacterias are present in highly diverse and extreme environments with significant fluctuations in e.g. temperature, salinity, pH, and water availability.

Since 1995 when the first cyanobacterial genome became public, a large number of cyanobacterial genomes have been sequenced and technologies for traditional as well as synthetic biology based molecular technologies have been developed.

The ability of cyanobacteria to use solar energy and atmospheric CO_2 as energy and carbon sources, respectively, together with their faster growth rates (versus plants) and the relative ease with which they can be genetically engineered make cyanobacteria very promising for use in biotechnological applications.

Native and engineered cyanobacteria have been used at Uppsala University, and others as model systems to examine, demonstrate and develop photobiological H_2 production microorganisms and systems.[43] [44]

In the last years there has been a very strong advancement, both academic and commercial, to use a standardized genetic engineering methodology (synthetic biology) to develop efficient photosynthetic microbial cell factories for direct generation of a portfolio of biofuels directly from solar energy.[45] [46]

The last years the group in Uppsala has developed a general approach to design, engineer, construct and analyze cyanobacteria for biofuel production. The experimental design is followed by the construction and characterization of the cyanobacterial cells

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[42] Solar Biofuels web site, www.solarbiofuels.org

[43] Tamagnini et al (2007)

[44] Ekman et al (2011)

[45] Angermayr et al (2009)

[46] Heidorn et al (2011)

In cyanobacteria, two natural pathways for hydrogen production can be used: H_2 production as a by-product during nitrogen fixation and as a product of the activity of the bidirectional hydrogenase. Using any of these pathways limited amounts of H_2 can be evolved using wild-type strains, at levels that are insufficient for commercial production of H_2 as a competitive energy carrier.

Several bottlenecks have been identified, some of which have been addressed:

- H_2 uptake by the cells,
- Low energy efficiency and turnover of the nitrogenase and/or the hydrogenase,
- Limiting amounts of active H_2-evolving enzymes,
- High O_2 sensitivity of the nitrogenase and/or the hydrogenase,
- Electron flow inhibition by accumulation of ATP in a hydrogenase-driven system,
- Low quantum efficiency due to too large antennas in both Photosystem II (PSII) and PSI,
- Electron-consuming pathways competing with an efficient electron transfer to the hydrogen enzymes.[47]

Efficiency of cyanobacterial hydrogen production

At present reported cyanobacterial based systems generating H2 (native or engineered) state solar energy efficiencies from under 1% to close to 2%. The higher values are observed when using low light intensities; increased light intensity will lower the efficiency.

New laboratory results show that there are possibilities to increase these efficiency significantly by using new types of hydrogenase in genetic engineered cells

Genetic engineering/ Synthetic biology

The vision of cyanobacterial synthetic biology is to build up a repository of standard genetic parts shared among the scientific community to speed up the successful genetic engineering for the sustainable production of valuable products.

An optimized gene encoding the plant enzyme isoprene synthase resulted in an increased expression of the protein by a factor of about 10 in the cyanobacterium Synechocystis compared to when the original plant gene was expressed in the same cells.[48] Cyanobacteria have also been genetically engineered and demonstrated to produce H_2.[49]

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[47] Tamagnini et al (2007)

[48] Lindberg et al (2010)

[49] Ducat et al (2011)

Thermochemical hydrogen production

In thermochemical water splitting, also called thermolysis, heat alone is used to decompose water to hydrogen and oxygen. It is believed that overall efficiencies of close to 50 % are achievable using these processes.

Water is a very stable molecule and needs very high temperatures to decompose. Water will generate H_2 and O_2 spontaneously without special measures around 2500 ^{o}C, but materials stable at this temperature and also sustainable heat sources are not available. Therefore chemical reagents and more complex chemical processes have been proposed and explored to lower the temperatures. Research in this area was prominent from the 1960s through the early 1980s, e.g. in connection with potential use of waste energy from nuclear, especially breeder, reactors. However, essentially all R&D stopped after the mid-1980s, until recently. There are more than 300 water splitting cycles referenced in the literature. All of the processes have significantly reduced the operating temperature from 2500 ^{o}C down to the range 500-1000 ^{o}C, but typically they require higher than ambient pressures.

In the context of solar energy the basic idea is to use concentrated solar thermal energy, similar to the solar collection technology in CSP, to run these cycles. The processes are, however, still far from competitive to other ways of producing hydrogen from water, like electrolysis. Other problems are the large amount of materials, material handling and the corrosive environment for the thermolysis cycles.

Photo(electro)chemical hydrogen production

Fujishima and Honda were the first to demonstrate that water can be photoelectrochemically split into hydrogen and oxygen by UV-light illumination of a titanium dioxide (TiO_2) photoanode, which is connected to a platinum counter-electrode. Light absorption in the semiconductor generates reactive electron-hole pairs. Being an n-type semiconductor, holes may be transferred across the semiconductor-electrolyte interface where they drive water oxidation (oxygen evolution), while electrons are collected by a charge collector and transported to the counter-electrode where hydrogen is evolved.

Iron oxide in its alpha modification (α-Fe_2O_3, hematite) has recently attracted considerable interest. Due to its 2.2eV band gap, hematite absorbs light with wavelengths below 600nm, i.e. a rather large fraction of the solar spectrum. Additionally, Fe_2O_3 is nontoxic and inexpensive, and it exhibits a good stability against photocorrosion. While photoelectrochemical water splitting requires an electrochemical cell with anode and cathode, photocatalytic water splitting is based on semiconductor nanoparticles or composite nanoparticles in which photoexcitation, charge carrier transport occur in/on the single nanoparticle, with no need for an external applied voltage. Charges are thus not collected and transferred to a counter electrode in this case. Instead, both oxidation and reduction reactions occur on one and the same nanoparticle. This implies that hydrogen and oxygen are evolved in close proximity to each other, meaning that hydrogen and oxygen have to be separated and not allowed to react back to water. The biggest advantage of this approach is its inherent simplicity and low cost.

Titanium oxide has traditionally been the working horse for photocatalytic water splitting. Its conversion efficiency is, however, extremely low, even when adding co-catalysts. A large variety of other binary, ternary and quaternary metal oxides have been explored but none of them has successfully resolved the inherent conflict between good light absorption properties and high photostability. More recently, oxynitride semiconductors have shown interesting properties for photocatalytic water splitting, mainly due to their bandgap being significantly smaller than that of TiO_2 and their advantageous charge carrier mobilities. A prominent example is $(Ga_{1-x}Zn_x)(N_{1-x}O_x)$, an oxynitride photocatalyst devised by Domen's group that can decompose water under visible light.[50] A recent nanotechnology approach to reduce the back reaction and thereby improve the overall efficiency of the process is the use of carefully designed core-shell nanoparticles, which act as hydrogen evolution catalyst and simultaneously block the back reaction.[51]

Artificial photosynthesis

Artificial photosynthesis takes yet a different approach in that light absorption occurs in a synthetic antenna complex rather than a semiconductor. The excitation energy is transferred to a reaction centre, which generates a charge-separated state. A water oxidation catalyst converts water to oxygen and protons, thereby feeding electrons to the reaction centre. The fourth component is a proton reduction catalyst, which reduces protons and electrons to hydrogen gas. While the ultimate dream is to engineer all these functions into a single monolithic device, most research thus far has focused mainly on the individual components. In particular, the search for artificial water oxidation catalysts that employ earth-abundant elements is very active. Complete artificial photosynthesis has yet not been demonstrated in a man-made system thus far.

In the last 15 years, the knowledge about natural photosynthesis has increased dramatically, and the three-dimensional structures of photosynthetic reaction centres, the oxygen evolving complex and hydrogenase have been determined. These discoveries fuel the hopes for improved man-made systems. Artificial photosynthesis research seems in fact be reaching a stage where device considerations are becoming feasible. Nonetheless, much more research is necessary before hydrogen production by artificial photosynthesis will be technically and economically feasible on a large scale.

Efficiency of photochemical hydrogen production

Lab efficiencies reported for photoelectrochemical water splitting may be misleading for at least two reasons; (i) testing may have been carried out under non-standard illumination conditions or (ii) a bias voltage may have been applied

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50 Maeda et al (2006)

51 Yoshida et al (2009)

to the photoanode but not taken into account properly when determining the efficiency. Standardized testing conditions, which would allow for a direct comparison of results coming from different laboratories, are being developed, but they have not yet penetrated the literature. Also, efficiency must not be seen as the only parameter describing the state of the art - high efficiency cells have often limited durability.

For photocatalytic water splitting, it is common to specify the material's internal quantum yield for a selected wavelength range, which does not allow one to estimate the overall solar-to-hydrogen (STH) conversion efficiency under sunlight illumination. Hitherto no artificial photosynthesis system, which is capable of running all steps simultaneously, has been reported and overall efficiency can thus not be specified.

The highest reported solar-to-hydrogen conversion efficiency for a TiO_2-based single junction photoelectrochemical device under AM1.5 illumination is 0.83 %.[52] This number can be compared with a PV cell of 15-20 % efficiency, where the generated current is for electrolysis of water with an efficiency of ca. 70 %, yielding an overall efficiency of more than ten times larger.

Higher efficiencies are possible for tandem devices and/or multi-junction systems. In the former case, a solar cell is used as an additional driving force. In the latter case, two or more semiconductors with different band gaps are combined in order to better match the solar spectrum. An example is NREL's p-$GaInP_2$/GaAs tandem cell, which shows a hydrogen production efficiency of >12%, yet with very limited durability (20 hours).[53] Stable STH conversion at 4.5 % efficiency was demonstrated for a WO_3/dye-sensitized TiO_2 tandem cell.[54]

The theoretical maximum efficiency of photochemical water splitting is largely governed by the photoanode material's bandgap. For a bandgap of 3 eV (titanium oxide), one obtains a maximum efficiency of 1 %, while a material with a band gap of 2 eV (hematite) in principle should allow water splitting at 15 % efficiency under AM1.5 illumination.

Photochemical carbon dioxide conversion

The basic scheme for photochemical carbon dioxide conversion is very similar to photochemical water splitting, with the main differences being that carbon dioxide, together with water, are used as reactants, and that the main reaction products are low molecular weight hydrocarbon molecules rather than hydrogen. The basic idea is thus to "recycle" the waste product and greenhouse gas carbon dioxide into storable fuels, which, as opposed to hydrogen, are compatible with existing fuel infrastructure.

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52 El-Sayed et al (2011)

53 Khaselev/Turner (1998)

54 Graetzel (2001)

The light driven conversion of CO_2 has a history, which goes back into the late seventies when Halmann used an electrochemical cell composed of a p-type GaP cathode, a carbon anode and an aqueous, carbon-dioxide containing electrolyte to produce a mixture of formic acid, formaldehyde and methanol.[55] Titanium oxide has been the working horse also for CO_2 conversion, although other materials such as ZnS and CdS have been reported to act as photocatalysts for CO_2 reduction. Just as for water splitting to hydrogen, a common bottleneck is the poor efficiency of the process; the efficiency of existing systems is far below 1 %, i.e. there is a large need for improvement.

Although the principle has been proven and considerable progress has been made, the efficiency of sunlight-driven photochemical fuel production from CO_2 is still in its infancy and has to be increased a great deal if the approach is to leave the lab-scale and become technically and economically viable.

3.2.2 Market introduction and commercialisation

As is obvious form the above description solar fuel production is still predominantly a research field, and is decade(s) behind solar electricity with regard to market entry and development. Still some comments relating to possible market entry are appropriate.

Photobiological hydrogen production

There is a growing interest in genetic engineered cyanobacteria for production of solar fuels such as ethanol, 1-butanol etc., as alternative to other hydrogen production methods and sources. Interest in development of such biological engineering is, from a market point of view, connected to what the market asks for. The latter are likely fuels for compression, ignition and jet engines, where hydrocarbons and alcohols still have an advantage over hydrogen, not the least due to distribution system infrastructure.

There seems yet not to exist any companies that produce or in the short term plan to produce hydrogen with help of cyanobacterias. However, there are a number of companies sharing the same kind of thinking and way of developing genetic engineering, including synthetic biology, to develop ways to produce other fuels such as ethanol, 1-butanol, isoprene, etc. Examples of companies involved in biological production of solar fuels are presented in the following.

Sapphire Energy Inc is a private company that use synthetic biology to create microorganisms/cyanobacterias to produce different ”solar fuels”. Sapphire Energy has already production facilities in San Diego, Orange County in California, Las Cruces and Columbus in New Mexico and plans at the moment a production facility in New Mexico with a bioreactor in the size of 400 hectare.

The company has already technology for biological production of synthetic gasoline, synthetic diesel oil and synthetic jet-fuels (algae, sunlight and CO_2).

[55] Halmann (1978)

Solazyme has developed indirect systems for production of solar based drop-in fuels, as for example synthetic gasoline, diesel oil and jet-fuels. In 2010 Solazyme delivered 80 000 litres of algal derived maritime diesel and jet-fuel to the US Navy.

Even if the market and the production capacity continuously grow for Solarzymes in-direct fuels they have also stated an interest in direct systems and fuel production (H_2).

Algenol Biofuels have constructed direct ethanol producing cyanobacteria by introducing genes from yeast.

Photochemical hydrogen production

Thus far no commercial systems for photochemical hydrogen production are available. While a 10cm x 10cm PEC tandem cell demonstration device was presented by the UK-based **Hydrogen Solar** in 2006, operation of the company was discontinued shortly thereafter.

Sun Catalytix is a recently founded company that commercializes a new type of affordable oxygen evolution catalysts for water splitting based on cobalt phosphate. The technology is based on research carried out at MIT.

HyperSolar (is a US-based company that is developing a low-cost technology to produce hydrogen and natural gas from (waste)water and carbon dioxide using sunlight.

3.2.3 International bibliometric analysis of solar fuels

Bibliometry analysis has been performed for international research activities in solar fuels in the same way as for the international research for solar cells, as presented in chapter 3.1.7.

An important comment regarding bibliometric analysis in general is the following; the precision and fairness of bibliometric analysis are critically depending on using the right keywords. If someone is publishing and not using these keywords in titles or abstracts, too few publications result. If the same keywords are used also in other than the actual context, false hits result. Therefore especially the trends and gross features are emphasized, not the details and absolute numbers.

Photochemical hydrogen production and artificial photosynthesis

Due to the ambiguity associated with the term “artificial photosynthesis”, searches including this term are likely to include results for both hydrogen production and carbon dioxide conversion. Therefore, the bibliometry analysis in a first step is focused on analysing to what extent this is the case. Searching for “solar hydrogen production” and/or “water splitting” without including “artificial photosynthesis” in the search generates a total of 3 452 hits. Repeating the search with “artificial photosynthesis” included produces an additional 902 hits, i.e. 4 354 in total. Excluding “CO_2” and/or “carbon dioxide” from the search has a rather pronounced effect – about 400 records are excluded. Out of these 400 records, only about half actually deal with CO_2 conversion; the other half deals with hydrogen production. Therefore it has been chosen to include the term “artificial photosynthesis” in the search, being aware that on the order of 200 items deal with CO_2 conversion; excluding artificial photosynthesis from the search would instead have implied that several hundreds of relevant records had been omitted.

Finally it can be noted that only approximately 25 % of all publications on thermochemical hydrogen production include “solar” (and are thus captured by the search). In the majority of cases, the high temperatures necessary to drive thermochemical reactions are provided by other means (e.g. nuclear power) and are thus not of primary interest here.

Looking at the total scientific production in the “solar hydrogen” area, it is clear that this area is considerably smaller than what has been described for photovoltaics and solar cells above. A possible reason for this could be that the first reports demonstrating water splitting date back to the late sixties/early seventies and thus appeared ca. 30 years later than the first solar cells. Other possible reasons are of course differences in research funding of different technologies.

Breaking down the search results according to country provides the picture according to table 3.7.

Table 3.7: Bibliometry results “artificial photosynthesis” for the 10 countries giving the largest contributions

Country	Number of hits	Country	Number of hits
1. USA	1 064	6. Switzerland	174
2. Japan	781	7. India	166
3. China	558	8. France	158
4. Germany	252	9. Italy	149
5. South Korea	202	10. Australia	122

If all countries in Europe are summed together the number of publications are 1 119 in total. Among the Nordic countries Sweden has a number of publications that is more than three times the total for the other countries together. Over 90 % of the Swedish publications deal with artificial photosynthesis.

Table 3.8: Bibliometry results “artificial photosynthesis” for the Nordic countries

Country	Number of hits
Sweden	119
Finland	18
Denmark	16
Norway	2

On a per capita base Switzerland excels with 22.5 publications per million head (pmh), followed by Sweden, which also has a high value of 12.8 pmh. Japan and Australia have similar per capita numbers, namely 6.1 and 5.6 pmh, respectively. South Korea has a per capita production of 4.1 pmh, thus exceeding the values for both the US (3.5 pmh) and Europe (1.3 pmh).

Just as in the PV-case, the number of published articles and the number of citations has been increasing steeply over the years, although growth rates are perhaps somewhat lower than for PV. Interestingly, of the ca. 82 500 citations, ca. 24 500, i.e. almost 30 %, are self-citations, indicating significant "inbreeding".

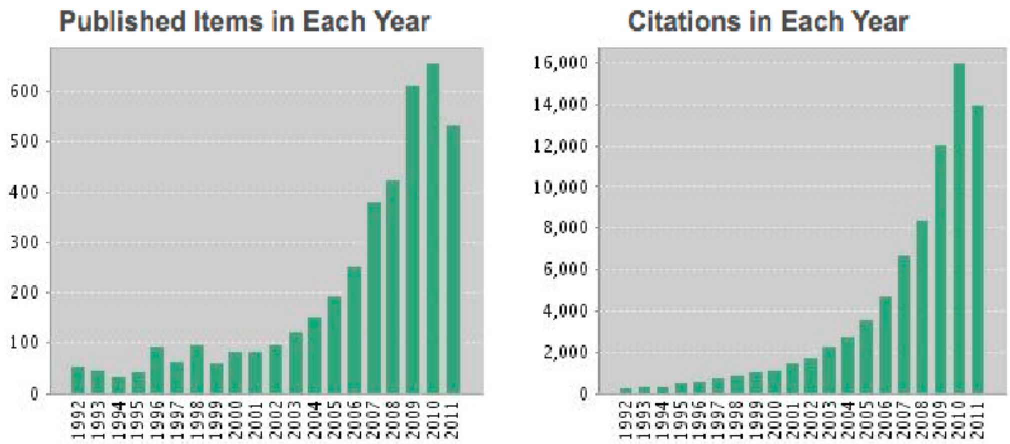

Figure 3.3: Publications and citations for search words connected to artificial photosynthesis, photoelectrochemistry and "solar hydrogen" 1992 – Nov 2011 (all countries)

Nano and plasmonics are recent trends also in the area of solar hydrogen. The number of hits when including "nano" was 1 205 and for "plasmon/plasmonics" 22 were found.

The "nanofication" of research is extremely pronounced in this case – more than 25 % of all articles include the term "nano" (most commonly found terms are nanoparticles (508), nanostructures/nanostructured (269) and nanotubes (242)).

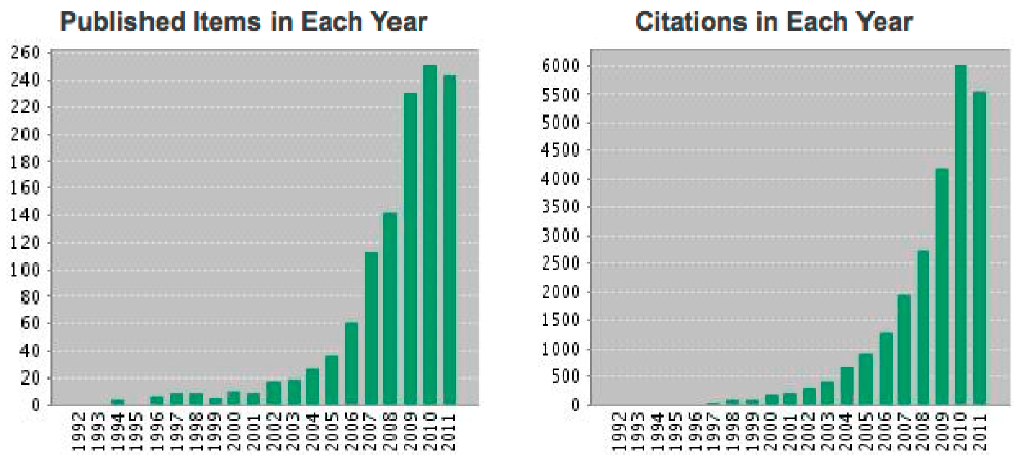

Figure 3.4: Publications and citations for search word "nano" connected to artificial photosynthesis, photoelectrochemistry and "solar hydrogen" 1992 – Nov 2011 (all countries)

Of the 22 publications dealing with plasmonics, 14 have been published in 2010 or 2011. The earliest record dates to 2006. Only one of the 22 publications also includes the term “lithography” or “lithographic”.

Photobiological hydrogen production using microorganisms

The publication rate in the field of photobiological hydrogen production was, according to figure 3.5, rather stable during the period 1992–2001, where the year 1998 is a striking outlier.

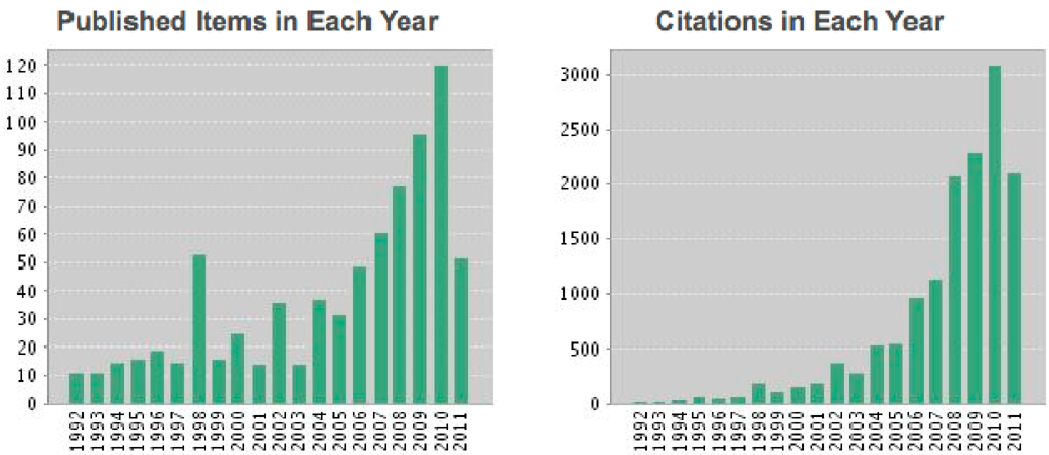

Figure 3.5: Publications and citations for search words related to photobiological hydrogen production 1992 – Nov 2011 (all countries)

Since around 2002 both published items and citations in each year are growing steadily, yet not as much as for solar cells and photochemical hydrogen production. The total number of records is 852, i.e. about a factor five smaller than for photochemical hydrogen production.

The field shows a remarkable self-citation frequency of almost 40 %.

A mere 2 % of all hits include the term nano, and plasmon/plasmonics occurs in only two items., The five most active countries are the US (207), Japan (124), China (89), Germany (74) and India (55). Sweden is the 9th most active country with a total of 27 hits.

3.2.4 Larger centres / initiatives and key research groups

Sweden has a strong position at the international forefront of research concerning solar fuels in general but most significantly in artificial photosynthesis. The Swedish research efforts and research competence is presented and described in chapter 4.

The Nordic Energy Research organisation has supported artificial photosynthesis and photobiological fuel production for a long time, starting already in the mid-1990-ies for artificial photosynthesis. CAP coordinated the program BioH2 which ended 2010 with 11 partners in seven countries. Finland presently coordinates the program Aquafeed (starts Nov 2011) with seven partners in four countries.

"Catalysis for Sustainable Energy" (CASE) is a large centre at the Technical University of Denmark that started its activities in 2009, with emphasis in solar water splitting and carbon dioxide conversion among several topics with combined experimental and theoretical effort.

As described in chapter 3.1.8 the EU has funded extensive research in PV for long time. For solar fuels this has been smaller in volume but there are significant efforts of relevance for Sweden. The CAP has initiated and coordinated three large networks in FP 4, FP 6 and FP7. In FP 4 and FP 6 these networks were the only on solar fuels in the EU. In FP 7 there are more networks on solar fuels. There is one network coordinated from Italy (Solhydromics) and one from Switzerland (Nanopech). In the field of artificial photosynthesis and photobiological hydrogen, SOLAR-H2 is coordinated from the Swedish Consortium and is the largest at present with 12 partners in eight countries. Solar hydrogen is included in the EU FCH JU, Fuel Cell and Hydrogen Joint Undertaking, where both Uppsala University and KTH are members of the research group that can influence the yearly project calls. In the biological parts of solar fuels science the EU is currently enlarging its activities with several recently installed networks. In 2011 two new networks on photobiological fuels production (much synthetic biology) have started, one coordinated from Finland (Photobiofuel) and one from Belgium (SUNBIOPATH FP7).

In addition to the activities conducted at European level with support from the EU there are transnational initiatives supported by the European Science Foundation (ESF) and national research programs in several countries.

In 2010 the ESF launched a EuroCore program named Eurosolarfuels-Molecular Science for solar fuels. This proposal was led from the Swedish Consortium. The call text covers all parts of molecular science for solar fuels, from biological approaches to artificial photosynthesis.

Germany has a number of larger networks active in the field. The Helmholtz Foundation recently refocused part of their PV program to solar fuels, in particular materials for solar fuels. A strong, mainly biological network is the BMBF project *Design of Natural Systems for Light-driven H_2 Production* with partners in Muelheim, Berlin FU, Bochum, Bielefeld and Karlsruhe. A second strong grouping centred in Bielefeld is targeted on biological fuel production using algae.

In UK at the Energy Futures Lab at Imperial College London, research is focused on integrating science and engineering with the aim to deliver a prototype reactor for domestic and industrial use. Other significant solar fuel research in UK is performed at the Glasgow Solar Fuels Initiative, Imperial College and Queen Mary university of London (mainly algae and cyanobacteria) and a group with representation from Cardiff, Nottingham, Oxford and Queen Mary University of London performs the recent project "Transforming Sustainable Chemicals Supply: (nano) engineering catalytic CO_2 photoreduction".

The presently largest European network for solar fuels and biofuels is in the Netherlands – The Biosolar Cells project. Another significant projects in the Netherlands in the solar fuels area is at Technical University of Delft concerning BiMOx photoanodes and photocathode materials; tandem-type hetero-junctions of Fe_2O_3 with another n-type semiconductor with the aim to split water without the need for an additional bias voltage. At the Leiden University density functional theory is used to study mechanism of photo-oxidation of water on oxide semiconductor surfaces.

In Switzerland the PECHouse Photoelectrochemistry Centre of Competence at EPFL (Grätzel et al.) research is targeted on oxide semiconductor based PEC, Photoelectrochemistry systems. Influence of doping and nanostructuring is explored together with effects of interfacial layer between oxide semiconductor and charge collector. Plasmon-enhanced water splitting is a new avenue that recently is being explored. At ETH in Zürich the EMPA laboratories investigates perovskite-type photocatalysts for water splitting and the Solar Technology Laboratory (PSI) is exploring hydrogen production via thermochemical cycles and solar thermal decarbonization of fossil fuels.

Also in France and Italy there is ongoing research in the field of solar fuels.

Outside Europe the US Department of Energy (DOE) has shown a strong commitment to Photoelectrochemistry hydrogen production. Internationally competitive activities are found at several nodes, for example

- Massachusetts Institute of Technology (MIT): replacing expensive platinum components with cheap catalysts based on cobalt and phosphorous.
- National Renewable Energy Lab (NREL): multi-junction photoelectrochemical systems for hydrogen production based on Ga-compounds. Research into more efficient, lower cost materials and systems that are durable and stable against corrosion.
- University of California in Santa Barbara: Ti- and Pt-doped hematite photoelectrodes.
- Georgia Institute of Technology: TiO_2 nanotube photoanodes.
- Lawrence Berkeley National Laboratory: nanoscale heterostructures (nanorods) for photocatalytic hydrogen production.
- Hawai'i Natural Energy Institute (HNEI): exploring different (hybride) photoelectrode configurations designed for high efficiency and low cost.
- The ANSER Solar Energy Research Center at Argonne-Northwestern (a DOE Energy Frontier Research Center): nanostructured materials for photovoltaic and photochemical energy conversion; molecular assemblies that use solar energy to oxidize water and generate hydrogen (artificial photosynthesis for water splitting).

- Center for bio-inspired solar fuel production at Arizona State University (a DOE Energy Frontier Research Center): various aspects of artificial photosynthesis
- Penn State: photochemical carbon dioxide conversion using titania nanotubes
- DOE Energy Innovation Hub "Joint Center for Artificial Photosynthesis" (JCAP) at Caltech and Lawrence Berkeley National Laboratory with a funding of 122 million USD over five years.
- Helios Solar Energy Research Center (Helios SERC): scientific program at Berkeley, which is aimed at developing fuels from sunlight.
- Energy Frontier Research Center "Solar Fuels and Next Generation Photovoltaics" at the University of North Caroline at Chapel Hill.

The present list only shows the networks mainly focusing on artificial processes in materials and to some extent in molecular systems. However, the number of networks and large laboratories/centres focused on development of photobiological processes for solar fuels and biofuels is similar. Some centers mentioned (for example Arizona) have both activities (similar to the Swedish CAP), while most others are only focussed to the biological pathways. Important centers in this research arena are for example found in San Diego, UCLA and neighbouring universities, St Louis (maybe the largest), Rutgers, Indiana, Berkeley but there are several more.

The main research efforts in Japan are concentrated to

- The University of Tokyo: the development of visible light-driven photocatalysts based on oxynitrides (e.g. (Ga1-xZnx)(N1-xOx)) and oxysulfides
- Tokyo University of Science: construction of Z-scheme systems employing visible-light-driven photocatalysts
- National Institute of Advanced Industrial Science and Technology (AIST): Ni-doped indium-tantalum oxides for photocatalytic water splitting
- Australia has strong participation in international programs together with European and US partners but also national programs. The competence in the area is mainly concentrated to
- University of New South Wales in Sydney: titania photocatalysis; oxide semiconductors for PEC hydrogen production; Si-based photocathodes for PEC H2 production.
- University of Western Sydney: oxide semiconductors for photoelectrochemical water splitting (with a focus on TiO_2); defect chemistry
- ANU Canberra drive projects on artificial photosynthesis. This grouping is very visible and works for a Global Artifical Photosynthesis (GAP) project which is met with interest at many places.

- Monash University –catalyst design and participates in international networks with US partners.
- Brisbane University participates in the large international Solar Biofuels consortium and national networks on photobiological hydrogen production.

3.2.5 Trends and potential for further development

The US Department of Energy aims at achieving a STH Solar to Hydrogen conversion efficiency of 12 % and a device lifetime of 5000 hours for photoelectrochemical hydrogen production by 2018. The target for hydrogen production cost is set to less than 3 USD/gge (gallons of gasoline equivalent corresponds to 5.50 SEK/ liter gasoline) by 2017 for various production methods. In order to achieve these goals, research is being carried out along several lines:

- Combinatorial chemistry approaches are used to screen large libraries of materials for their PEC water splitting properties – both experimentally and theoretically. Key parameters are the material's band gap and stability.
- Interface engineering is pursued to avoid the formation of a "dead layer" at the metal oxide – charge collector interface in PEC water splitting (Grätzel, van de Krol).
- Nanostructured semiconductors are used to increase the surface area and to comply with short carrier diffusion lengths (EPFL cauliflower structures, nanotubes, etc.).
- Ion implantation is investigated as a method to dope pre-fabricated nanostructures.
- Metallic nanoparticles are used to enhance light absorption via localized surface plasmon resonances, allowing to reconcile opposing requirements for light absorption and carrier transport. Au-TiO_2 and Au-Fe_2O_3 (Thimsen, Thomann, CTH) are the first systems which have been investigated. Plasmon-enhanced photocurrents seem feasible, but current understanding of the underlying mechanism is poor.
- Hybrid structures are constructed with the aim to improve charge separation.
- Tandem cells and multi-junction systems are ways to more optimally exploit the solar spectrum than is possible with a single bandgap material.
- Development of cheap, long-term stable catalysts is of great importance with respect to achieving the cost goals.

A general, obvious trend is that research in the area is more and more organized into centers - numerous centers have been formed in the past 1–3 years.

4 Research and development in Sweden

4.1 Development of research and market in Sweden before 2005

4.1.1 Public support for research and development

Research in photovoltaics in Sweden was before 2005 conducted primarily at the Ångström Solar Center, at Uppsala University. The research program was focused on three components – thin-film solar cells (CIGS), nanostructured solar cells (Grätzel cells) and smart windows. The research was funded by the Swedish Energy Agency and MISTRA by about 16 million per year.

The activities in Ångström Solar Center started in 1996 and had a stated objective to achieve a commercially applicable product, in other words a clear move towards the commercialization of the results produced. This strategy paid off among others in the form of Solibro AB. The research in the Ångström Solar Center was internationally well known and research carried out was considered at the absolute forefront of research. The interest in the results obtained was large, including keen international interest in the results and the production methods developed within the program.

Research was conducted not only in the Ångström Solar Center. At Chalmers University research was done on plastic solar cells (conducting polymers) and nanostructured solar cells. Research in polymer solar cells is performed at Linköping University. Applied research was performed at the Industrial Research and Development Corporation, IVF, on e g nano-crystalline solar cells.

Within the national development program SolEl 03–07 development and studies were performed on interesting applications for solar cells. The programme was funded by the Swedish Energy Agency and Swedish Research Council Formas together with industrial stakeholders, with an annual budget of around 4.1 million SEK.

Artificial photosynthesis and photobiological fuel production was supported by the Nordic Energy Research organisation for a long time, starting already in the mid-1990-ies for artificial photosynthesis. The Swedish Consortium for Artificial Photosynthesis (CAP) was initiated in 1993 and started its activities in 1994 with support from the K&A Wallenberg Foundation. Research on photocatalytic processes related to hydrogen production was ongoing at Chalmers in EU and Nordic projects.

4.1.2 Public support for market development and technology deployment

A limited number of demonstration projects were implemented with support from the state, e g Universeum in Göteborg, Bo01 in Malmö and Hammarby Sjöstad in Stockholm. The support for market deployment of solar cells was principally focused on targeted support for building integrated solar cells. In 2005 the cumulative installed capacity of solar PV in Sweden was approximately 4 MWp.[56]

4.2 Development of research and market in Sweden 2006–2011

The main part of governmental support to research, development and market introduction of new energy technology is in Sweden canalized through the Swedish Energy Agency. This also applies to support for research and development on solar energy, but it does not mean that the public research funds to solar energy only are distributed through the Swedish Energy Agency. Research can also be supported by funds administered by the Swedish Agency for Innovation Systems VINNOVA, the Swedish Research Council Formas and the Swedish Research Council (Vetenskapsrådet).

4.2.1 Swedish Energy Agency support for research and development

Since 2006, more than 316 million SEK have been granted by the Swedish Energy Agency for research and development in solar power and solar fuels, including the funds allocated for the period 2011 – 2014. The support is provided in the form of loans and grants to private enterprises and in the form of grants to universities and research centres and to international activities. The public funding share is all together 62 % where the remaining part is funded by the industry and industrial stakeholders together with universities and research centres.

The deployment of funds for research and development is summarised in table 4.1.

Table 4.1: Funds from the Swedish Energy Agency to solar energy research and development 2006–2014 (status June 2011)

	Amount awarded (million SEK)	Co-financing (million SEK)	Total (million SEK)	Public funding share (%)
International activities	0.433	10.367	10.800	4
Loan	0	0	0	–
Grant	0.433	10.367	10.800	4
Private enterprises	78.098	115.112	193.210	40
Loan	*13.725*	*14.792*	*28.516*	*48*
Grant	64.373	100.320	164.693	39
Universities and research centres	238.325	71.998	310.124	77
Loan	*0*	*0*	*0*	–
Grant	238.325	71.998	310.124	77
Total	316.566	197.477	514.133	62
Loan	*13.725*	*14.792*	*28.516*	*48*
Grant	302.031	182.685	485.617	62

[56] Swedish Energy Agency (2007)

Private companies

Recipients of public support for research and development among private enterprises are all together eight companies according to table 4.2.

Table 4.2: Funds from the Swedish Energy Agency to solar energy research and development 2006–2014 in private enterprises (status June 2011)

	Amount awarded (million SEK)	Industrial co-financing (million SEK)	Total (million SEK)	Public funding share (%)
Midsummer AB	58.516	73.203	131.719	44
Loan	*8.000*	*11.727*	*19.727*	*41*
Grant	50.516	61.476	111.992	45
NLAB Solar	3.821	26.399	30.220	13
Loan	0	0	0	-
Grant	3.821	26.399	30.220	13
Solibro AB	1.551	0	1.551	100
Loan	*0*	*0*	*0*	-
Grant	1.551	0	1.551	100
Absolicon AB	4.000	1.525	5.525	72
Loan	*4.000*	*1.525*	*5.525*	*72*
Grant	0	0	0	-
Solarus AB	4.950	4.950	9.900	50
Loan	*4.950*	*4.950*	*9.900*	*50*
Grant	*0*	*0*	*0*	-
Energibanken I Jättendal AB	1.100	0	1.100	100
Loan	0	0	0	-
Grant	1.100	0	1.100	100
Elforsk AB	6.000	9.000	15.000	40
Loan	*0*	*0*	*0*	-
Grant	6.000	9.000	15.000	40
Total	78.387	115.077	193.464	41
Loan	*16.95*	*18.202*	*35.152*	*48*
Grant	61.436	96.875	158.312	39

The results of each of the research projects are described on an overall level in the following.

Midsummer AB has received support for research into thin film CIGS solar cells and development of technology and equipment for manufacturing of CIGS solar cells, including support for a project on recycling of production waste from solar cell manufacturing. The main project supported by the Energy Agency aims to demonstrate Midsummer's technology for cost-effective mass production of thin film solar cells by construction of a manufacturing line including technical development and business development. According to the support application the project has a potential to develop Swedish business competitiveness and to generate significant export.

Midsummer's basic idea is to develop equipment that can mass produce solar cells and sell them to module manufacturers, at very competitive prices. In the manufacture of Midsummer's thin-film solar cells, silicone is not used. Midsummer has 10 employees and is located in Järfälla.

NLAB Solar is a company focused on development of dye-sensitized solar cells (DSCs), also referred to as Grätzel cells. The support from the Swedish Energy Agency is focused on improvement of a technology for low-cost production of energy-efficient color sensitized solar cells. The support project was initialised 2011 and is planned to continue until 2014.

Absolicon AB (former Logosol AB) received loan support in 2008 from the Energy Agency for commercialisation of the so called Arontis concentrating solar collector. Absolicon is today an established provider of the solar collector developed by the company and has several reference facilities in different applications for simultaneous production of electricity and heat.

Support to **Solarus AB** is given for implementation of a commercialisation project during three years from the end of 2010 until the end of 2013. The company intends to introduce its concentrating solar collectors on the international market and there focus is on adaptation and development of products, services and organization. The company's products have been developed by Swedish research at Lund University, Ångström Laboratory, Solar Energy Centre at Dalarna University and Vattenfall laboratory in Älvkarleby. The basic concept is a solar concentration system for either only heat or only electricity production or as a hybrid for both heat and electricity production.

The support received by **Energibanken** is as Swedish representative in the International Energy Agency Photovoltaic Power System Programme (IEA PVPS). The representation has been limited to participation in Task 2 – Performance, Reliability and Analysis of Photovoltaic Systems – during 2006 and 2007 and Task 10 – Urban-scale grid-connected PV applications – during 2006–2010. Both tasks were concluded in 2010.

Elforsk AB is jointly owned by Svensk Energi and Svenska Kraftnät with the purpose to rationalise sector-wide research and development. Most of Elforsk's work is carried out in the form of coordinated framework programmes, including the solar electricity programme SolEl. SolEl is an applied research and development programme for solar cell systems. The programme has been running, in different stages, for a full 15 years. The programme is financed to 60 % by energy companies, manufacturers, purchasers (property owners and municipalities) and construction entrepreneurs and to 40 % by the Swedish Energy Agency. The main focus of the 2008–2010 period was to increase the use of solar cells in Sweden and promoting Swedish business in the photovoltaic industry.

In a recent programme evaluation[57] of the latest SolEl programme period it is found that SolEl is a successful programme that has established a well-functioning forum (platform) for the analysis of obstacles and opportunities for the market introduction of solar electricity. An extensive network has been built up around the programme. It has become a hub between different actors, such as purchasers, construction entrepreneurs, energy companies and public authorities.

Universities and research centres

The universities and research centres receiving support from the Swedish Energy Agency for research and development are summarised in table 4.3.

Table 4.3: Funds from the Swedish Energy Agency to solar energy research and development 2006–2014 in universities and research centres (status June 2011)

	Amount awarded (million SEK)	Co-financing (million SEK)	Total (million SEK)	Public funding share (%)
Chalmers	17.291	1.830	19.121	90
Karlstad University	3.100	0	3.100	100
KTH - Royal Institute of Technology	43.240	26.359	69.599	62
Linköping University	22.918	0	22.918	100
Lund University	13.890	0	13.890	100
Umeå University	2.400	0	2.400	100
Uppsala University	135.236	43.809	179.045	76
Total	238.125	71.998	310.124	77

Uppsala University and Ångström Solar Centre

As seen from the table the emphasis on research and development of solar energy seems to be largely concentrated to Uppsala University and activities related to the university. Uppsala University's share of all approved grants for R&D from the Swedish Energy Agency to solar energy is about 57 %. A natural explanation for the high proportion of research funding is that the Ångström Laboratory, which is the leading institution for solar energy research in Sweden, is located here.

A closer examination of the projects supported by the Swedish Energy Agency shows that the emphasis of support is on research concerning CIGS thin film solar cells and artificial photosynthesis. The total support granted to the research on thin film solar cells at the Ångström Solar Centre, in three subsequent projects 2006 – 2014[58], amounts to approximately 55 million.

[57] Wahlström/Rydehell (2011)

[58] "CIGS thin film solar cells, phase 2", "CIGS thin film solar cells, phase 3" and "Ångström Thin Film Solar Centre 2010–2014"

Solar cells

the research on thin film solar cells is focused on further development of technologies for low cost CIGS solar cells with high efficiency as well as alternative solar cell materials. An influential part of the efforts for development of manufacturing techniques is application of vacuum based techniques for coating of thin film solar cells, both co-evaporation and sputtering. Both methods are used in the CIGS solar cell industry today.

The project CIGS thin film solar cells, stage 2 during 2006 – 2009 was partly intended to provide research and development assistance for the development of Solibro AB, a Swedish production facility for solar cells. After the German solar company Q-Cells AG acquired Solibro AB and production facilities were built in eastern Germany, this part of the grant was discontinued and about 15 MSEK of the awarded grants was never distributed. The focus of work has subsequently been more research-oriented.

In spring 2009 the projects receiving support from the Energy Agency were evaluated. The evaluators agreed that research was very good, in some areas excellent and recommended that the agency would continue to finance operations. They also recommended increased collaboration with CIGS companies in the Stockholm-Uppsala region.[59]

In the final report for the project CIGS thin film cells, stage 3 it is reported that conditions for extended support to the companies have been established, partly through research assignments, but also by making equipment available for the companies to rent.[60]

The research on alternative solar cell materials is focused on avoiding use of materials that are, or are expected to be, rare within a 10-20 year period, such as the metals indium and gallium. Two materials are of special interest, Cu_2ZnSnS_4 and $Cu_2ZnSnSe_4$. Also the buffer layer in CIGS cells is subject to research efforts with the aim to minimize use of environmentally harmful heavy metals in manufacturing of solar cells, such as cadmium. The research is both experimental and fundamental in its character and is heavily dependent on the analytical techniques for material and electrical characterization at the Ångström Laboratory as well as the solar cell material synthesis lab.[61]

The research has received support, apart from the Swedish Energy Agency, from Vinnova and from various foundations focused on scientific research. The research is also a part of the strategic research programme StandUP for Energy, a result of the Government's commitment to high quality research in areas of strategic importance to society and the business sector.

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59 Fahlman/Machirant (2009)

60 Edoff (2010)

61 Marika Edoff, Ångström Laboratories Uppsala University, e-mail 14-09-2011

Solar fuels and Artificial photosynthesis

Sweden has a strong position at the international forefront of research concerning solar fuels in general but most significantly in artificial photosynthesis. Emphasis in research is represented by the Consortium for Artificial Photosynthesis (CAP) with its main activities at Uppsala University and by the Solar Cells & Solar Fuel network at KTH and Stockholm University in Stockholm and Chalmers in Göteborg. Other research initiatives are represented by the relatively recent operation "Solar Light as Fuel"[62] in the research environment of Umeå University. Large funding from, among others, the Swedish Energy Agency and the K&A Wallenberg Foundation forms the basis for this research. The picture completes by several past and present projects at Chalmers funded by the European Commission, Mistra, the Swedish Energy Agency, Formas and the Foundation for Research and Development.

Research in the field, with relevance for Sweden, is also on-going in other Nordic countries. The Nordic Energy Research organisation has supported artificial photosynthesis and photobiological fuel production for a long time, starting already in the mid-1990-ies for artificial photosynthesis. CAP coordinated the program BioH2 which ended 2010 with 11 partners in seven countries. Finland presently coordinates the program Aquafeed (starts Nov 2011) with seven partners in four countries.

In Sweden the work in the field of artificial photosynthesis started in the mid-1970´s. The progress was slow until 1993 when The Swedish Consortium for Artificial Photosynthesis (CAP) was initiated. CAP started its activities in 1994 with support from the K&A Wallenberg Foundation. Initially CAP focused on biomimetic chemistry for artificial photosynthesis, mimicking the donor side reactions of Photosystem II. This involved the design and mechanistic studies of photosensitizer-manganese and –tyrosine systems combined with comparative studies of analogous reactions in the natural enzyme Photosystem II. The Consortium has gradually grown in size and scientific scope, from less than 10 researchers initially to its present size of approximately 50. It has also broadened its scientific scope and presently the research is divided in two legs or areas. In the oldest leg synthetic metal organic catalysts are used to accomplish the reactions, so called artificial photosynthesis. In this part of the project deep fundamental knowledge is also gathered about for example natural photosynthesis, proton coupled electron transfer and multiple electron transfer reactions, all vital for successful development of artificial photosynthesis. In the second leg, photosynthetic microorganisms that are manipulated genetically and in recent years developed for synthetic biology approaches are used to produce and distribute hydrogen as a fuel. Both legs are supported by joint grants from the Energy Agency and K&A Wallenberg Foundation. Today the consortium is a world-leading collaboration in artificial photosynthesis, combining research on synthetic and biological systems in close interaction.

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62 Solljus som bränsle

Before 2004 CAP was located at three universities in Uppsala, Lund and Stockholm. In 2004, CAP was split into two parts. One part in Uppsala/Lund, still named CAP and the other part at KTH/Stockholm University, now known as Swedish Network for Solar Cells & Solar Fuels. The research activities performed in this KTH-SU group is described more in detail together with other activities at KTH and Stockholm University in the following sub-section.

From 2005 CAP is supported from the K&A Wallenberg Foundation and the Swedish Energy Agency with major grants.

KTH, Stockholm University and Centre for Molecular Devices

The second largest recipient of support for research and development in solar energy is the Royal Institute of Technology (KTH) in Stockholm. The research at KTH is focused on in first hand dye-sensitized solar cells (DSC, Grätzel solar cells) and other molecular solar cells and nanostructures but also in development of a sunlight-powered system for generation of hydrogen.

A co-operation is since 2005 established between KTH, Uppsala University and the industrial research institute Swerea IVF in The Centre for Molecular Devices (CMD). The overall aim of the CMD is to create a center of excellence for fundamental studies on complex molecular systems bridged with development of applications in the field of molecular electronics with focus on dye-sensitized solar cells. CMD is also developing biotechnology and applications in molecular electronics, such as organic light emitting diodes, molecular probes and sensors, etc. With support from K&A Wallenberg Foundation, Chinese authorities, the Swedish Energy Agency, the Swedish Research Council, Vinnova, BASF AG and BMBF,[63] the group have managed to build a successful network for the synthesis of catalysts and photosensitizers. This new network is named The Swedish Network for Solar Cells and Solar Fuel.

The center activities include basic physical chemical research for fundamental understanding of the components, interfaces and devices, organic synthetic chemistry for design and preparation of dyes, inorganic synthetic chemistry for design and preparation of nanostructured metal oxide materials as well as electrolyte systems, and engineering research for up-scaling and process development. Immaterial property rights generated by the center are handled in the company Dyenamo AB. The Centre's international competitiveness is underlined in an evaluation performed on assignment by the Swedish Energy Agency in spring/summer 2011.[64] The research team is in the evaluation said to have produced strong outputs in all aspects of its research (publication number, impacts, citations) and new scientific discoveries. A great step has also been taken towards practical implementation via the pre-commercialization activities included in the program since 2008.

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63 The Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung), Germany

64 Kasemo et al (2011)

A separate coordinated evaluation of the projects Hydrogen Gas from Solar Energy and Water – From Natural to Artificial Photosynthesis (CAP project)[65] and Molecular catalyst for Solar Energy Conversion (KTH-Stockholm University project)[66] was also performed during spring 2011.[67] The target achievement for the CAP project is in the evaluation assessed to be very close to production of a complete cell for solar hydrogen production and significant achievements have been attained in these areas, although a functional and practical water oxidation system has not yet been achieved. For the KTH-SU group the target achievement have been assessed as substantially progressive. A complete cell for water splitting has been reported, although it's efficiency is low. This is assessed as good progress, but many hurdles to produce a potentially useful water splitting device remain.

At KTH there is also research on solar cells in other areas decoupled from the centre, for instance related to modelling and simulation of large-scale integration of solar cells in the grids.[68]

Linköping University, Chalmers and Karlstad University

Research on polymer solar cells is going on both at Linköping University and Chalmers in cooperation also with Karlstad University. Polymer solar cells are entirely organic and can be produced with very low manufacturing cost but with the current disadvantage of fairly low efficiency and short life-span. The research at Linköping University with support from the Swedish Energy Agency concentrates on molecular solar cells, primarily at the Departments of Physics, Chemistry and Biology. There is a strong publication record, and strong synergies between other polymer research on electro-opto active polymers. There is also basic research related to various charge excitation-transfer-separation phenomena with support from e.g. the Swedish Research Council. At Karlstad University a new professorship and recruitment[69] has just been announced in the area of sustainable energy, including solar energy. The research on polymer solar cells at Chalmers, in two on-going projects[70] with support from the Energy Agency, focuses on the relation of the chemical structure of the polymer to the device performance. As in Linköping there is a strong publication record. with support from e.g. the Swedish Research Council. There is an extensive co-operation between the research groups on polymer solar cells in Linköping and at Chalmers. Both research groups cooperate with Karlstad University, particularly in the area of material physics with focus on morphology in polymer layers.[71]

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[65] "Hydrogen from Solar Energy and Water - From natural to artificial photosynthesis"

[66] "Molecular catalysts for solar energy conversion"

[67] Hahn-Hägerdahl et al (2011)

[68] "Smooth PV - modeling and simulation of large-scale integration of PV in the electricity networks"

[69] Dr. Markus Rinio from Fraunhofer Institute, Germany; starts around 1 July 2012

[70] "POLarge: Polymer solar cells; stabilized morphology and scaling", "Synthesis of materials for polymer solar cells with high efficiency"

[71] Ellen Moons, Karlstad University, e-mail 03-12-2011

One project[72] on artificial photosynthesis is on-going at the Department of Physical Chemistry at Chalmers, with the purpose to study electron and energy transfer for the development of molecular electronics and artificial photosynthesis. There is also collaboration with the Uppsala project on DSSCs. At the Department of Applied Physics there is combined experimental and theoretical research on plasmonic enhancement of PV cells, both on silicon and newer types of materials.

At Chalmers also research on hydrogen production from solar energy takes place at the Department of Applied Physics. Two projects[73] are on-going with the aim to use nanophotochemical cells for hydrogen production from sunlight and water. The above mentioned nanoparticle plasmonics for enhancement of light harvesting is used also in this project.

Lund University

The research on solar energy at Lund University can in great extent be characterized as basic research to study the photochemical quality of sunlight and new nanomaterials for solar cells.

The internationally prominent research at or related to the Nanometer consortium in Lund has a significant fraction devoted to solar energy. The work is focused on materials synthesisNanowires, nanodots and other nanostructures are explored for efficient light harvesting. Such structures can potentially be used as standalone solar energy harvesting elements but also as "add ons" on existing materials like silicon in order to increase efficiency. There are also more applied activities e.g. a start-up company Sol Voltaics AB and projects with support from Vinnova (Green Nano), E.ON, Nordiska Rådets Top-level Research Initiative (NaNordSun) and EU-FP7 (AMON-RA).

At the Department of Chemical Physics the focus of the research is to study the light induced processes in novel materials for solar cells (organic polymers, dye or quantum dot sensitized metal oxide semiconductors and semiconductor nanowires) and the corresponding devices, as well as materials for solar fuel production (artificial photosynthesis). Access to new materials is established through collaborations within three Swedish research consortia – the Swedish Consortium for Artificial Photosynthesis (CAP), the Center of Organic Electronics (COE, Linköping and Chalmers) and the nanometer consortium in Lund (nmC@LU).

There is also one example of applied research in a project performed 2006–2007 with the purpose to study and develop building integrated concentrating elements for photovoltaic systems.[74]

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72 "Controlled electron and energy transfer for the development of molecular electronics and artificial photosynthesis"

73 "Solar Hydrogen", "Nano-Photochemical cells for hydrogen production from sunlight and water"

74 "Building Integrated concentrating elements for photovoltaic systems"

Distribution of support for research with different orientations

In figure 4.1 the distribution of support to research in the areas solar cells, thermal solar power, artificial synthesis and photochemical splitting of sunlight and water for production of hydrogen are illustrated together with beneficiary universities.

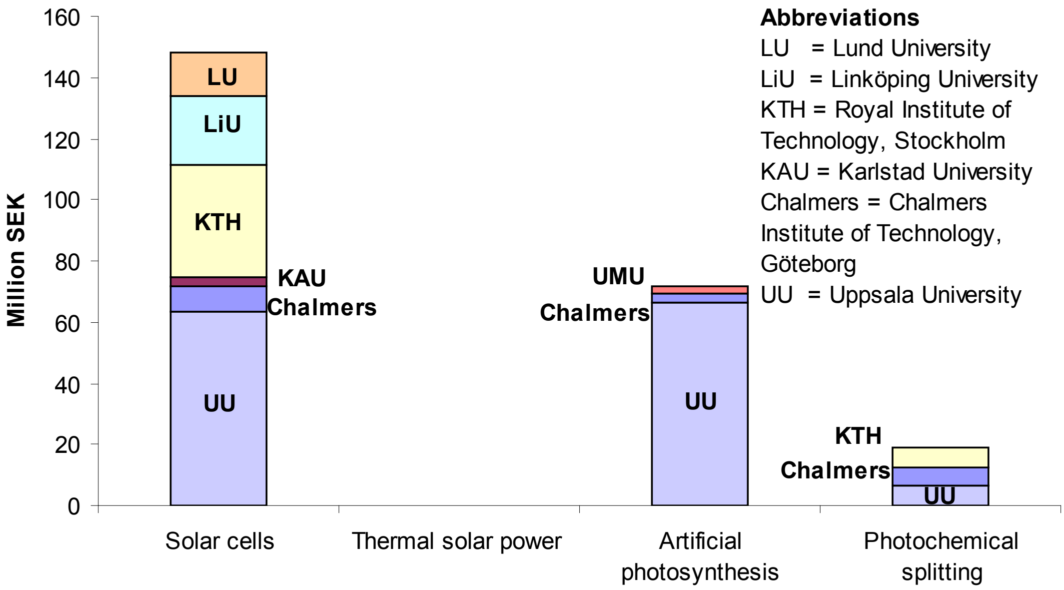

Figure 4.1: Distribution of approved grants from the Swedish Energy Agency 2006–2014 to solar energy research in Swedish universities and research centres (status June 2011). Source: Records of applications for research funding from the Swedish Energy Agency 2011-06-20

As seen in the figure the main body of research support is distributed to research on solar cells (note though that 15 MSEK were never distributed to UU since German Q-Cells acquired Solibro AB). Uppsala University is the main beneficiary for research both on solar cells and artificial photosynthesis and together with KTH on photochemical/photobiological water splitting.

As described above research on solar cells is on-going for different types of solar cells in different research environments. In figure 4.2 the research efforts on different types of solar cells are illustrated on an overall level.

The most supported technologies are the thin film together with DSC and polymer solar cells. Borders between different technologies are not static and fixed. Several projects in the category "others" cover issues common to multiple technologies or are not possible to categorize based on available information.

There are several collaborations between the institutions in different universities in the Centres, for example in Ångström Solar Centre, Consortium for artificial photosynthesis and Centre for molecular devices, which has several intertwined funding streams, see chapter 4.2.2.

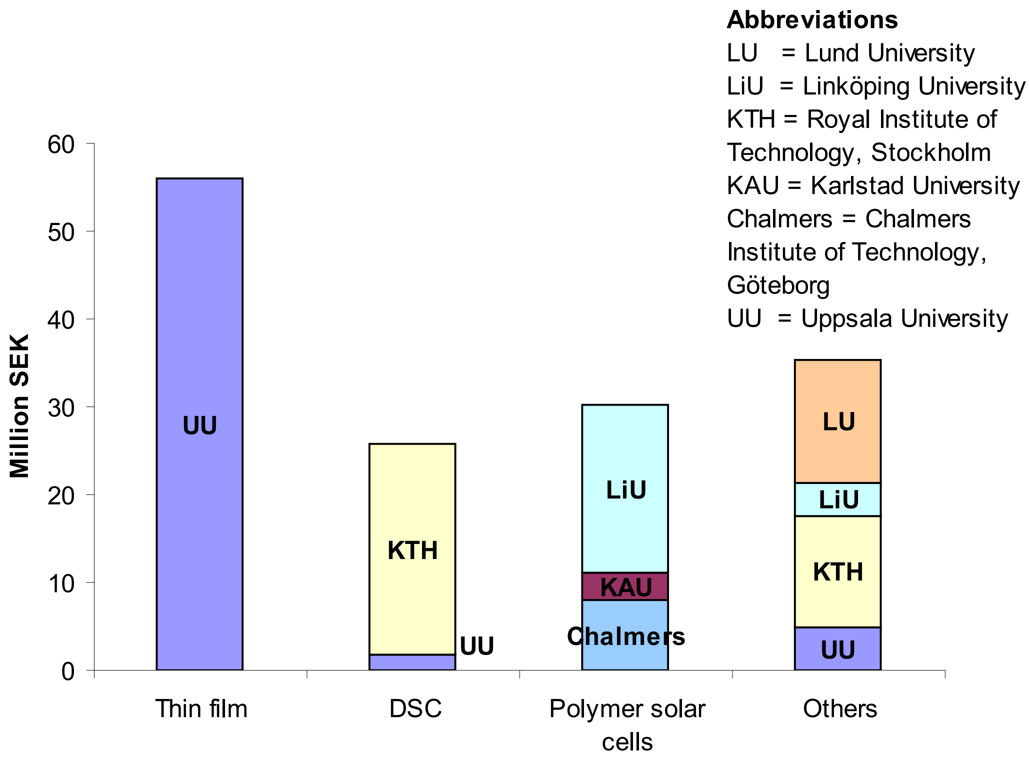

Figure 4.2: Distribution of approved grants from the Swedish Energy Agency 2006–2014 to research on solar cells in Swedish universities and research centres (status June 2011) Source: Records of applications for research funding from the Swedish Energy Agency 2011-06-20

4.2.2 Other public support to research and development

As mentioned in the introduction of chapter 4 also the Swedish Agency for Innovation Systems VINNOVA, the Swedish Research Council Formas and the Swedish Research Council (Vetenskapsrådet) support solar energy research and development in Sweden in addition to the universities themselves.

The Swedish Energy Agency collaborates since 2006 with the Research Council in terms of energy targeted basic research. Applicants submit their applications to the council's annual call for applications in science and engineering sciences and have the possibility to include an energy attachment. When applicants attach an energy annex, they agree that their application may be transferred to the Swedish Energy Agency for funding. Several of the research projects included in the Swedish Energy Agency´s portfolio are based on applications to the Research Council.

The research activities funded by Formas are in general connected to Formas' "core business", research in the areas environment, agricultural sciences and spatial planning. During the period 2006 – 2014 projects related to photovoltaics are represented in the topics of Energy in the built environment, Urban Development and Natural Resources and Recycling according to table 4.4. One project concerning solar water splitting is performed under the topic General Environmental research.

Table 4.4: Projects supported by Formas Source: Formas web site June 2011

Project	University	Duration	Funding (million SEK)
Development and characterization of building integrated PV/T hybrids	Lund University	2005–2007	0.92
Recycling of production residue at solar cell manufacturing	Chalmers	2009–2011	1.536
Elipsometry on coatings and devices for solar energy and energy efficiency	Dalarna University	2010–2011	0.754
Solar energy in urban planning	Lund University	2010–2012	2.4
Sustainable fuel production via solar water splitting and CO2 conversion	Chalmers	2010–2012	4.074
Selective reflectors based on natural and artificial quasi-regular structures for energy-related issues	Linköping University	2010–2013	3.55

VINNOVA supports research in solar energy both as individual projects connected to their calls and as part funding of research programmes together with the Energy Agency. Examples of the former is support to two projects in the call called Green Nano 2008 targeting to facilitate and shorten the lead time for commercialization of research using nano-technologies for improved environmental performance. The two projects are in total financed with 16,2 million SEK to NLAB Solar and Sol Voltaics.[75]

In the research program Research & Grow (Forska & Väx) solar cell research is represented by one project performed by Absolicon AB.

Together with the Energy Agency Vinnova supported the Centre for Molecular Devices during 2009 – 2011. The support from the Energy Agency is 17,6 million SEK and support from Vinnova is 4 million SEK.

Among private funders of research in Sweden the Knut and Alice Wallenberg Foundation has shown a strong involvement in research in solar energy. The foundation has supported the Consortium for Artificial Photosynthesis since the mid-1990s with a total of 97 million SEK, whereof 70 million since 2005. The program Solar Cells and Solar Fuels at KTH has received 46 million since 2006.[76] In October 2011 the Foundation awarded the research environment "Solljus som bränsle" recently created at Umeå University a grant of 40.4 million SEK for the project "The artificial leaf: light-driven".[77]

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[75] Sol Voltaics, Nanowire-based high-efficiency solar cells for green electricity; NLAB Solar, Development of transparent Grätzel cells

[76] The Knut and Alice Wallenberg Foundation web site, http://www.wallenberg.com/kaw/beviljade-anslag/fotosyntes.aspx (retrieved 18-10-2011)

[77] The Knut and Alice Wallenberg Foundation web site, http://www.wallenberg.com/kaw/beviljade-anslag/kommunikeer.aspx (retrieved 03-11-2011)

4.2.3 Bibliometric analysis of research in Sweden

Bibliometry analysis has been performed for research activities in PV solar cells and solar fuels in Sweden in the same way as for the international research for PV solar cells, as presented in chapter 3.1.7, and for solar fuels, as presented in chapter 3.2.3.

An important comment regarding bibliometric analysis in general is the following; the precision and fairness of bibliometric analysis are critically depending on using the right keywords. If someone is publishing and not using these keywords in titles or abstracts, too few publications result. If the same keywords are used also in other than the actual context, false hits result. Therefore the trends and gross features and relative numbers are emphasized, not the details and absolute numbers.

PV solar cells

The same type of publication rate and citation rate versus time, as presented in chapter 3.1.7 for the five leading countries, is displayed for Sweden in figure 4.3. However, here show both the combined "solar cell" together with "photovoltaic" result since 1992 and the 2000–November 2011 result are displayed. The publication rate is very rapidly increasing the last three years.

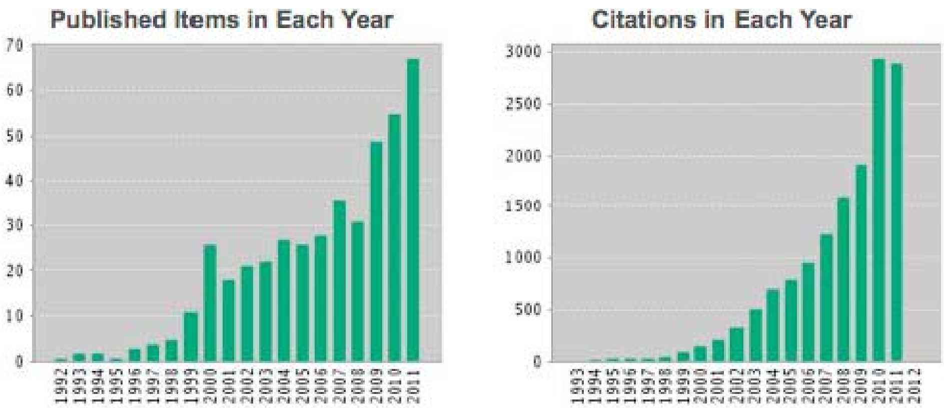

Figure 4.3a: Publications and citations for the search words "solar cell" + "photovoltaic" 1992 – Nov 2011 for Sweden

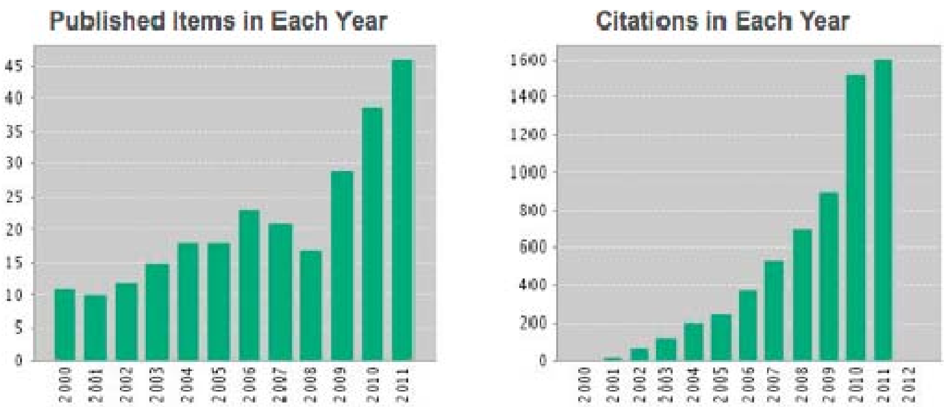

Figure 4.3b: Publications and citations for the search word "photovoltaic" 2000 – Nov 2011 for Sweden

An analysis of the publications from different university regions in Sweden shows that the Uppsala region is dominating according to table 4.5. Here the serch words “solar cell” + “photovoltaic” were used, i.e. the same as in table 4.3a.

Table 4.5: Bibliometry results for Swedish university regions; “solar cell” + “photovoltaic” for all years

University region	Number of hits
Uppsala	167
Linköping	123
Göteborg	102
Stockholm	96
Lund	50

The same dissection, as was made for the five leading countries in chapter 3.1.7, with additional key words are shown in table 4.6.

Table 4.6: Bibliometry search for Sweden with additional key words added to “solar cell” + “photovoltaic” for all years

Additional key word	Number of hits
Silicon	18[1]
Thin films (all kinds including Si, CIGS, and organic)	225[2] (48)[2] (122)[2]
Grätzel/DSSC/DSC	121
Organic or polymer	213[3]

[1] There are no Si thin films in this number. With Si thin films included six more hits would be added.
[2] This large number results if only “film” is added as search word. If “thin film” is used the number reduces to 48. If “film” but not “organic” and not “polymer” are used the result is 122.
[3] This number may be too high, since the words “organic” or “polymer” may be used in other contexts together with the other types of solar cells, e.g. in connection with “dye” or coatings. If the number of hits obtained when ”dye-sensitized” is combined with organic is subtracted, the quoted number reduces to about 50.

Consistently with the international bibliometry also the search words ”nano” and ”plasmon” or ”plasmonics” were investigated. The number of hits for ”nano” in the Swedish search was 10 and for ”plasmon/plasmonic” it was 8.

The Swedish picture is very different from the “world average” in the ranking of the number of publications for different types (materials) of solar cells. Sweden is much under-weighted in the silicon area and dominated by organic/polymer, thin films and DSC. This reflects that Sweden never entered the silicon solar cell “race”, neither research wise nor industrially, while some research groups for a long time have been active in the other areas. The large number for thin films hits reflects the quite successful Uppsala research and development in this area.

The high number for DSCs is explained by the long-term research funding and successful research activity in Stockholm–Uppsala. In the polymer/organic solar cell area there are several groups contributing to the quite high number, in

Linköping University, Uppsala University, Karlstad University, Chalmers and the Royal Institute of Technology (KTH) in Stockholm.

The emerging areas “nano” and “plasmonics” are mainly represented by Lund and Gothenburg, but especially nanotechnology is also inherent in the other universities’ research.

4.2.4 Solar fuels from photochemical hydrogen production

The bibliometry covering Swedish research in the field of solar fuels is performed with the distinguishing search words as described for the international bibliometry presented in chapter 3.2.3.

As presented in chapter 3.2.3 the total number of publications in Sweden is 119. A clear increase in publication frequency is observed during the period 1997-2005, after which the output seems to level at ca. 13-14 publications per year. Citation frequency, on the other hand, shows a constantly increasing trend.

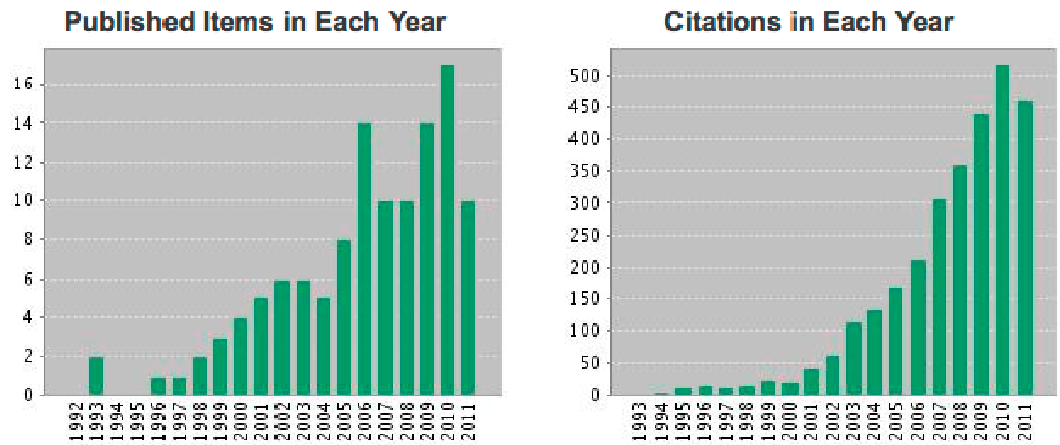

Figure 4.4: Publications and citations for search words related to solar fuels 1992 – Nov 2011 for Swedish universities

The number of publications found for different university regions in Sweden is as presented in table 4.7.

Table 4.7: Bibliometry results for Swedish university regions

University region	Number of hits
Uppsala	68
Stockholm	58
Lund	29
Göteborg	20
Linköping	0
Total	175

The Consortium for Artificial Photosynthesis (Uppsala and Lund) stands for the majority of publications, followed by the Stockholm region and Göteborg. Also here, the sum is larger than the total number of entries due to collaborations between two or more universities.

Nano and plasmonics occur much less frequently in Swedish entries than globally. The number of hits for ”nano” in the Swedish search was 12 and for ”plasmon/plasmonic” was one (1). This is very likely due to the fact that the majority of publications deals with artificial photosynthesis, where these concepts might not be as promising as for photochemical hydrogen production.

As for solar cells, the Swedish picture differs significantly from the global picture. It is likely, in the case of solar fuels, attributed to the emphasis in artificial photosynthesis, which is found in the Swedish research. Swedish research related to nanotechnology and plasmonics is in a global perspective very strong in other contexts, such as ICT[78] and bio-sensing, which may imply that research for solar fuel could be expanded in these fields.

Solar fuels from photobiological hydrogen production using microorganisms

As presented in chapter 3.2.3 Sweden is the 9th most active country in publications related to photobiological hydrogen production using microorganisms with a total of 27 hits, of which 17 are from Uppsala University.

Also for Sweden, the cumulative output for photobiological hydrogen production is roughly five times smaller than for photochemical water splitting. The number of published items has been rather constant since 1995 and lies at an average of close to two publications a year, in clear contrast to the global picture. Despite this constant output, the citation frequency has increased steadily since 2001. Another striking difference as compared to the global situation is that the self-citation frequency in Sweden is below 5 %, a remarkably small number.

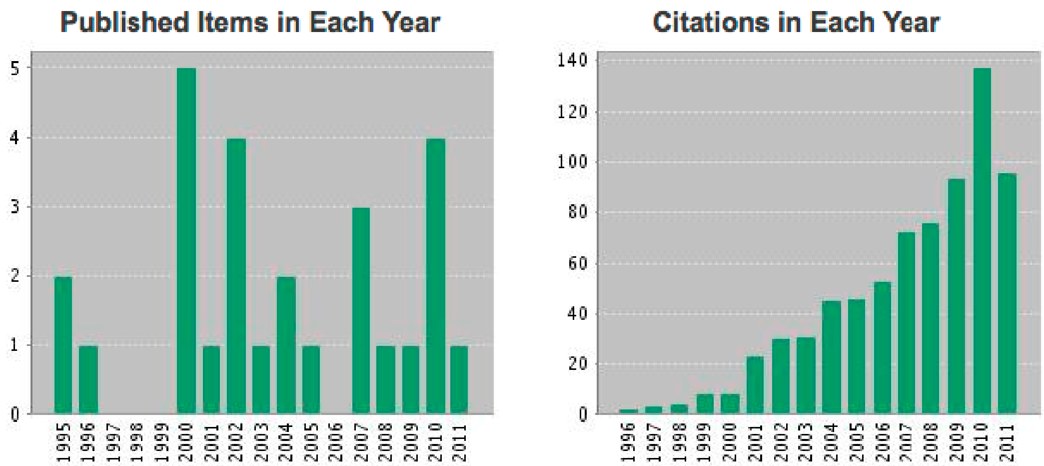

Figure 4.5: Publications and citations for search words connected to photobiological hydrogen production1992 – Nov 2011 in Sweden

[78] Informations and Communications Technology

4.2.5 Public support for market development and technology deployment

The electricity certificate system, designed to promote the production of electricity from renewable energy sources, was introduced in Sweden in May 2003. It replaced the previous investment subsidies in renewable energy sources. In theory the certificate system includes support to solar installations, but few solar installations can be said to have occurred as a result of the support. According to the Swedish Energy Agency's report The electricity certificate system in 2010[79], there were only nine approved solar electricity installations in the scheme in 2009. One of the conclusions in the Energy Markets Inspectorate investigation Net Charge (net metering) and proposed new rules for electricity self-generation[80] published in November 2010. The Inspectorate recommends that the Government provides the Swedish Energy Agency the task of investigating the possibility of simplifying for small electricity producers to take advantage of the system's benefits.

To further promote the construction of photovoltaic installations an investment subsidy programme, a tax credit of up to 70 % of the investment cost of PV installations placed on buildings used for public purposes, was introduced in May 2005. The subsidy, which totalled 150 million SEK, was granted to cover the total cost of construction of facilities, including design, materials and installation. The subsidy programme was effective until December 2008 and resulted in 110 new installations and an increased solar cell capacity of nearly 3 MW, almost a reduplication of the total installed capacity before the commencement of the programme in early 2005. However, many believe that the programme's greatest merit has been as information carrier. It has helped to create a positive attitude and awareness of solar cells.[81]

On 1 July 2009 a new state subsidy program for investments in solar cells for the period 2009-2011 was introduced. A total budget of 222 million SEK has been set aside for the subsidy over the three years. The subsidy programme is for all user groups and not only for public buildings, as the previous investment support was. An expectation was therefore that the new subsidy program will thus have a greater distribution in both plant size and the type of user.

An evaluation of the program[82], conducted in spring 2011, has analyzed that nearly one hundred projects have received subsidies. The total peak power (W_p) for these installations is approximately 1.2 MW_p. The solar modules used are almost exclusively based on crystalline silicon cells. Out of the almost 100 installations nine are based on thin film CIGS cells.

The evaluation concludes that subsidies are crucial for the Swedish market for solar cell installations. The absence of rational methods for disposing of surplus electricity to the grid is considered to be the main obstacle to market growth for solar cells in Sweden.

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79 Swedish Energy Agency (2010)

80 Energy Market Inspectorate (2010)

81 Swedish National Board of Housing, Building and Planning (2010)

82 ÅF Industry (2011)

Different facilitation opportunities for grid connection of photovoltaic installations have been proposed. One result is the new regulations that were set in 2010, which make exceptions for small systems. A producer that has a fuse at a maximum of 63 ampere and is producing electricity with a power of maximum 43.5 kW will no longer need to pay for the grid tariff as long as the producer during one calendar year draw more electricity from the national grid than the producer feeds in. However, many players in the solar industry also propose that changes in the tax system have to be made, so that net charge of tax for purchased electricity and supplies of electricity from small installations can be achieved.

4.3 Strengths and weaknesses in Swedish research initiatives

The analysis of Swedish research and development efforts and activities provides a basis for the identification of overall strengths and weaknesses of the Swedish approach and situation. The strengths and weaknesses identified and formulated in the following form, together with an analysis of conditions and challenges on the international market in chapter 5, a basis for the assessment of opportunities for continued Swedish research efforts as presented in chapter 6.

Strengths

Sweden has some very strong, internationally competitive **research environments** in the area of solar cells, especially in dye sensitized solar cells, thin films, polymer/organic solar cells and more recently nanotechnology based solar cell concepts. Several of these activities, but not all, have grown out of Sweden's long standing strength in materials science and nano science. Only the thin film PV area has led to commercial products. Sweden also has strong activity in basic research on solar fuels especially the area using molecular complexes (artificial photosynthesis) and micro-organisms. Here there is no activity close to commercialization. The real strength is thus for all the above areas, except possibly thin films, the research environments, with many generic components in the solar energy harvesting area. This is likely to be of long standing importance for the expected growing solar energy activity world-wide, not the least for education of people for an emerging industry.

Weaknesses

- Sweden has very little activity in the leading Si based PV technologies.
- Engineering level activities are much weaker than the physics-chemistry oriented research. This is rather natural, since real products in most cases lie quite far in the future or will not emerge at all. However, for Swedish industry with a potential to be suppliers of components or subsystems and act as contractors this may be a weakness for the future. It may also be a weakness for education to not have activities at the engineering level.
- There is very little academic activity in the CSP area – which for the future may be a similar weakness as mentioned in the previous point. There is however a strong private financed R&D engineering activities in some export industries.

5 Market opportunities and challenges

5.1 Market conditions in general

Solar irradiation is abundant all over the globe but the intensity varies significantly between different places on the earth. Most of the solar energy technologies represent a small environmental burden and thus a positive impact for the future. Even though the impact from solar energy generation today represents a small fraction of total energy consumption, the long term potential is great.

The actual deployment of solar energy will depend on the degree of continued innovation and development of technologies, cost reductions and supportive public policies.

There is today a great variety of PV and other solar technologies in development. Some of them have the potential for large cost reductions and others might have more difficulties to compete as they require toxic or rare precious materials that might be difficult to handle in a large market.

Some basic facts are

- The sun is only shining during daytime. Thus, storage of the produced electricity is required. Large transnational and trans-regional, eventually global distribution nets may remedy this situation, but this lies very far into the future. In countries with a peak related to air conditioning needs, such as in Japan, West US and parts of Germany correlation between availability and demand is better and the limitations related to storage and transmission is less accentuated.
- Solar power is the most intermittent renewable technology that has been developed. Just a passing cloud can stop the production. This fact must be taken into consideration when planning the role of PV in the electricity system in similar ways as with for instance wind power. Excess power must be taken care of and storage is needed for peak demand. On the other hand, in cloud free areas (deserts) it is known exactly when the sun shines.
- In major parts of the world there is significant variation of the sunlight between the seasons. Some kind of seasonal storage is required (again assuming transcontinental or other very long distribution nets are not built). By co-ordination with other power technologies and storage means (e.g. water dams) the intermittent production from the sun can be regulated.
- Solar PV (silicon) has shown a long lifetime and today performance guarantees over 20 years are not uncommon.
- The operation and maintenance costs for PV system are very low in comparison to other similar power production technologies.

- PV systems require a large area in comparison with many other power technologies. The necessary area can be a problem if PV systems would compete with for instance food production. On the other hand there are visionary ideas and experiments to grow e.g. vegetables on the partly shaded areas under solar cell arrays. The costs for disposal of the land area can also be a significant share of the investment costs. Available areas like roofs or areas adjacent to main motorways, airports, etc. can be useful areas for PV systems as these areas are difficult to use for other purposes. The same applies of course to deserts.

The market conditions for solar electricity are very different in different countries or regions.

- The cost to produce electricity from PV or other solar technologies is still high in most countries and the solar technology has without subsidies in general difficulties to be competitive today. The costs to produce electricity by solar technologies are however decreasing and may have reached grid parity in some regions already today.
- Subsidies related to production, especially so-called feed-in tariffs, have created a considerable growing market in several countries, historically in particular in Germany, but now also in for instance Italy, France and other countries. The producer of for instance solar electricity receives a premium paid by all electric consumers as an extra fee.
- Some countries and states in the USA and also in some other countries allow using net-metering systems. In principle the delivery to the grid is measured by the meter rotating backwards when electricity is delivered to the grid.

The domestic market for solar power in Sweden is today very small but increasing. Sweden is not foreseen as one of early adopters of solar electricity technologies. The electricity prices and costs for electricity production by other means than solar are still relatively low and the solar irradiation is smaller compared to continental and especially Southern Europe. The electricity system in Sweden has a very low carbon burden as it is today dominated by hydropower and nuclear power.

These conditions may change in the future, as the electricity prices in Southern Sweden will soon increase and come close to Northern European prices and the nuclear power might be phased out in a foreseeable future. The consumer’s costs for electricity distribution are rising and expansion of the power grids is often difficult to achieve in the short and medium term. Together these aspects will strengthen the drivers for renewable technologies and distributed generation and then also for solar technologies. Consequently solar technologies will have better possibilities to come closer to grid parity, also in Sweden.

In figure 5.1 published by EU JRC Ispra 2011 the predicted influence of solar electricity among renewable electricity production in Europe up to 2020 is described. According to the prediction PV will increase and have a minor but significant role to play among renewable energy technologies in 2020.

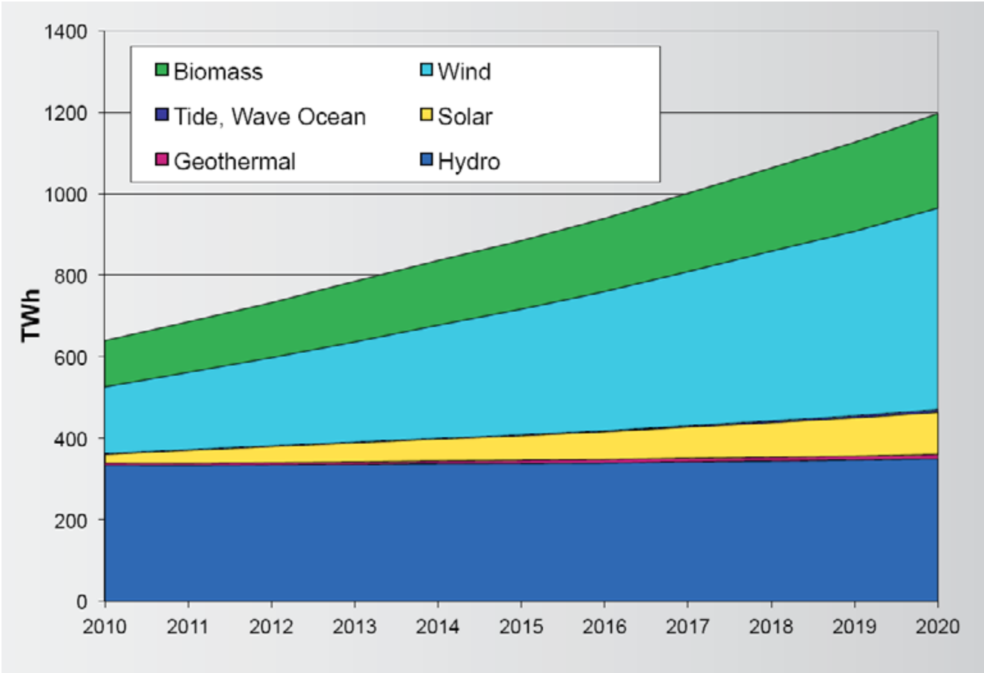

Figure 5.1: Planned European renewable electricity production within the EU member states according to the National Renewable Energy Action Plans Source: JRC PV Status report (2011), Ispra

Anyhow, the increase and domination of wind power and biomass is significantly bigger than solar energy. Hydropower will continue to be large and important but the expansion of hydropower is difficult mainly because of local environmental restrictions. The other renewable technologies such as geothermal power and ocean power are not expected to have an important influence in 2020 in this scenario.

5.2 The PV market

The world solar cell production and installation of PV systems has increased massively the last years. Up to year 2006/2007 the major part of the production was located in Germany and Japan. The production in these countries is still increasing quite significantly but the major increase is made in China and Taiwan and they lead the production capacity today.

China has become the major manufacturing area followed by Taiwan, Germany, Japan and South Korea. According the the JRC Ispra, China will in the coming years dominate the world production of PV together with Taiwan. In 2015 China might have close to 50 % of the world-wide production capacity. The new five year-plan (2011–2015) in China is alleged to involve a fundamental restructuring of the economy and is considered as a “green” plan. For solar energy the aim is

10 GW[83] installed capacity in 2015 and 50 GW by 2020 as a part of the goal of having 15 % non-fossil energy by 2020. One hundred so-called "New Energy Cities" will be constructed, and also a number of "Green Provinces" with at least 80 % renewable energy.[84]

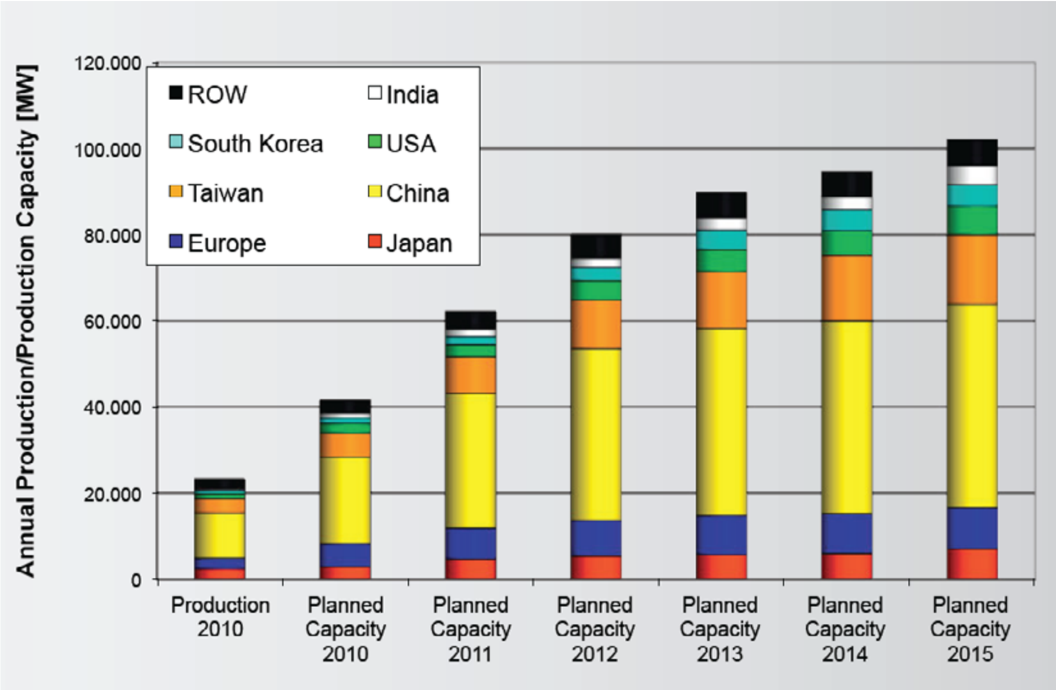

Figure 5.2: World PV Cell/Module production with future planned production increase. Source: PVstatus report 2011 JRC, Ispra

The survey made by JRC Ispra includes 350 companies. The Photovoltaic Industry has changed dramatically over the last few years. Among the 15 biggest photovoltaic manufacturers in 2009, only three had production facilities in Europe, namely First Solar (USA, Germany and Malaysia), Q-Cells (Germany and Malaysia) and Solarworld (Germany and USA). First Solar is still the biggest company followed by Suntech from China. Among the top ten manufacturers in 2009 four companies were from China and two from Japan[85].

The biggest uncertainty for the ambitious expansion plans is of course the expectation that the market will grow accordingly. Most markets are still dependent on public support, feed-in-tariffs or other kinds of subsidies. The wafer based silicon solar cells are still the main technology and in 2010 the market share was about 85 %. The predicted increasing market for solar cells will still be dominated by crystalline silicon modules in the coming years.[86]

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83 Recently reviewed and doubled (to 10 GW) following Fukushima.

84 Widén (2011)

85 JRC PV Status report (2010)

86 JRC PV Status report (2011)

The most extensive increase in PV installations during the last years occurs mainly in Europe, particularly in Germany and in Italy, although other markets have recently grown in installation capacity. The total world-wide installations were at the end of 2010 estimated to be 39 GWp of which 29 GWp in Europe. The large market expansion in Europe is primarily driven by favourable subsidies in some countries, with feed-in-tariffs that make investment in PV installations favourable for users. However, the remarkable increase in installations seen especially during 2010 was also caused by a significant decrease in cost. It can be mentioned that the installed power in GWp of solar power exceeded the installed power in GWp of wind power plants in Europe in 2010.[87 88]

The installations in the USA and Japan have also had a major increase but with a slower pace compared to Europe. In 2008 the subsidies were exceptionally favourable in Spain, a country with a large amount of sunlight.

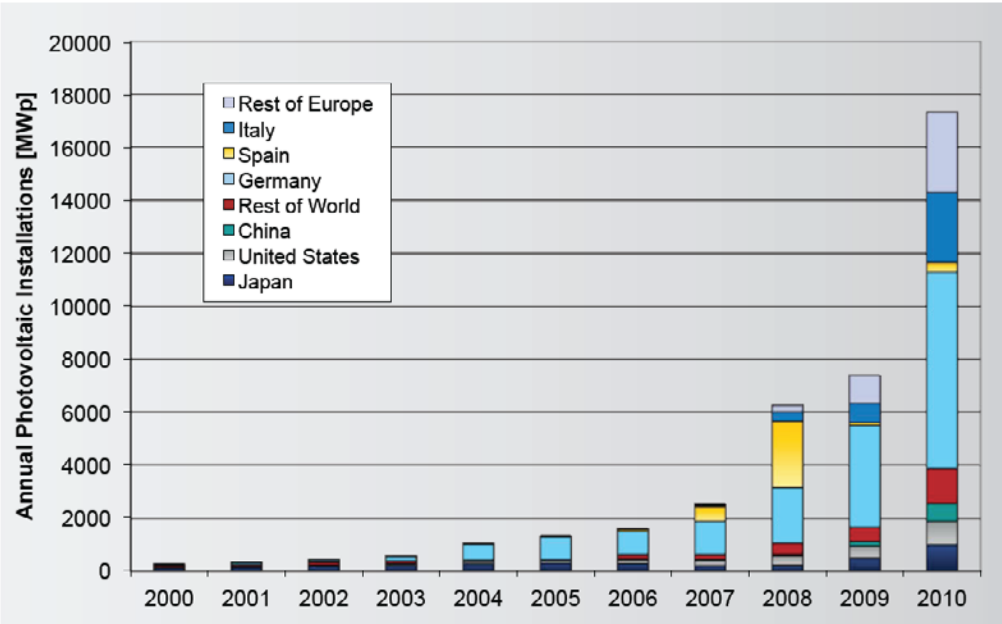

Figure 5.3: Annual PV installations. Source: PV status report 2011 JRC, Ispra

The positive effects of this massive market expansion are that the production of PV has been highly industrialised, leading to significant cost reductions. Also the costs for the raw material have gone down. The previous temporary shortage of solar-grade silicon in principle occurred because all silicon for PV production came from scrap from the electronic industry. The high growth-rates of the PV industry over the last years have triggered the industry and resulted in the market entrance of new companies producing sole solar-grade silicon. The PV industry has therefore been more independent and the availability of solar-grade silicon is today considered secured. One typical example is the Norwegian company Elkem Solar that recently has been acquired by the Chinese stakeholder Bluestar[89].

87 EurObservER (2011)

88 EWEA (2011)

89 Ny Teknik (Swedish technology and IT newspaper), September 2011

One effect of the market development of PV during the last years is that the production capacity and the market expansion not necessarily are in the same regions any longer. This might be a drawback over a longer period as the research and development activities could change from Europe and USA to China and Taiwan, as the major R&D-consumers will be there.

In order to maintain the extremely high growth rate of the PV industry, different pathways most probably have to be pursued at the same time:

- Continuation to expand solar grade silicon production capacities in line with solar cell manufacturing capacities;
- Accelerated reduction of material consumption per silicon solar cell and Wp, e.g. higher efficiencies, thinner wafers, less wafering losses, etc.;
- Accelerated ramp-up of thin-film solar cell manufacturing;
- Accelerated CPV introduction into the market, as well as capacity growth rates above the normal trend.

Further photovoltaic system cost reductions will depend not only on the technology improvements and scale-up benefits in solar cell and module production, but also on the ability to decrease the system component costs, as well as the whole installation, design, operation, permission and financing costs. A continuation and expansion to more countries of the on-going subsidies especially the feed-in-tariff system and similar systems is considered to be essential for a continuation of the market growth in the foreseeable future.
For the Swedish export industry there will be several opportunities to supply components, software and system knowledge in the solar power market including c-Si systems.

5.3 Concentrating Photovoltaic Cells, CPV, market

Similar to other technology areas, new products will enter the market, enabling further cost reduction and possibly higher efficiencies. Concentrating Photovoltaics (CPV) is an emerging market. There are several tracks depending on the concentration ratio and thus the need for cooling. In order to maximise the benefits of CPV, the technology requires high direct normal solar irradiation and these areas have a limited geographical range – the “Sun Belt” of the Earth, typically encompassing the Southern USA and the Mediterranean countries and other desert like areas.

The market share of CPV is still small compared to PV, but an increasing number of companies are focusing on CPV. In 2008 about 10 MW of CPV were produced.[90] Market estimates for 2009 are in the 20 to 30 MW range and for 2010 about 100 MW are expected.

[90] JRC PV Status report (2010)

5.4 Thermal solar electricity, CSP, market

The different technologies of CSP are described in chapter 3.1.5. There is in Sun Belt areas a competitive situation between CPV and CSP technologies for optimal project sites for large projects. Both technologies work best in direct sunlight locations without clouds – they both use reflectors to concentrate sunlight, and these optics cannot concentrate diffuse sunlight.

Table 5.1: Current and Predicted LCOE of CSP Technologies[91]

LCOE [EURcts/kWh$_e$]	Parabolic Trough	Solar Power Tower	Dish Stirling
Current (2010)	17.2	24.1	28.1
Future (2025)	12.8	9.7	14.0

In Europe the requirements for economic electricity production with CSP are fulfilled for a number of countries around the Mediterranean Sea but the real "European Sun-belt" is in North Africa. A group of leading European industries have established the DESERTEC foundation for promoting the deployment of CSP-technology in the North-African deserts, with the stated aim of providing 15 % of the European electricity requirements, as well as meeting local demand.

It looks like the CSP market so far has a bright future especially for larger projects. About 17.5 GWp of CSP power projects are under development worldwide, and the United States leads with about 8.7 GWp according to GTM Research, Spain ranks second with 4.5 GWp followed by China with 2.5 GWp.

About 1.17 GWp of CSP power plants already are online. Spain is home to 582 MW of them followed by the United States with 507 MW. Iran takes the third place with 62 MW according to GTM. These figures were published in June 2011.

The parabolic through technology can be used in very large plants, in the USA is currently a plant in the range of 400 MWe under erection and similar plants are planned for North Africa.

For Solar tower plants seems 100 MW_{th} be an optimal size with the current available technology, corresponding to a 160 m high tower.[92]

Development of CSP technologies is similar to conventional power plant engineering. The project developers for CSP include Solar Millennium and Abengoa Solar using parabolic trough technology, BrightSource Energy with solar tower technology, Penglai Electric has received a contract to build a 2GWp solar tower plant in China, Renovalia parabolic dish with Infinia Stirling engines and NextEra Energy parabolic trough. All these companies are building very large plants[93].

If the price for PV plants continues to decrease it can, however, be a threat to the CSP technology as a whole.

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[91] Strand et al (2011)

[92] Strand et al (2011)

[93] Wang (2011)

5.5 The market for Solar Hydrogen

The commercial market for solar hydrogen is still far away, depending not only on the solar technology but also on the commercialisation of hydrogen as an energy carrier. The hydrogen fuelled vehicles are still in a demonstration phase. The technology has been and is demonstrated today in several places. There are local buses and fleets of vehicles using hydrogen as a fuel. Several fuel cell car concepts are readily developed and made available by the major car manufactures. These cars have performance and comfort as traditional passenger cars but the cars only exist in a limited number, less than 1000 vehicles in total.

An intermediate market could be to produce solar hydrogen and together with CO_2 produce methane that can be introduced in the natural gas grid or used directly as transport fuel. This technology is studied and developed both in Germany and in one Nordic project, these project are today using wind power instead of solar. HyperSolar is a US-based company with the aim to commercialize this technology.

The main drivers for hydrogen as fuel are

- The possibilities to use a local produced fuel and thus avoid the import of fossil fuels.
- The environmental benefits, improvements of local emissions as well as decrease of CO_2 and other GHG emissions.
- The possibilities to create new industries and jobs in the future hydrogen fuel sector.

The artificial photosynthesis and water splitting technologies have to compete with and challenge more conventional direct solar hydrogen technologies such as PV-electrolyser systems which today have an efficiency between 10-15 % from sun to hydrogen. This efficiency will most probably increase significantly with new electrolyser technologies, for instance high temperature pressurised solid oxide electrolysers,[94] together with new materials where efficient solar harvesting properties are combined with efficient electrode properties for the desired reactions in layered films or core-shell nanostructures.

[94] IPCC (2011)

6 Conditions and opportunities for Swedish research and industry

6.1 Summary of the current status of Swedish research

As is obvious from the bibliometry study and various reports from research groups, Sweden's situation is characterized by;

- Internationally strong academic standing in the PV subareas DSSC (one of the top 2-4 international groups), thin films and organic/polymer cells.
- Internationally strong academic standing at the basic research level in the two areas molecular-complex-based "artificial photosynthesis" for direct fuel production and microbiology oriented hydrogen production.
- The PV research has a much stronger market mind set/awareness compared to the solar fuel area.
- A few emerging, internationally strong but relatively small activities exist in (i) nanotechnology for PV solar cells and (ii) plasmonics for various types of PV cells.
- The relative efforts among what is called first and second generation PV research is much over-weighted towards second generation in Sweden compared to the international situation; there are very few research activities in the silicon PV area in Sweden.
- The research situation described above is based on underlying highly competitive basic research in chemistry, physics and materials science and in one case on (micro)biology.
- There are only few examples where the fundamental physics, chemistry and materials science are matched by engineering research.
- There is very little fundamental or engineering research related to CSP in Sweden as judged from bibliometric searches and public financed research.

6.2 Summary of Swedish industrial activities and challenges

Industrial activities in Sweden related to solar energy have to date mainly focused on development and production of thin film PV, except for composition of modules of silicon and other solar cells. The most clear examples of industrial progress in this area is Solibro AB, which was the result of a targeted effort to commercialize the results of the research on thin film PV at Ångström Solar Centre, and Midsummer AB. Solibro was acquired by Q-Cells in Germany in 2009[95] and

[95] From 2006 to 2009 it was a joint venture between Q-Cells and Solibro AB (where Sjätte AP-fonden was the largest shareholder).

Midsummer today has, through a focus on automation, gained an opportunity to produce CIGS solar cells at comparatively low production costs.

There are significant industrial activities in CSP, with relatively limited underlying academic research. KTH, Department of Energy Technology, has established research activities in the field of CSP as a part of the research program TURBOKRAFT, financed by the Swedish Energy Agency together with Swedish industrial partners. One of the industrial partners, Siemens Industrial Turbomachinery AB, has developed steam turbine technology optimised for CSP applications and is now one of the leading suppliers of steam turbines to CSP projects world-wide.[96]

Another example, is the delivery from Alfa Laval to the largest CSP plant in the world, which is constructed in USA, Alfa Laval supplies Packinox heat exchangers which have been developed for molten salt thermal storage systems. The order was signed in May 2011.[97]

However, the commercial challenge on thin film PV and other alternative technologies to silicon PV has increased, i.e. the entrance barrier has increased, since the price for silicon solar cells today is substantially lower than was previously believed to be possible except on a much longer term. For the alternative technologies to have a commercial opportunity, it is estimated that they must [98]

- Have the potential to reach efficiencies over 15 % within a few years,
- Have the potential to reach production costs below 0,5 USD/W,
- Have a “verified” life time of more than 20 years,
- Refrain from dependency of exotic rare materials.

Such a development requires research efforts to achieve an industrial edge as well as the investments already done by the industry put demand on further research efforts. However, there will be market segments showing more differentiated needs. For example in building integrated PV (BIPV) where module efficiencies below 10 % could be well accepted and consumer applications which may not need as long life time as 20 years. However, the statements are well suited for the purpose to increase the supply of solar power.

The industrial opportunities are however not only dependant on the development in the production of materials for the development of solar cells. A strategic choice for the industry could be to market the extensive systems knowledge that has been developed through participation in the Swedish research and development activities on solar energy. Thereby the industry would be less dependent on any uncertain successes in the areas related to alternative materials and technologies. Other interesting areas for Swedish companies could be software development, instrumentation and test centres for different solar technologies.

[96] Strand et al (2011)

[97] Dagens Industri (Swedish daily business newspaper), 31-05-2011

[98] Lars Stolt, Solibro a.o 2011

6.3 Possible action plans

Different action plans can be identified for the future targets of Swedish research in solar power and solar fuels with the main elements as described in the following.

i. Continue the **current scheme of research funding**, **which essentially is a responsive, bottom up scheme** in the sense that strong research groups compete about available funds, are evaluated with primarily scientific evaluation criteria, with some relevance criteria added, and perform long term basic research with some additions of application/engineering elements on top. This scheme maintains strong research environments and satisfies long-term scientific competitiveness, if regular international evaluations are made. An unexploited potential that could be mobilized for this scheme lies in the generally very strong materials science and nano-science research in Sweden. This approach is not bad, when one deals with an area that can be regarded as "emerging" rather than mature, and where it is difficult to discern more specific and immediate industrial technologies, directions or needs. It also satisfies the need to follow what happens at the international research frontier, and to some extent (but not all) educational needs. However, to constitute an appropriate contingency plan this scheme must be complemented as outlined below.

ii. Establish **a much more focused and strategic R&D agenda, which is strongly guided by a top down approach**, where funding is to a large extent based on an industrial strategic agenda and its identified needs. These needs and opportunities will have very different time scale, from immediate to long term. An inventory needs to be made by discussions with Swedish industry. The inventory should describe industries already active on the solar power and solar fuel arena, at what systems level (single components, subsystems, systems, services,….) they are active etc., and furthermore (to the extent it is possible), which industries that have plans or ambitions to enter the arena, and again at what systems level. The inventory should also include mapping of the political ambitions on the energy arena.

iii. A balanced mixture between i. and ii. The meaning of "balanced" becomes a key. In this approach, the challenge is to find **the right mixture between a bottom up, long term, quite basic and generic research content** (i. above), **and a top down, "needs and opportunities" driven R&D structure** (ii. above), with shorter time scales (not always short in an absolute sense, but shorter than the bottom up components). Furthermore, to be really successful, such an approach requires a strong communication between the top down and bottom up components and actors. The targets for the R&D could preferably be set up in consensus between different stakeholders in Sweden such as industry, the innovation system, researchers, end user organizations, the Swedish Energy Agency and other financers/funding agencies. Also the political agenda needs to be considered in some way. This mixed bottom up and top down approach furthermore requires regular evaluations of quality with an international measure stick and dynamic reconsideration of the balance between the bottom up and top down components. The balance between bottom up and top down driven activities will be different in different areas depending on their maturity.

iv. **Coordinate different governmental agencies' funding schemes** of solar power and solar fuel research in order to make iii more effective and targeted.

v. When entering the interface between research and technology and market development an action plan based on i. –iv. above may be enhanced and fertilized by public sector **advanced technology procurement**. This falls outside the research program, but the two are on the other hand strongly interdependent of each other and would involve both industry, the innovation system, academia, the public sector and the political agenda.

6.4 Targets for future Swedish research on solar power and solar fuels

Solar energy is likely to be a large contributor to a sustainable energy system on a long-term time scale. Today it delivers less than 0.1 % of worlds electricity use[99] but already more than three percent in a country like Germany, with more than 600 TWh annual use and not the most sunshine compared to more southern countries. The growth rate is difficult to predict, since it depends on several uncertain factors like the rate of consumption of fossil fuels (related to peak oil, peak gas, peak coal), how large "harvestable" such reserves are, and especially to what extent coal will be used, the role of nuclear power in the future, the role and magnitude of biomass as an energy raw material, national and international regulations and agreements, the global economic development and also the development and competiveness of other renewable energy sources like wind power, geothermal energy, ocean energy etc.

In that situation the positioning of Swedish solar power and fuel research is a real challenge. A too optimistic/aggressive positioning may result in disappointments and a backlash, while a too pessimistic/defensive positioning may result in missed opportunities and competitiveness for Swedish industry, especially export industry, and society at large.

The least risky investments with public funding is in areas, which have strong generic components and components that produce values for solar energy development, independent of which specific PV, CSP or solar fuel systems that come in practical use and/or, which produce other values, outside the solar energy area, i.e. spin off effects. The rather basic research efforts that are currently made in Sweden, to a significant extent fulfil these criteria. They provide a basic platform for education and production of educated people in the solar energy area (but far

[99] US/EIA (2011)

from covering all these aspects), and they produce basic knowledge about materials and processes of broad value (spin offs). Furthermore they provide coverage of what happens at the international research frontier.

The more targeted, specific and applied the funded efforts are the more critical it is that they meet clearly identified needs and opportunities in society at large – both in the private and public sectors. Therefore it is important that an inventory of such needs and opportunities are made, as mentioned in the previous paragraph.

The overall goal for the research agenda can be formulated as to establish a kind of preparedness or contingency plan, meeting demands as follows:

- To create a flexible R&D structure and situation in Sweden that serves as a contingency plan for successive and competitive entering into the implementation phases of the solar power and solar fuel areas, as the opportunities and needs appear.
- At the academic level these R&D activities should be characterized by an appropriate balance between scientific and engineering activities, a balance that may be very different between different areas, depending on their maturity with respect to practical implementation, and which will change over time.
- The contingency plan aspects should include educational needs and needs of personnel for industries that engage in or plan to engage in the solar power and solar fuel areas. It should also cover needs of knowledge and expertise for the public sector/political level (e.g. governmental authority and department levels), especially for long-term planning and international cooperation.
- Systemic aspects should be covered by the above, including the need of modelling tools and high quality test centers in all areas, where Sweden already has global competitive knowledge.
- The knowledge base should include financial and economic level knowledge and knowledge of instruments to facilitate introduction/adoption of desired technologies.
- Public sector advanced technology procurement can be a means of connecting and cross-fertilizing bottom up and top down activities. This would also connect to innovations and the innovation system.

7 Proposal for design and direction of future Swedish research

A proposal for design and direction of a future Swedish research program in the area of solar power and solar fuels supported by the Swedish Energy Agency has been elaborated based on the analysis and discussion of previous chapters. The design of the program will differ depending on the budget available, which implies that the proposal has to pay regard to the least possible measure to achieve the desired effect but also the desired action to achieve the best effect.

7.1 Basic corner stones

The proposal is based on the basic corner stones as follows.

I. Continued support of on-going internationally competitive research activities and environments, according to the bottom up principle. This activity should be based on scientific excellence, and have relevance to the solar power and solar fuel areas. The emphasis is thus on international excellence and competitiveness in research, but should also include educational aspects (for society and industry). Generic aspects that are robust in the sense that they create basic values, independent of specific technology choices and developments, are especially valued. Besides the activities that are already on-going and generally receive excellent international evaluations, there is a large “latent potential” in the very strong academic materials science and nano-science activities in Sweden. This potential could be activated for solar power and solar fuels R&D by additional or redistributed funding. The same comment applies to molecular and microbiology.

II. Complement I. with ”top down” based efforts in more specific areas, where needs and opportunities of such activities are identified. This will require a deeper analysis, than is possible in this report, of the needs and opportunities that can be identified for Swedish industry and society, today and for a foreseeable future. In those areas, efforts will to a larger extent than in I. require activities at the engineering and systems studies/analysis/modelling levels. The ambition must be to increase the interactions between bottom up and top down activities. Such interactions will simultaneously benefit basic research, top down activities, education and interactions with industry.

III. As a means to achieve and execute both I. and II. with synergies between them, nodes with critical masses should be created or maintained, that are able to simultaneously perform both I. and II.

IV. Take actions to achieve better coordination of the R&D efforts supported by public funding. Since the scheme proposed here spans from long term very basic research to research that meets more immediate needs, and since the Swedish public funding for these types of research is distributed on several funding agencies, it is obvious that some coordination is needed. There are already some coordination schemes in operation, but they can certainly be strengthened. The Swedish Energy Agency appears as the most suitable agency for such coordination.

On a basic level a research program with its main point in I. reflects the desired action to achieve the best effect but most probably it will show the need of a larger budget. A pure action in accordance with II will most probably result in a more cost effective research, provided a qualified analysis is made pointing out the specific research requirements.

7.2 Additional recommendations

The history tells that Swedish research activities in the solar energy field have been oriented to be in the forefront of research on new materials and alternative systems, i.e. alternative to Si based PV systems. The research has resulted in the creation of internationally high profile competence centres in Sweden with leading knowledge in niche technologies like thin film CIGS, dye sensitized solar cells and organic solar cells. Only the first one has reached the market though.

The fast development of production technology, with corresponding decreasing costs, for crystalline silicon may be a paradigm shift in the solar energy world. In this context the absence of special expertise in c-Si technology in Sweden could be a decisive disadvantage as the c-Si technology might be the leading technology for the foreseeable future, combating other "challengers" via continuous improvement in performance and cost. A strategic choice to be discussed is if Sweden should reconsider and find niche areas within the crystalline silicon technology where a leading knowledge may be gained and may be beneficial to Swedish industry. The latter may be found, not in solar cell or module production, but at higher or lower systemic levels.

The solar hydrogen and other more complex fuels technologies have a very long term horizon and the development is currently to a great extent dependant on the introduction of hydrogen as a fuel for transport. The related direct production of other fuels that are easier to store and for which infrastructure exists, may be a new opportunity. The solar hydrogen technologies, including artificial photosynthesis and microbial hydrogen production, will most probably not reach commercialization in the coming decade. According to the goals of the EU-initiative FCH JU, commercialization might appear in 10 years' time, but this has been a moving target previously. The different technologies suggested for hydrogen production by solar energy should benchmark on other technologies that can be used for production of hydrogen from renewable sources, such as PV/wind together with electrolyser technologies. The closely related schemes to produce other fuels than hydrogen (alcohols etc), and to combine the techniques to bind CO_2 to achieve a CO_2 sequestration effect, have at least the same (probably longer) time scales as hydrogen production. This statement is not a critical remark with respect to research efforts at the basic (bottom up) level, where extremely advanced and generic scientific challenges exist for excellence in science. It is merely pointing out that top down type activities are hard to identify and risky to implement. Market introduction, if and when, are unpredictable in this area.

The support from the Swedish Energy Agency for research in new technologies should be considered from the view of the Agency's mission to promote the conversion of the Swedish energy system in a more sustainable direction. If existing values represented by research excellence enter the risk zone of being lost due to a change of balance between top down and bottom up initiatives, the responsibility for public funding of such activities should be transferred to appropriate programs that promote this kind of research. This is one reason why a more developed coordination of Swedish public funding in the actual area is proposed as above.

Although falling slightly outside the present assignment, the above mentioned ***public sector advanced technology procurement*** is an interesting possible component in a comprehensive and coordinated effort to develop Swedish R&D in the solar power and solar fuel areas, maybe especially in the former one. The basic role of advanced technology procurement would be that Sweden according to identified needs and opportunities and established long term political agenda, decides to purchase systems and demonstrators that promote the entrance of Swedish industry and society into the solar energy harvesting arena. Such a program would no doubt strengthen the connections and collaborations between top down and bottom up activities and actors. It would also connect to the innovation system for sustainable energy.

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Glossary and Abbreviations

Abbreviations and specific expressions used in the report.

AM1.5	Reference Solar Spectral Irradiance; at specified atmospheric conditions e.g. an absolute air mass of 1.5
ANR	Agence National de la Recherche (France)
a-Si	Amorphous Silicon – material used for thin film solar cells
CAP	Consortium for Artificial Photosynthesis
CdS	Cadmium Selenide – material used for thin film solar cells
CdTe	Cadmium Telluride – material used for thin film solar cells
CIGS (CIS)	Copper Indium (Gallium) Selenide – material used for thin film solar cells
CNRS	Centre National de la Recherche Scientifique (France)
CO_2	Carbondioxide
CPV	Concentrated photovoltaics
c-Si	Crystalline silicon based solar cells
CSP	Concentrated Solar Power or Thermal Solar Power
DME	Dimethyl Ether
DOE	US Department of Energy
DSSC (DSC)	Dye Sensitized Solar Cells, frequently referred to as Dye Sensitized Cells (DSC)
EPIA	European Photovoltaic Industry Association
EPSRC	Engineering and Physical Sciences Research Council (UK)
ESF	European Science Foundation
EU FCH JU	EU Fuel Cell and Hydrogen Joint Undertaking
EU PVTP	European Photovoltaic Technology Platform
EUR	Euro
Formas	The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning
gge	Gallons of gasoline equivalent
GTM	GreenTech Media
H_2	Hydrogen
IEA-PVPS	IEA Photovoltaic Power Systems Program
IR	Infrared radiation - electromagnetic radiation in the wavelength range from 0.75 micrometer to 1000 micrometers
JRC	European Commission Joint Research Centre
JSPS	Japan Society for the Promotion of Science

LCOE	Levelized cost of energy. LCOE analysis considers costs distributed over the project lifetime, expressed as cost per kWh
MEXT	Ministry of Education, Culture, Sports, Science and technology (Japan)
MIT	Massachusetts Institute of Technology
multi c-Si	Multicrystalline Solar cells – also known as polycrystalline solar cells, A material used to make photovoltaic cells, which consist of many crystals
nmC@LU	The nanometer consortium in Lund
NREL	National Renewable Energy Laboratory (US)
OPV	Organic/polymer Solar cells
PEC	Photoelectrochemical
Photon	A particle of light that acts as an individual unit of energy.
pmh	Per million head
PV	Photovoltaic. Pertaining to the direct conversion of light into electricity. A PV cell is the smallest semiconductor element within a PV module to perform the immediate conversion of light into electrical energy. Also called a solar cell.
R&D	Research and Development
SEK	Swedish kronor
Si	Silicon - A semi-metallic chemical element that makes an excellent semiconductor material for photovoltaic devices. It crystallizes in face-centered cubic lattice like a diamond. It’s commonly found in sand and quartz (as the oxide).
$SrTiO_2$	Strontium Titanate
Suns	Amount of solar concentration – one Sun equals 1,000 W/m^2 at the point of arrival
TiO_2	Titanium dioxide
USD	US Dollars
UV	Ultraviolet light - electromagnetic radiation in the wavelength range of 4 to 400 nanometers
Vinnova	The Swedish Governmental Agency for Innovation Systems
Wp	A unit used to rate the performance of solar cells, modules, or arrays; the maximum nominal output of a photovoltaic device, in watts (Wp) under standardized test conditions, usually 1000 watts per square meter of sunlight with other conditions, such as temperature specified.
μc-Si	Micro crystalline solar cells

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The Swedish Energy Agency is a national authority that works for a safe, environmentally friendly and efficient energy system. Through international co-operation and commitment, we can contribute to reaching the climate goals.

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